EFFECTS OF LAND COVER ON GROUNDWATER DYNAMICS IN MIDDLE YALA CATCHMENT, KENYA

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A Thesis submitted to the School of Engineering and Built Environment in partial fulfillment of the requirements for the award of the degree of Master of Science in Water Resources Engineering of Masinde Muliro University of Science and Technology.

October, 2024

DECLARATION

This thesis is my original work prepared with no other than the indicated sources and support and has not been presented elsewhere for a degree or any other award

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CERTIFICATION

The undersigned certify that they have read and hereby recommend for approval of Masinde Muliro University of Science and Technology a thesis entitled; **'Effects of land cover on groundwater dynamics in middle Yala Catchment'.**

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DEDICATION

This research thesis is dedicated to my family, my grand Parents, my Parents, wife: Eclai Isichi my children: Yvonne, Bournissen and Jeriel

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ABSTRACT

Groundwater depletion is on an increasing trend. Soil moisture content plays a major role in plant growth, nutrient transport, and oxygen balance. Assessment of soil water balance is crucial for understanding water dynamics to optimize water and fertilizer use. The main objective of the study was to examine the effects of land cover on groundwater in the middle Yala catchment, Kenya.. The specific objectives of this study were to investigate the groundwater recharge rate, to evaluate soil water distribution in the vadose zones for various land uses and to simulate the effects of various land cover on the flow in the vadose zone. Rainfall, Evapotranspiration, and root water uptake will be the main components of water balance. Therefore, intensive field experiments and HYDRUS-1D numerical modelling were applied to investigate the effects of land cover on groundwater dynamics. Primary data in this study were collected under varying environmental conditions: tree canopy and grassland plantations. Secondary data were collected from the weather station in Vihiga County. The HYDRUS 1D model was used to simulate the relationship between the two simulated scenarios under varying soil texture. Rainfall and soil data were combined with temperature and humidity collected by TMS sensors as model variables to determine the trends in water fluctuations. The findings revealed grassland sites maintained an average volumetric moisture content (VMC) of 32–35%, while eucalyptus sites dropped to as low as 18–20% during peak dry periods. The impact of seasonal rainfall patterns varied on the soil moisture, and the rate of simulated recharge in grassland was 4.2 mm/day on average as opposed to 1.6 mm/day on average in the area with eucalyptus cover. The model was able to well describe the trends in soil moisture in grassland but the interactions with eucalyptus were a problem. Finally choosing vegetation covers that boost recharge of groundwater and recommends controlled growth of eucalyptus is significant to sustainable farming. Future research suggestions are the long-term monitoring, investigation of various vegetation effects, and the combination of climate change and remote sensing technology. These observations are important in enhancing management strategies of groundwater and how land cover practices contribute to sustainability of groundwater in the area.

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ABBREVIATIONS, SYMBOLS AND ACRONYMS

ACPWL	Accumulated potential water loss
AET	Actual Evapotranspiration
BCG	Bungoma County Government
CN	Curve Number
ENSO	El Niño Southern Oscillation
FAO	Food and Agriculture Organization
HRU	Hydrological Response Units
LC	Land Cover
LVBC	Lake Victoria Basin Catchment
MTI	Moist Tube Irrigation
MVMC	Monthly Volumetric moisture content
PET	Potential Evapotranspiration
RMSE	Root Mean Square Error
RSR	Root Mean Standard Ratio
RWU	Root Water Uptake
SM	Soil Moisture
STICS	Simulator multidisciplinary pour les Cultures Standard
SWAP	Soil-Water-Atmosphere-Plant
SWAT	Soil and Water Assessment Tool
SWC	Soil Water Content
TMS	Temperature Moisture sensor
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural organization
VMC	Volumetric soil moisture content

OPERATIONAL DEFINITION OF KEY TERMS

Groundwater This term was used to define water below the earth's Surface within soil pore spaces and fractures of rock formations

Vadose zone This term was used to define the unsaturated zone between groundwater surface and water table where root activities occur.

Ground Water Dynamics This was used to define the different behavior of water in the vadose zone under varying seasons in varying land covers.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

This chapter covers general overview of the study with objectives and possible application of study in future

1.2 Background of the study

Groundwater makes up 99% of Earths available fresh water sources, it is the Earth's most accessed freshwater source. Groundwater has in most cases been poorly managed and even abused. As highlighted in a report by UNESCO, there is need to manage ground water sustainably as the global demand of water is projected to increase by approximately 1% yearly over the next 30 years. Our overall dependence on groundwater is expected to rise as surface water availability becomes increasingly limited due to climate change. Sahara Africa and the Middle East have adequate volumes of available groundwater supplies that can be abstracted in order to maintain water security. However, consideration for future generations and for the economic, financial and environmental aspects of storage depletion should not be obviously considered without adequate hydrogeological assessment (Lall et al., 2020).

Groundwater dwells in saturated zones below the ground. Wang et al., (2019), reported that recharge is highly influenced by climate change and human activities. Goundwater recharge, defined as “the rate at which aquifers are replenished,” plays a critical role in maintaining groundwater sustainability (Schreiner-McGraw & Ajami, 2021). One of the most important human activities is changes in land cover. Land cover refers to the natural and human-made features present on the Earth's surface, including forests, water bodies, and built structures (Siddik et al., 2023). Changes in land cover influence groundwater by altering the distribution of water balance components (Olarinoye et al., 2023).

Land cover is crucial in regulating different patterns of soil moisture where it greatly determines the rate of infiltration, surface runoff, and evapotranspiration, especially during the growing season (Fu et al., 2000). Several studies have been carried out which demonstrated varied spatial distribution of water resources between trees and groundwater (Fernández et al., 2008). The studies majorly highlight the role of available water in shaping the structure of herbaceous layers and open-tree strata being emphasized (Van Der Waal et al., 2009). The studies that have been carried out have provided inadequate information on the effect of land cover on water dynamics

Ecosystem sustainability, regulation of solute transport, heat transfer, and controlling regional runoff majorly rely on soil water (Acharya et al., 2017). Meteorological factors, topography, land cover, and soil characterization are greatly influenced by dynamics of soil water (H. Qi et al., 2019). Vertical movement of soil water is influenced by soil horizonation, soil organic matter, root distribution, and soil structures hence changing soil hydrological processes. Soil water redistribution is influenced by, evapotranspiration, plant water uptake, soil surface infiltration, and precipitation.

This study was conducted in the Middle Yala Catchment, Kenya, an area experiencing land cover changes that have significant implications for groundwater recharge and sustainability."The domestic and municipal water demand in the Yala catchmentis estimated to be 533 million cubic meters per year (Hamza & Getahun, 2022)). An approximately 32.3 million cubic meters was being extracted monthly, processed, and utilized for municipal, domestic, livestock, irrigation, and industrial activities(Kemunto, 2018). In the catchment, the average daily water supply per person is around to be 20 liters for rural populations and 50 liters for urban populations.

1.3 Statement of the Problem

The world population is drastically increasing, a recent prediction by the United Nations shows that by 2025, the approximately 8 billion mark will be surpassed. The projection further details that in 2045 there will be more than 9 billion people (Gerland et al., 2014). Population increase comes along various land cover activities as human populations strive for livelihoods, farming, and settlements, thus stressing natural hydrogeological setup. The reliance on surface water may soon be challenged with increased vulnerability to pollution and the effects of climate change. According to Arsiso et al. (2017), changes in surface water resource depletion and reductions in stream flow will pose significant threats to sub-Saharan African nations in the forthcoming decades and this may lead to over-reliance on groundwater. Recent studies show that Africa is heavily reliant on groundwater and the trend is increasing with respect to the growth in population (Foster et al., 2020). However, increased land cover activities have negatively influenced groundwater recharge therefore, posing a forthcoming limiting factor to economic growth (Yahya et al., 2020). Land cover activities have different effects on the rate of precipitation and infiltration especially in areas with reduced forest cover. Various land cover activities play a key role in soil water distribution. Human development activities such as infrastructures and farming lead to different runoff coefficients, hence affecting groundwater recharge. With increased initiatives to curb effects of climate change, more artificial forests are being developed. However, some of the tree species planted aggressively compete for subsurface water hence affecting groundwater recharge.

Rapid urbanization, agricultural development and deforestation have all significantly affected ground water flow in Kenya. The urban localities, like Nairobi and Mombasa, have experienced reduced groundwater recharge due to the presence of numerous impervious areas, which has complicated surface water to sink in and exacerbated surface drainage (Gichuhi and Gitahi, 2021). The natural groundwater recharge has been affected by intensive farming and irrigation in agricultural regions that leads to soil compaction and changes the rate at which water enters the ground (Owuor et al., 2016). The natural water cycle has been disrupted by deforestation in areas such as the Mau Forest Complex, resulting in soils having a difficult time retaining water, and groundwater being difficult to replenish. Additionally, this has perpetuated the water depletion downstream (Rwigi, 2014). Reforestation has also changed the patterns of groundwater circulation in cases when non-native species that consume a lot of water have been introduced (Reisman-Berman et al., 2019). Changes in land cover, and changes in the weather have also contributed to groundwater resources not being easily managed or sustainably managed. Over the years, groundwater has been depleting astronomically in relation to contribution in the Yala catchment (J. Okungu, Adeyemo, & Otieno, 2017).

It is against this backdrop that this paper will examine the impact of land cover on ground water processes by examining the relationship between land cover activities and soil characteristics against ground water recharge. This is important because it gives information on the sustainable practices of ground water management that can be adopted to come up with policies. Other policies that are already in place, like Kenya Water Act of 2016, which focuses on sustainable land and water application, are also supported by the study.

1.4 Research objectives

The main objective for this study was to investigate the effects of land cover on groundwater dynamics in Middle Yala catchment.

1.4.1 Specific Objectives

The specific objectives were;

i. To investigate the groundwater recharge rate
ii. To evaluate soil water distribution in the vadose zone for various land cover.
iii. To simulate the effects of various land cover on the water flow in the vadose zone.

1.4.2 Research questions

The research questions were;

i. What is the groundwater recharge rate in the middle Yala Catchment?
ii. What is the soil water distribution in the vadose zone of middle Yala Catchment?
iii. What is the effect of land cover on the water flow in the vadose zone?

1.5 Significance of the Study

Groundwater is an essential natural resource that acts as a primary source of drinking water for millions of people worldwide and playing a crucial role in sustaining ecosystems. Understanding how land cover practices impact groundwater dynamics is essential for effective water resource management, sustainable land cover planning, and the preservation of ecological balance. This study provides crucial data to inform land cover planning decisions, guiding policymakers to make informed choices that balance economic development with environmental protection. The study findings will contribute to the advancement of scientific knowledge in the field of hydrogeology and environmental science. It also provides valuable data that could be used in future research and modelling efforts to refine our understanding of complex groundwater systems

1.6 Justification of the Study

It was critical that the vadose water distribution and characteristics under various land cover in River middle Yala catchment be understood and be documented so as to come up with recommendations that may enhance sustainable land cover practices to that enhance ground water recharge for current and future. In the absence of scientific research, leadership would not have appropriate basis for future planning and future development and water development. It would not be possible for the authorities to plan for ground water utilization as since the surface water is being depleted and polluted.

1.7 Scope of the study

This study was conducted in the Middle Yala Catchment, located within the Lake Victoria North Catchment. It was limited by the availability of rainfall data, which spanned 20 years, including current data from May 2023 to July 2024. Simulation and forecasting for future conditions under varying soil conditions were performed. However, there are other known land cover cases with missing or inconsistent historical data, and the Middle Yala Catchment could be one of them. This scenario was anticipated, and the missing data gaps were addressed by applying suitable methods. The study focused on parameters related to the vadose zone and rainfall data and utilized HYDRUS 1D modelling, which is intended to represent water and solute transport in unsaturated soils (vadose zone) which directly aligns with the research objective of this study(Šimůnek, 2015).

1.8 Basic Assumptions of the Study

The assumptions made on this research were founded on some basic assumptions that would guarantee the reliability and validity of the findings. To begin with, it was presumed that the hydrological information especially the water supply peculiarities of the previous and the existing data of 1970-2015 were gathered in good faith and were accurate. This was an essential assumption because the research used this information in deriving the right results of the simulation and any anomalies would have invalidated the findings of the study.

Another assumption in the study was that the vadose zone properties and particularly water demand could be relied upon without a significant error. These qualities were significant in that they were dependable to establish that groundwater dynamics could be simulated and analyzed. These data were valid as they formed the basis of the research because any kind of inaccuracies would have led to false conclusions.

The other assumption was that whatever was produced out of the literature and was employed to compare the works of different authors was that which did not change along with most of the changes in the world. This has been done on the basis of this assumption so that the context of the research was always topical and results of other research could be used in the area of the research.

The study also assumed that the materials and methods used were suitable and common in the field and this enhanced reliability and validity of the results anticipated. The choice of the suitable materials and methods is also highly critical to the scientific research and they were assumed to be necessary to render the study successful.

Finally, in the data analysis, the assumption was that outliers or bad measurements that could have affected the data were not considered in the data analysis. This was done on an assumption in order to ensure validity of the conclusions drawn on the study, so that only valid and correct data were taken into account in the analysis. All these assumptions gave a solid background to the study that guided the course of the study and made the findings as valid and practical as possible.

1.9 Thesis Organization

This study is organized in five chapters. Chapter One, Introduction, introduces the study concept by illustrating background of the entire study, problem statement, study objectives, research questions, significance of the study, justification, scope, and basic assumptions.

Chapter Two, Literature Review, entails examination of both simple and technical aspects of thematic areas concerning the research objectives, based on past studies. The review evaluates water resources in general, examines water vadose water and reviews information concerning water legislation and integrated water resources management. It also reviews literature concerning hydrologic modeling with the focus on vadose water; and application of HYDRUS 1D for river soil water. The section finally analyses the conceptual framework.

Chapter Three, Research Methodology, describes the area, outlines the research design, data collection, and data analysis procedure. The research methodology explains the procedures that were observed from data entry, calibration, validation and analysis using the HYDRUS 1D software.

Chapter Four, Results and Discussions, is organized into three sections: groundwater recharge rates, soil water distribution in the vadose zone, and the simulation of land cover effects on water flow in the vadose zone using HYDRUS 1D. The chapter presents the study's findings, analyzing the data collected and discussing how different land cover impact groundwater dynamics. The results are interpreted in the context of the study's objectives, comparing observed data with model predictions, and assessing the implications of these findings on water resource management in the Middle Yala Catchment.

Chapter Five, Conclusions and Recommendations, illustrates as summary of issues generated from the study findings in terms of the conclusions of the study. Recommendations have also been illustrated in view of the inferences drawn from the findings. Finally, areas for further research have been suggested by the author.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This section reviews the literature relevant to both the fundamental and technical aspects of the thematic areas aligned with the research objectives. It begins with an overview of global water supply and demand dynamics, examining current utilization patterns and the challenges posed by pollution and competing users. The impact of the hydro political factors and administrative issues on water use is also reviewed and points at the complexities involved in governance and policy making in the management of water resources. It also presents the importance of authorities in formulating and implementing water policies which is crucial. The review has ended with the introduction of different models employed in soil water modelling, especially the HYDRUS 1D model, its application and its relevancy to the study. The conceptual framework is also introduced in this chapter, and it explains the relationship between the research objectives and the overall study, giving a systematic way of understanding the relationship between land cover, soil water dynamics, and groundwater recharge.

2.2 Soil water dynamics

The existence of water in the soil is essential for the growth and existence of plants and vital for ecosystem survival. It is contained in the spaces between the soil or particles and the maximum capacity for water to be held in the soil depends on its porosity. Andrade et al. (2020) states that the water in the soil is always affected by a number of things including rainfall, rainfall evaporation, temperature, and vegetation. Similarly Singh and Thompson (2016) stated that soil erosion is effective by the soil water content - therefore making soil water an extremely important aspect in the conservation and management of soil.

Soil water is one of the most needed resources which have direct impact in the soil; for example, the moisture level, nutrient availability to plants and the level of aeration in the soil. The water in the soil can occur in different forms depending on the nature and functions of soil water; the forms are gravitational, capillary and hygroscopic water. The volume of water soil can store or redistribute is determined by the sizes of soil pores and their distribution based on the soil texture and structure (Bansal et al., 2022). The fact that clay soils can retain water well is usually due to the small pore spaces, yet this does not automatically mean the availability of water to plants and the ease by which water will move through the soil (Ngugi et al., 2015). When the total pore water fills the space, the soil becomes saturated.

Precipitation is the primary source of soil water, and it can be easily lost through processes such as transpiration and percolation into aquifers and groundwater reserves (Hoekstra, 2019). The majority of fresh water consumption is linked to biomass production for human consumption. However, water policies tend to focus on agricultural irrigation, which accounts for approximately 25% of the global water requirement for agriculture. Additionally, around 10% of humanity's water needs are allocated to industrial and domestic water supplies, representing a relatively small portion of direct human water requirements (Gavrilescu, 2021). The increasing demand for water in agriculture, especially under the pressures of climate change and the expansion of arid regions with soil water deficits, necessitates the implementation of effective soil water management policies for both agricultural and natural ecosystems.

Soil erosion is a major factor especially in dry soils, the absence of moisture may cause greater slaking than pre-wetted soils with lesser slaking. The dry soils are likely to acquire cement-bonding and hydrophobic characteristics that enhance the mechanical resistance to detachment and the aggregate breakdown leads to erosion of the soil becoming less, thereby decreasing the rate of soil erosion. As it has been found, the moderate level of water in the soil can encourage the fast development of bonds between particles of soil, organic matter, and erosion is slowed down (Kwon et al., 2020). On the other hand, when soil water increases, it makes the bonds among the soil particles to become more easily broken, thereby increasing erosion. Likewise, when the soil water content is too little, the soil particles cannot settle into low energy states because there is no lubrication, resulting in increased cohesion and a higher erosive rate.

The water content of soil also brings about an interesting influence on the level of groundwater especially in the shallow Aquifers. The surface of the earth may have an effect on capillary rise (the upward movement of water through the pores of the soil) thereby impacting the overall storage of water in the vadose zone. The vadose zone is located above the water table yet below the surface and represents a system in its own right, having a determined volume capable of carrying groundwater waves (Radcliffe et al., 2002). The finite thickness of the vadose zone may impose a capping effect for low frequency fluctuations of the groundwater table that may significantly affect the dynamics of such fluctuations.

The relationship between ground water and soil water is a complex, yet important aspect of considering hydrological cycle interpretation and efficient water management action. The vadose zone acts as a barrier mediating movement of water between the surface and ground water table. This becomes important to having consistent groundwater levels and surface usable water (G. Singh et al., 2018). The capillary rise in the vadose zone is dependent on the soil's texture, structure, and moisture content and all of these also play a role in determining the water holding and transferring ability of the soil.

Manik et al. (2019), explain that in an agricultural setting, soils play a critical role in regulating water status, forming optimal yield of crops and soil health. Water saturation in the soil can lead to water logging that eliminates oxygen from crop roots and can lead to root rot, while too little water can cause drought stress, slowdown plant growth and productivity. Thus, it is crucial to understand the forces that can affect the dynamics of water in the soil, such as land cover practices, soil texture, and soil structure, in developing effective water management practices.

Furthermore, land cover change also affects water dynamics in soil by altering the hydrological balance at the catchment level. For example, deforestation can reduce soil water capacity, increase runoff, cause soil erosion, and also limit groundwater recharge rates (Kundu et al., 2017). Conversely, reforestation and conservation practices can enhance groundwater recharge and retention capacity in soils, ultimately supporting sustainable water resources.

Land use changes can have a significant influence on soil water movements in a basin, affecting not only soil moisture but also the complete hydrological balance of the basin. Changing agricultural areas or urbanising forests can change the natural water cycle and reduce groundwater recharge, decrease infiltration, and generate increasing surface runoff (Lana-Renault et al., 2020). Over time, this change can have implications for future water availability, especially during drier periods or drought conditions.

2.3 Rainfall and the water cycle

Rainfall is the key element of the hydrological cycle as it is the main source of water that enters the terrestrial ecosystem. Rainwater distribution and fate depend on a number of factors which include vegetation cover, soil type, topography and land cover practices. The sequential routing of rainwater as postulated by Shaxson (2003) and informed by other previous researchers such as the Food and Agriculture Organization (FAO) offers a breakdown explanation of how rain water engages with the environment after arriving at the surface of the earth. The interactions are important in the dynamics of soil water, especially as regards to the growth of plants, recharge of ground water, and surface water runoff. It is summarised as shown in the figure 2.1 below.

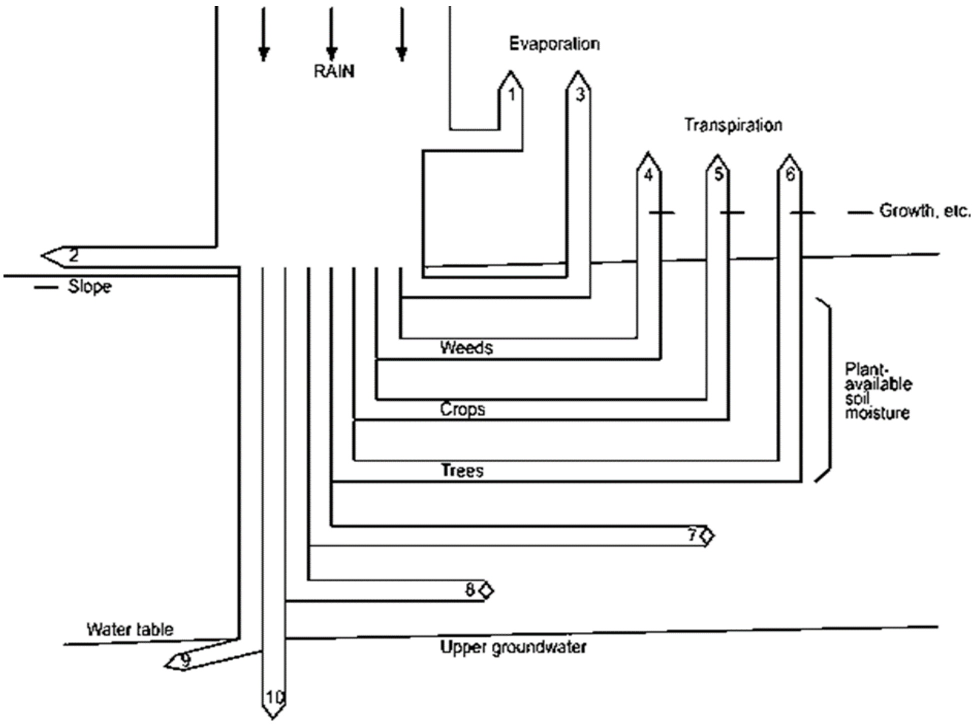

Figure 2-1; Rainfall and water cycle (Shaxson & Barber, 2003)

2.3.1 Direct Evaporation from Wetted Leaf Surfaces

When precipitation occurs on foliage or ground cover, some quantity of the water may be intercepted by the leaves and other parts of the plant structure above the soil. This water then returns directly to the atmosphere and is lost from the hydrologic cycle without ever reaching the soil profile. The amount of water lost through interception is moderated by the characteristics of the vegetation such as cover density, leaf area, and weather conditions like temperature and humidity. In a densely forested ecosystem, there may be a significant amount of water that will evaporate through the leaves of the plant and be withdrawn from the soil moisture and groundwater recharge system by reducing the amount of water that is available to infiltrate into the soil (Dawson & Goldsmith, 2018).

2.3.2 Surface Runoff/Stormflow

When rainfall exceeds the ability of the soil to uptake rainwater, the water travels across the land surface into small streams, rivers, or other bodies of water, known as surface runoff. The process occurs more readily on compacted or impermeable soil types, steep slopes, or an area with limited vegetative cover. Surface runoff can contribute to soil erosion, nutrient loss, and land degradation, particularly where land management methods are inadequate. Surface runoff also influences the stormflow of rivers and streams and can lead to flooding and increase the amount of pollution to aquatic bodies. Effective management of surface runoff is necessary for reducing soil erosion, protecting water quality, and maintaining hydrologic balance within a watershed (Balasubramanian, 2017).

2.3.3 Direct Evaporation from the Soil Surface

When precipitation water gets into soil, some of it might evaporate directly back to the atmosphere, particularly in hot and dry conditions with exposed soil. The rate of direct evaporation from soil is influenced by soil texture, water content, and the presence of plants or mulch cover. Fine-textured soils, such as clay, tend to retain moisture better and slow the rate of evaporation. In contrast, coarse-textured soils, such as sand, tend to lose moisture more quickly. Plants or mulch cover also help to reduce evaporation by providing shade and reducing the soil surface temperature. These factors are significant in arid and semi-arid environments where conserving water is extremely important (Oweis et al., 2012).

2.3.4 Soil Moisture at root-range of existing weeds, crops, trees, available to plants.

Some of the rainwater infiltrates the soil, where it is held as soil moisture in the root zones of plants such as crops, weeds, and trees. Soil moisture is critical to plant growth and the functioning of an ecosystem. Soil moisture is influenced by soil texture, structure, organic matter, and root distribution. Clays and loams are fine-textured soils with a higher water-holding capacity, and therefore more moisture becomes available to plants over time. Sandy soils with coarse-textured soils, which have reduced water-holding capacities, might have to receive more frequent rain and/or irrigation to ensure sufficient moisture in the soil to support plant growth. Soil moisture in the root zone is useful in supporting various physiological functions such as nutrient uptake, photosynthesis and transpiration. Irrigation, mulching, and cover cropping of soil are important in controlling soil moisture in agriculture to ensure plant growth, and production of crops is sustainable (Oweis et al., 2012).

2.3.5 Soil Moisture within Root-Range of Existing Plants but Held at Tensions Unavailable to Them

Plants do not have access to all the soil moisture in the root zone. The soil moisture is retained at different degrees of tension in the soil matrix based on the size of the pore and the nature of the soil particles. The low tension water (capillary water) is available to the plants, whereas high tension water (hygroscopic water) is strongly adsorbed to soil particles and can hardly be extracted by roots. Such water is located in the tiniest pores in the soil and needs more energy to be removed, which in most cases the roots of plants are not capable of doing. The percentage of unavailable water also depends on the type of soil as clay soils normally have a higher percentage because of their fine texture and large surface area. The distribution and availability of soil moisture is an important understanding in the management of soil water, particularly in areas where there is a shortage in water supply (Shaxson, 2003).

2.3.6 Soil Moistures Held at All Tensions, but Below Root-Depth of Existing Plants

Subsurface soil water may as well be found below the root zone of most plants and therefore be inaccessible to the plants. This moisture can exist at different tensions and can remain in the soil over long periods before it is either drawn up to the surface through the influence of capillary forces or pulled down to the surface by the influence of gravity. The existence of moisture at these depths can help recharge ground water provided that it reaches the water table sometime down the line. This deeper moisture can be accessed by some deep rooted plants or trees particularly in places with well developed soils. This moisture however is inaccessible to most crops and plants which have shallow root systems. Soil moisture management on various depths is significant to support the growth of plants in areas with scarce rainfall or droughts (Nippert and Holdo, 2015).

2.3.7 Water Not Captured by Roots and Small Pores, Moving to Groundwater and Streamflow.

Water that does not settle into plant roots, or small pores in the soil, may flow on down the soil profile and eventually reach the ground water table or be part of stream flow. Deep percolation or infiltration process is one of the main processes involved in groundwater recharge that is very important in ensuring the long-term water availability. The texture and structure of the soil, moisture content, vegetation cover and land management practices also affect the rate of infiltration and deep percolation. High infiltration soils (sandy soils) promote fast water flow, which improves the recharge of ground water. On the other hand, soil with low infiltration rate such as clay soils can inhibit water movement, which may cause surface run off and lower ground water recharge. Impermeable layers or hardpans may also increase the hindrance to flow of water causing perched water tables. Practices of good land management which increase infiltration and deep percolation are crucial in the preservation of ground water sources especially in regions with high water demand (Barlow & Leake, 2012).

2.3.8 Leakage to Deep Groundwater Beneath the Catchment Floor

In other instances water that gets into the soil can keep on flowing downward beyond the root zone and shallow ground water table and finally reach deep ground water aquifers. It is referred to as leakage or deep drainage, and restores deep groundwater reserves that form significant sources of water to human consumption, agriculture and industry. The permeability of the soil and underlying rock layers, and the occurrence of fractures or faults through which the water can move determine the rate of leakage to deep groundwater. Deep groundwater recharge may form a large fraction of the hydrological cycle in high-rainfall regions, and may be an important water source in times of drought or water scarcity. In arid and semi-arid areas, however, where precipitation is low and evaporation is high, the recharge of deep groundwater can be insignificant, and groundwater resources will be depleted slowly. Managing deep groundwater resources in a sustainable way necessitates a comprehensive knowledge of the processes of leakages and recharge, as well as introducing policies and practices to preserve these valuable resources (Seiler and Gat, 2007).

2.3.9 Vadose zone

The unsaturated zone, commonly referred to as the vadose zone, is defined as the space found between the surface of the earth and the regional water table or level of groundwater. This area includes both saturated and unsaturated sub-surface soil (also referred to as regolith), and a capillary fringe, which is a zone of water that exists perched above the water table level of groundwater, due to the capillary potential of the unsaturated materials (Nimmo, and Lokens, 2009). Depth of the vadose zone can vary tremendously, from less than one meter to several hundred meters, depending on the distance to the water table (Arora et al., 2019). The unsaturated zone plays a vital role in influencing the movement of water, the movement of solutes, and the spreading of contaminants in the terrestrial subsurface.

Water in the vadose zone occurs as a mixture of solid, liquid and gas; the subsequent complexity influences the flow of water in the vadose zone, and consequently changes in the relative proportions of these phases causes them to change properties, including hydraulic conductivity. The relative contents of water and air of the vadose zone can vary greatly which makes the phenomena of unsaturated flow be sensitive to this (Nimmo and Likens, 2009). Such variations result in challenges for understanding and governing water transport and the importance of examining the interactions in this zone will be essential in managing the water resources.

The vadose zone is additionally important for the various ecological and hydrological processes. The vadose zone is home to a lot of different microbes including bacteria, fungi, protozoa and viruses which are critical components of nutrient cycling and pollutant degradation (Selker et al., 1999). The deeper portions of the vadose zone can also become much more extreme, where there is limited water availability and nutrient supply, but microbial communities contribute to the balance of terrestrial habitats.

In addition to its biological component, the vadose zone is important for groundwater recharge and plant-water interactions. Recharge of groundwater occurs as water from the vadose zone reaches the aquifers and affects water availability (X. Liu et al., 2019). Vegetation sources moisture from the vadose zone and the ability of vegetation to access that moisture depends on the amount of moisture retained in soils and the adhesive forces holding the moisture in place. Dry soil forces all plants to generate a higher suction to access water, which can result in low transpiration and wilting in plants (Soylu et al., 2014). This relationship shows the importance of understanding soil water dynamics so that agricultural practices and irrigation, which greatly increases water use around the world, can be managed..

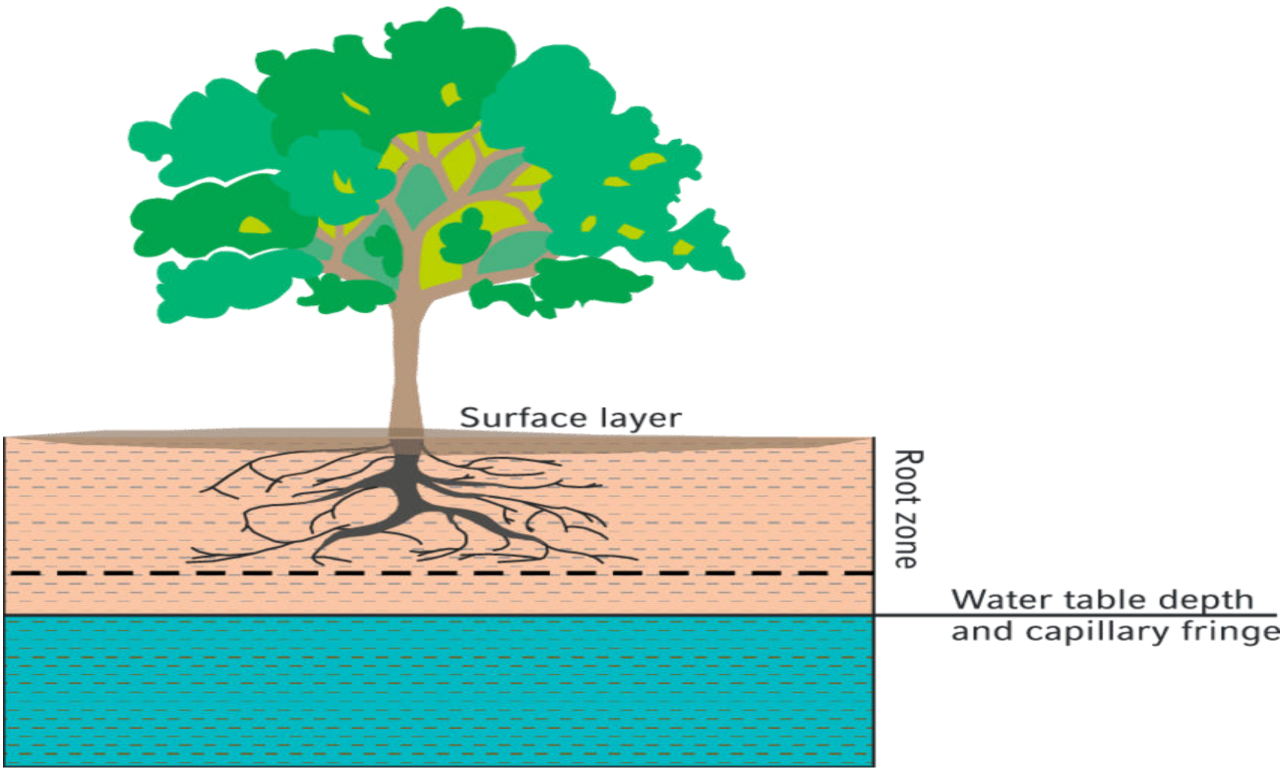

Figure 2-2: Vadoze Zone

Source: Alley, Reilly, and Franke (1999)

2.4 Effects of land cover on groundwater

Soil-water content is a measure of volume of water contained in soil. It can also be referred to as water content and is an indicator of the quantity of water existing in soil (Xu et al., 2021) . The main source of soil water is the rain; implying that areas that experience high amounts of rainfall have higher soil water content as compared to areas with low rainfall. Rainfall is the main source of soil moisture. Land vegetation is highly dependent on water which is a key factor that affects survival, growth of plants and supportive from environment to vegetation (Xu et al., 2021). Different plants have varying water consumptions as a result of root structure, depth and the rate of respiration.

2.5 Tree Canopy

The effect of tree canopies on ground water is highly complex due to ecological processes they cause. The first is transpiration, which involves the uptake of the water by the roots of the trees and the loss of the water to the atmosphere via the leaves. This is the process along with the evaporation of soil surfaces, which is referred to as evapotranspiration. A large cover of canopy increases evapotranspiration, which may decrease recharge of groundwater and result in low groundwater levels at least in well-wooded spots. Deep-rooted trees are able to intercept large volumes of groundwater, which may reduce the amounts of water that other plants have and affect the rate at which groundwater is replenished (Sun et al., 2016). Seasonal changes also influence the influence of tree canopies, during the growing season, high rates of transpiration can deplete the groundwater and in the dormant season, low uptake of water may enable groundwater levels to bounce back. Also, certain tree species may be able to perform hydraulic redistribution, whereby water in the deeper layers of soil is moved to the shallower layers by the roots. It may lead to changes in the local groundwater processes and recharge (Acharya et al., 2018).

2.6 Grassland Cover

Grasslands are important in regard to groundwater-based dynamics because they affect the process of water infiltration and recharge. Their root systems are also vast and their soil structures are porous thereby increasing the rate of penetration of water into the ground. Grass roots provide avenues through which rainwater can penetrate the soil thereby refilling aquifers. In rainy seasons, grasses serve as natural sponges, cleaning up water and holding it in the root zone areas, and in the process, reducing surface run-offs and alleviating floods. Grasses transfer stored water in transpiration and evapotranspiration as the groundwater increases, which serves as a buffer to drought and increases the level of ecosystem resilience. Grasslands also play a role in enhancing the quality of ground water through controlling erosion. Their deep root systems provide stability to the soil and minimize the likelihood of erosion and transportation of sediments into the surface waters hence preserving the quality of groundwater by avoiding the transportation of sediments and contaminants (Snyman, 2000).

2.7 Forest Cover

Forest ecosystems significantly affect groundwater quality and quantity (Kezik & Hacisalihoglu, 2022). Forests provide high-quality freshwater in a sustainable manner, but they also consume more water compared to other ecosystems due to interception and transpiration. Forests influence the microclimate and the amount of precipitation reaching the soil surface. Changes in land cover from forest to herbaceous vegetation can alter the quality and quantity of stream waters in watersheds. Forests increase water retention time by delaying snowmelt in spring and maintaining frozen soils longer than open sites. Their greater soil porosity makes forest soils more permeable, reducing runoff during precipitation. This increased water-holding capacity of forest soils means that they retain more moisture during dry periods, which benefits the overall water regimen.

2.8 Urbanization

The process of urbanization and land-use modification has far-reaching effects on the dynamics of surface and subsurface water that changes the quantity and quality of water resources. Due to the increased population in cities, the natural landscape has been covered by impervious surfaces such as roads and buildings. This shift quickens surface water runoff and the travel time of water to rivers, which could dramatically affect the hydrological cycle (McGrane, 2016). As a result, the volume of groundwater that can be replenished to the shallow unconfined aquifers is much less, indicating the limited capacity of land to absorb and store water.

The impacts of land development on hydrology are typically assessed at small spatial scales, based on the assumption that these effects are minimal or negligible at larger scales. However, these impacts are even more cumulative as urbanization occurs over larger geographical regions. This development may approach the point where it can threaten the sustainable use of surface and groundwater resources, no less the ecological character of the landscape (Sharma, 2017). By nature of the hydrological system being interrelated where rainfall, evapotranspiration, surface runoff, unsaturated flow, and saturated subsurface water movement processes occur, to change one component of the system could have extreme ramifications.

2.9 Groundwater Recharge Rate

Groundwater recharge is a complex process that involves the downward movement of water through the soil layers into the aquifer influenced by various natural processes, weather, vegetation and subsurface geology. Further, groundwater recharge is also very important because it supports aquifer health, and water supply, and aids in regulating groundwater (Smerdon, 2017). therefore, when assessing groundwater sources important for both human uses as well as ecosystems, it is critical to assess recharge rates, timing and the spatial distribution of recharge.

While it is important, groundwater recharge is also one of the least understood components of hydrology, primarily due to the high spatial and temporal variability associated with it. The variability is caused by a range of natural processes (e.g., soil type and rainfall) and human activities (e.g., Land cover and urbanization - Moeck et al., 2020). Poor estimates of recharge will negatively impact the sustainability of groundwater through over-pumping, land subsidence and contamination exposure. Therefore, in response, recharge needs to be evaluated to support balancing groundwater use with the environment, and sustainability over the long term.

The recharge of groundwater takes place when rainwater or surface water like run-off flows in the ground and seeps through the soil to the aquifer. This process may occur either naturally or artificially by managed aquifer recharge (Seiler and Gat, 2007). The difference between infiltration, the capacity of soil to absorb water and recharge, the water remaining after deductions such as evapotranspiration needs to be differentiated. Recharge is the overall infiltration which penetrates the groundwater table and creates an important connection between surface water and underground system. The two methods of recharging are focused or diffuse (direct). Diffuse recharge occurs over wide regions in general, commonly through humid regions and focused recharge occurs in particular regions such as along streams or in depressions particularly in arid regions. In cities, impervious surfaces lead to the draining systems underlining the importance of focused recharge.

Given the complexity of groundwater recharge, uniform recharge rates in models can lead to inaccuracies, particularly in regions with varying soil properties or fractured bedrock. Overestimating or underestimating recharge can result in environmental risks such as contaminant spread, resource depletion, and land subsidence. Therefore, integrated hydrologic modeling, which combines groundwater and surface water models, is essential for more accurate estimates of recharge, water flow, and the movement of contaminants (Scanlon & Cook, 2002)

Groundwater recharge is especially vulnerable to anthropogenic influences such as climate change and land cover alterations, which endanger freshwater resources worldwide (Beigi & Tsai, 2015; Vorosmarty et al., 2000). Groundwater, serving as a primary water source for over 1.5 billion people globally (Ahmad, 2002), relies on recharge processes to remain available. Population growth, agricultural expansion, and urbanization have altered the volume, timing, and distribution of recharge, with significant global consequences. These alterations may impact ecosystems directly as well as indirectly, which makes groundwater management even more difficult.

The recharge of groundwater is hard to estimate as it cannot be directly measured over space and time (Earman and Dettinger, 2011; Moeck et al., 2020; Smerdon, 2017). Calculations are based on hydraulic head observation or water-balance approaches, both of which are subject to uncertainties related to other factors - observing evapotranspiration, surface-groundwater interchange, and local geology (De Vries and Simmers, 2002). These uncertainties are compounded, when assessing for future recharge rates due to climate change. Climate models have a reasonably accurate rate of climate change leading to temperature increases, but struggle with forecasting precipitation and atmospheric moisture (Fallah et al., 2020; Fatichi et al., 2016; Kent et al., 2017). These uncertainties are compounded by the atmospheric process and the difficulty with spatial downscaling (Bender et al., 2021; Huebner and Kaatze, 2016). The seasonality that precipitation and temperature represent are leading factors in determining future recharge rates (Moeck et al., 2020); therefore, it is important to accurately model future climatic conditions (Reinecke et al., 2021).

Additional uncertainties are related to the effects of elevated CO_2 on vegetation affecting estimates of groundwater recharge (Milly and Dunne, 2016). Climate models which do not actively simulate vegetation response, on CO_2 change, could result in underestimating runoff, and thus overestimating reductions in recharge. Regardless of these difficulties, recent models have shown major losses in recharge in areas such as the central United States, southern Chile, and the Mediterranean, and gains are anticipated in areas of the Arctic, East Africa, India, and Southeast Asia (Reinecke et al., 2021).

The diverse subsurface properties, such as hydraulic conductivities and porosities, in hydrological sciences, have major effects on the water balance and ground water recharge. Subsurface variability is not typically addressed in current large-scale hydrological models giving rise to erroneous predictions of recharge rates. Hartmann et al. (2017) note that the strongest subsurface heterogeneity territory, such as the carbonate rock regions in Europe, Northern Africa, and the Middle East, has a higher rate of recharge. These subterranean regions, which have undergone karstification, play a major role in supplying drinking water and the recharge rates are as much as four times greater than what is already projected. The paper highlights that effective management of groundwater should consider the rapid flow of water on the surface to the underground water and be based on the spatial differentiation of the recharge rates to ensure the correct and sustainable water resource management.

Scanlon et al. (2006) state that an international study of approximately 140 recharge study areas across arid and semiarid regions offers critical information regarding the processes, controls, and rates of recharge that are required to manage water sustainably. The study mainly employs the chloride mass balance (CMB) method to determine recharge. They are concerned with water resources analysis, dryland salinity (e.g. in Australia) and radioactive waste disposal (e.g. in the US). Megabasins (40374000 km2) lie in the range of 0.2 to 35 mm per year at an average rate, which takes into consideration 0.1-5 per cent of the long-term annual precipitation. Local recharge rates may also be very high, as much as 720 mm/y in areas with concentrated recharge beneath ephemeral streams and lakes. Recharge is sensitive to variations in land use and climate variability (both positive and negative), and its responses to other phenomena, such as the El Niño Southern Oscillation (ENSO), and historic climate changes have significant effects. To illustrate, recharge was three times higher in the southwestern US during frequent El Nino than during wetter La Nina seasons, and in Africa, it ranged between 30 mm/year of dry times to 150 mm/year of wet times. Alteration of the recharge rates has been a major effect of land cover change, including deforestation and agricultural conversion, in some cases by up to an order of magnitude. In the irrigation areas the recharge is between 10 and 485 mm/year but is mostly not able to match the rate of groundwater extraction thus resulting in ground water depletion. The synthesis offers useful information in the development of effective groundwater management strategies due to the variation in climate and land cover changes.

2.10 Soil Water Distribution in the Vadose Zone

The vadose zone, or the unsaturated zone, is an essential part of the hydrological cycle that exists between the ground and the water table. The vadose zone plays an important role in the movement and spatial distribution of water within soils, which is necessary for many hydrological and environmental processes (Arora et al., 2019). The vadose zone is characterised by the simultaneous presence of air and water in soil pores and the interactions within this zone depend on the soil's various properties and environmental conditions, and the complexity of water input. Vadose water enters the vadose zone mainly through precipitation and irrigation. In the case of precipitation, water exfiltrates the soil surface and is then subject to further hydrological processes such as infiltration, percolation, and redistribution in the vadose zone. Key soil properties such as soil texture and soil structure, will influence the rate of water entry into the soil. Infiltration rates are usually greater in sand and other coarse texture soils compared to other soil textures and a large pore size is part of the reason why water moves through these soils easily (Selker et al., 1999). In contrast, soils with finer textures such as clay will have less infiltration rates due to smaller pores, but they can infiltrate and hold larger amounts of water. Once it has entered the soil, water will percolate through the vadose zone and travel downward based upon gravitational and capillary forces and continue to create complex patterns of moisture distribution within soil.

The characteristics of a soil are particularly important when considering the distribution and storage of water in the vadose zone. The texture of soil mainly refers to the proportions of sand, silt, and clay particles it has, and thereby will affect the permeability of the soil and its ability to retain water (X Liu et al, 2019). Soils high in sand and other coarser materials are defined by low water holding capacity supplemented with higher rates of drainage and vice versa, soils rich in clay have a higher water holding capacity and therefore tend to drain slower. Water transport and storage can also be affected by the soil structure including the arrangement of soil particles and soil aggregates. Well structured soils that have good aggregate development, will typically have much better properties for both infiltration and retention than soils with poor structure.

In their investigation, Arora et al. (2019) evaluated and reported that both soil moisture and pressure gradients are influential in governing the transportation of water in the vadose zone are influenced by soil moisture and pressure gradients respectively. The wilting point represents the moisture content at which plants cannot uptake any water from the soil, while field capacity represents the maximum amount of moisture the soil can hold once water drains away. Soil moisture is the moisture in the soil found between its wilting point and field capacity, and it can vary depending on available water and its extraction by plants. Understanding how soil water changes is important for understanding the implications of water dynamics for plant health and groundwater recharge.

Soil water distribution in the vadose zone can be characterized and managed by using a variety of measurement and modeling tools. Soil moisture sensors, neutron probes, and a variety of other field-based soils moisture monitoring devices can be used to collect soil water content samples and track soil water content changes over time. For instance, hydrological models (e.g. HYDRUS) simulate water movement and solute treatment simulation in the vadose zone to analyze land cover scenarios on soil moisture while accounting drainage conditions and climate characteristics (Simunek et al., 2005). These different tools can ultimately be used to make predictions about how land cover, climate, and soil properties might affect soil water dynamics to improve water resource management and manage the conservation of the environment..

2.11 Modelling of soil water dynamics

Several models have been developed to simulate soil water and solute transport dynamics in different hydrologic and environmental studies. The choice of models depended on data availability for a landscape, flexibility of the model, and demands of the study area. In the following sections, some commonly used soil-water dynamics models are reviewed with a discussion on their features, advantages and limitations.

2.11.1 SWAT

In the early 1990s, Dr. Jeff Arnold developed the Soil and Water Assessment Tool (SWAT), which is a process-based, semi-distributed hydrological model, to predict the effects of land management practices on the yields of water, sediment and agricultural chemicals in large and complex watersheds (Arnold et al., 2010). The SWAT model operates by dividing watersheds into a great number of smaller sub watersheds or subbasins to simulate many hydrological processes (i.e surface runoff, infiltration, ET, nutrient cycling). The hydrological response units (HRUs) of each sub watershed are accounted for over several combinations of slope, soil type, and land cover type. This makes it possible to spatially model the influence of land cover and management within a watershed. The key data inputs for the model include weather data (e.g and precipitation temperature, evaporation, wind), soil data, topography data, land cover data, and management data, which determine how the watershed will respond, Once populated with data SWAT simulates water movement variables including infiltration, soil, lagoon, aquifer recharge, and surface flow. There are two methods of infiltration calculation in SWAT; the first is Curve Number (CN) for daily simulations and the second is Green-Ampt for hourly timescale data (Akoko et al., 2021). One of the advantages of the model is the spatial simulation of management response on top of its soil, water, and nutrient cycling simulation capabilities.

The SWAT model has had different versions released over time to bolster and advance model workarounds to capacities or wells installed processes. SWAT2000 was an early version of the model that had advancements to simulate pesticide transport and advancements to simulate nutrients cycling processes. SWAT2005 included these improvements with additional possible management practices, evolved weather integration for simulation, and improved hydrological process simulations. In SWAT2009, improvements led to better representation of slope characteristics at the level of hydrologic response unit (HRU) allowing for simulation of complex-terrain and water transport processes (Neitsch et al., 2005). Each updated version of SWAT has improved current model limitations and expanded scope and application, so the model can better simulate different land covers and climate scenarios.

SWAT has been more implemented in the United States, routinely in the Mississippi River Basin for agricultural practice evaluation as it relates to water quality, such as nitrogen and phosphorus pollution (Gassman et al., 2007). SWAT has also been used in Europe, in the Danube River Basin, to evaluate nutrient loads and sediment transport, producing qualitative data that supported water quality management plan and pollution prevention.

SWAT was also used in a number of river basins in Africa, such as the Nile and Limpopo, to simulate hydrological processes in response to changing land cover and climate. For example, in Kenya, SWAT was used in the Nyando River Basin to understand the effects of both deforestation and expansion of agriculture on sediment yield and water quality (Van Griensven et al., 2012). This study identified specific sites for sustainable soil and water conservation management options to mitigate erosion, while improving water management plans. In Asia, SWAT was used in the Mekong River Basin to understand the effects of changing land cover on water resources during a period of rapid agricultural and urban expansion (Nguyen et al., 2019). SWAT has also been used in climate change studies. SWAT has been used in studies in India, to simulate the effects of climate variability on water resources in the Ganges River Basin which indicated that potential climate changes could lead to less water availability based on changes in precipitation and temperature (Goyal et al 2018). These examples shows the many uses of SWAT in varied situations, from temperate agriculture to tropical to arid situations, to contribute to the understanding of sustainable land and water management practices across the globe (Baskaran et al., 2010; Rahman, 2011).

Although the SWAT model is widely applied, it has its drawbacks. The model is complicated and requires induction of substantial expertise in its setup, calibration, and interpretation of outputs. Calibration and validation are important to achieve reliable outputs, but this requires time, and is dependent on the availability of quality input data (Moriasi et al., 2007). The performance of the model is also compromised in areas experiencing extreme meteorological conditions and complex topography, particularly in relation to the simplifications that vary uniformly and present, as opposed to dynamic, soil moisture distributions and explicit water flow dynamics, both of which can impacts the reliability of outputs. The strengths of the SWAT model are in simulating upland processes in relation to channel processes, but it has a lack of biophysical and hydrological parameters in the plant compartment, which can limits predictions of vegetation and associated hydrological processes (Akoko et al., 2021). In addition, continued development of nutrient cycling processes and the abductive consequences of land use land cover changes on ecosystem services still limits the representation of complicated environmental feedbacks (Baskaran et al., 2010). Each of these limitations, that could be filled with an integrated socio-economic model, suggests future model limitations.

2.11.2 SWAP

The Soil-Water-Atmosphere-Plant (SWAP) model is a comprehensive, integrated simulation model used in environmental and agricultural sciences to predict and assess heat, water and solute fluxes in the soil-plant-atmosphere continuum (Kroes et al., 2018). SWAP has been found to be particularly suitable to complex assessments of soil-water interactions, crop growth, and investigations of vegetation-soil-atmosphere relationships (Van Dam et al., 2008). SWAP was created by the Department of Soil Physics of Wageningen University, Netherlands, and is versatile in its application to research, land management, or decision-making in agricultural and environmental sciences.

One of SWAP's key strengths is its ability to represent the soil profile and layering in detail, hence obtaining a detailed representation of soil properties (Van Dam et al., 2008). The detailed representation of soil properties allows for accurate modeling of soil-water flow. SWAP also simulates water in the soil profile under different soil, plant, and atmospheric conditions by including the processes of infiltration, evapotranspiration, percolation, capillary rise, and root water uptake (Wanders et al., 2012). The processes incorporated in SWAP also allow for modeling of surface runoff and subsurface drainage. In addition to water flow, the SWAP model also accounts for heat transport processes relevant to examining soil temperature profiles, energy balance, and the effects of these processes in crop growth and water movement (Kroes et al., 2018). The SWAP model has an incorporated plant component enabling the modeling of crop growth and root water uptake by using crop, or plant-specific data and/or models (Van Dam et al., 2008), which can be used to assess soil properties and water availability impacts on crop growth, crop health, and crop yield. SWAP also evaluates how meteorological inputs (i.e., temperature, relative humidity, windspeed, and rainfall) vary to simulate the interactions between the soil-plant system and the atmosphere.

The SWAP model should not only be able to simulate the transport dynamics of heat and water, but it can simulate transport dynamics of solutes through the soil profile to examine processes related to nutrient dynamics, leaching, and pollution control (Van Dam et al., 2008). The SWAP model has been applied to assess the impact of land management practices on water dynamics, nutrient dynamics, and crop yield (Eitzinger et al., 2004) and ultimately aid in predicting the transport dynamics of agricultural chemical through the soil profile, as it has been used historically in evaluating agricultural chemicals effecting groundwater quality. However, the model doesn't have a module for estimating and analyzing parameter sensitivity, which makes it difficult to calibrate.

2.11.3 STICS

The STICS model was developed by INRA, France since 1996, and it stands for Simulator multidisciplinary pour les Cultures Standard (multidisciplinary simulator for standard crops). The STICS model is a versatile and complex simulation model in agriculture and environmental science created by a group of tired researchers in France (Brisson et al., 2003). The STICS model is a full, process-based model that is capable of predicting crop growth, development and yield while considering the dynamic interactions between the crop, soil and environment. The STICS model can simulate soil water balance by simulating the processes of infiltration, evapotranspiration, runoff and percolation, and could be valuable to assess irrigation needs and water management on crop yield. For this reason, a STICS model is a strong complex model that is beneficial to all researchers, producers and policymakers by optimizing production, maintaining sustainability and adapting to changing environmental conditions.

2.11.4 HYDRUS-1D

The HYDRUS model serves as a tool for simulating recharge and root zone soil moisture distribution (Šimůnek, 2015). Additionally, Hydrus considers, though not limited too, such variables as warm and cold temperatures, humidity, wind, radiation, soil moisture, albedo, leaf area index, rooting depth, and soil hydraulic properties. For root water uptake assessment, HYDRUS uses a S-shaped function for rooting water uptake through hydraulic conductivity. For soil water retention, it uses the van genuchten-Mualem hydraulic model and/or single porosity model.

Studies using HYDRUS have shown that woody plant encroachment ultimately decreases groundwater recharge (Wine et al., 2015). Woody plant encroachment decreased deep drainage of water via the HYDRUS 1D model; the author attributes this to changes in rooting depth, growing season length, water stress on plants, and surface compaction. In a separate study performed by in in the article using HYDRUS, it was found that the eastern redcedar had less groundwater recharge as compared to grasslands (Wine et al., 2015) . Syminuk et al. (2005) simulated soil moisture recharge in semiarid rangelands on grass and shrub cover in achieving soil moisture recharge at different depth intervals.

While HYDRUS is a tool for simulating drainage and groundwater recharge, at this spatiotemporal scale, the distribution and depth of plant roots is very uncertain..

HYDRUS 1D model is a widely utilized numerical software application in the field of soil science and hydrogeology. Designed by Dr. Jirka Šimůnek at the University of California Riverside, this modeling program is developed to model the flow of heat, solutes, and water in the unsaturated zone of soils (Šimůnek & van Genuchten, 2008). The Richards equation is the foundation of HYDRUS 1D, which is a basic partial differential equation that describes water flow in unsaturated soils. This software is utilized to model and simulate processes of water infiltrating, redistributing, evaporating, and draining through the soil profile over time. Changes in hydraulics properties including hydraulic conductivity, water retention, and layering can be included in the model allowing the software to handle complex subsurface flow problems. HYDRUS 1D is particularly beneficial to hydrological and environmental studies. Researchers and practitioners have utilized the software to evaluate groundwater recharge, the effects of changing landcover on water resources, soil- and groundwater remediation approaches, and optimizing irrigation and water management in agriculture (Šimůnek et al., 2008).

HYDRUS 1D also includes a wide array of functionalities, including the simulation of solute transport. Therefore, the model could be used to understand contaminate, nutrient, and chemical fate and transport in the subsurface, and is valuable in remediation of environmental contaminates and for pollutant transport and water quality protection designs (Šimůnek et al., 2008).

In this study, HYDRUS-1D was used to model the vertical flow of soil water, root water uptake, and other (including infiltration, percolation, evaporation, and storage) processes in a one-dimensional soil profile, as it was the best option based on the analyses objectives. HYDRUS-1D establishes a well-documented record in the literature for examining soil-plant-atmosphere interactions in situ and has been validated in many soils, vegetation types, and climates (X. Wang, Zhao, Liu, Xiao, & Chen, 2020).

2.11.5 HYDRUS 2D/3D

To develop useful water management practices, it is important to model how water moves in the soil in agricultural ecosystems, whether those systems are irrigated or rainfed. Field measurements provide useful information; however, collecting these measurements can be expensive and time consuming. Thus, simulation models, and HYDRUS 2D/3D models, specifically, have become common practice to simulate the movement of soil water under various agricultural scenarios.

For example, Karandish et al. (2018) examined the impact of groundwater on soil moisture in a rainfed canola field, while the simulation models did provide useful information towards examining if a crop could produce in a shallow groundwater regime.

As well, García Morillo et al. (2017) and Autovino et al. (2018) applied the simulation model models HYDRUS 2D/3D to develop an efficient drip irrigation schedule for strawberries, and to provide an irrigation schedule that limit water stress at critical times during crop growth and development of olive trees, respectively.

HYDRUS 2D/3D has been widely used, for example, in modeling soil water in agricultural systems that are either solely or mostly rainfed moisture drivers, and modeling water movement in multiple dimensions has been assistive at analyzing water management practice in multi-contexts. For example, HYDRUS 2D/3D has enabled scientists to study soil moisture movement throughout the growing season in rainfed potato fields on sandy loam soil, a crucial component of determining the appropriate planting depth and schedule that can aid in capturing moisture during critical growth stages such as tuber formation. Plastic mulching has heavily relied on HYDRUS 2D to determine how water and heat move through the soil profile. (Kader, 2021 #80)

In semi-arid olive orchards with limited rainfall, HYDRUS 2D/3D simulation has helped determine moisture availability in the root zone and has also provided simulation of the seasonal water retention and shown proper soil management practices, such as mulching and soil amendments, can hydrate the soil and minimize water stress, thereby potentially providing yield stability and crop acceptance under water-deficit conditions (Egea et al., 2016)

Moreover, HYDRUS 2D/3D was used in fields containing sweet corn and different levels of rainfall. The simulations showed that both contour farming and no-till farming reduced runoff, improved soil moisture in the soil profile, and provided an even moisture supply for plants. These observations have importance in rainfed systems since moisture management in the root zone is vital for crop adaptation during variable rainy events (Research Square, 2020).

In other investigations, Egea et al. (2016) evaluated losses due to drainage and soil water dynamic in an olive orchard under fully and deficit irrigated conditions. The study also showed how irrigation timing changes the retention of water. Patel and Rajput (2008) used the model to evaluate soil water distributions in potato systems which was helpful in designing drip irrigation systems to reduce drainage losses. Dabach et al. (2013) evaluated amounts of irrigation for beans and bell peppers that were also found from the soil water amounts to produce irrigation schedules.

Additionally, HYDRUS 2D/3D has been used to determine the most ideal depth for placement of a drip irrigation system. Patel and Rajput (2008) found a placement depth of 15 cm is best for onions, while Ghazouani et al. (2013) discovered that 20 cm is ideal for eggplant when grown in sandy loam soil. From these studies, it is apparent water uptake by roots (RWU) should be taken into consideration when designing an irrigation system, as RWU affects how soil moisture is distributed in time and space.

Research regarding a Moistubes irrigation (MTI) system, which is a method of continuous irrigation, is limited compared to drip systems. W. Qi et al. (2021) determined that initial soil volumetric water content has a strong impact on water distribution of the soil with an MTI method, plus Zhai et al. (2023) documented that the volume of wetted soil increases with the application of pressure head. Y. Liu et al. (2022) and Fan et al. (2018) demonstrated that soil texture and the depth of Moistube placement influence the movement of water and volumes of wetted soil. Kanda (2016) discusses that Moistube Irrigation (MTI) is a viable subsurface irrigation system with potential efficiency for regions threatened by climate change and water scarcity. MTI applies moisture to the soil at a rate matching plant uptake and has been shown to perform better than subsurface drip irrigation (SDI) for tomato production in yields and water use efficiency, but it faces challenges, including lateral clogging of Moistubes. The study highlights that canola irrigation should be undertaken if South African farmers are to lessen their dependency on locally grown vegetable oils and suggests that the HYDRUS model could determine soil water movement and the suitability of MTI for canola production. Most studies into MTs were conducted in controlled environments without consideration of crop water uptake; however, using the model, Tian et al. (2016 as cited in Kanda 2019) found optimal Moistube depths for tomatoes and sunflowers to be 10–20cm deep depending on soil type. Unfortunately, there is still limited information about Moistube placement for a larger number of crops, in spite of the advantages offered by the model, it is difficult to calibrate and validate.

2.12 Conceptual framework

The current investigation utilized a conceptual framework created by Siddik et al., (2022), and adjusted it, to examine the effects of land cover on soil water dynamics. The study's conceptual framework depicts the relationship of land cover, soil water dynamics, and groundwater recharge. It connects the specific objectives of estimating groundwater recharge rates, quantifying soil water dynamics in the vadose zone, and modeling the effect of land covers, with an overall objective to understand land cover change and its influences on groundwater dynamics in the Middle Yala Catchment.

The framework incorporates the influence of different land cover types (i.e., forests, grasslands, and agricultural lands) on soil water dynamics, which includes infiltration, evapotranspiration, and percolation, and their influences on groundwater levels and groundwater recharge, which also encompasses soil properties, precipitation patterns and vegetation cover. The application of the HYDRUS 1D model helps facilitate the modeling and simulation of these interactions to understand potential outcomes on groundwater resources from land cover change..

By employing this framework, the study aims to contribute to sustainable land and water management practices that can mitigate the adverse effects of land cover changes on groundwater dynamics and ensure the long-term availability of water resources in the Middle Yala Catchment.

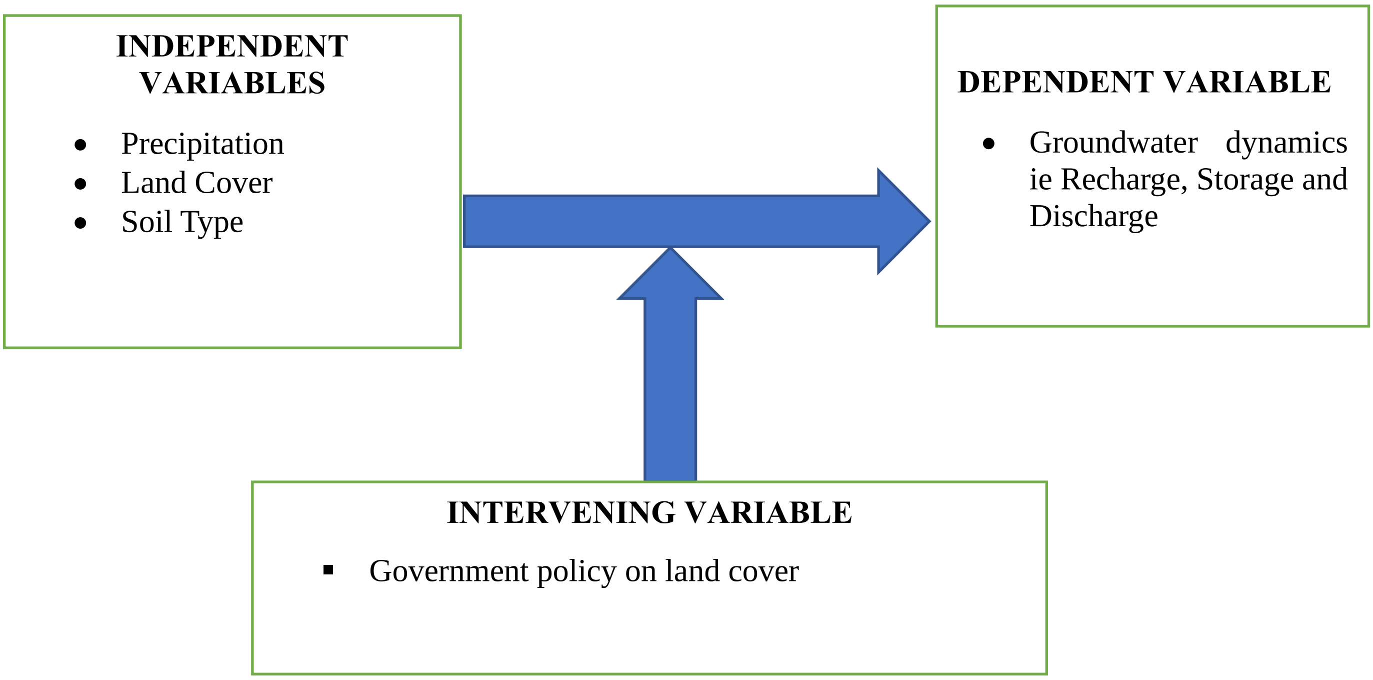

Figure 2-3: Conceptual framework showing Drivers, States, Effect, and Responses for ground water recharge.

CHAPTER THREE

METHODOLOGY

3.1 Description of the Study Area

One of Kenya's many transnational river basins, the Yala Catchment, releases water into Lake Victoria. With elevations ranging from 1200 m.a.s.l. in the lowlands to 2200 m.a.s.l. in the highlands, it occupies an area of 3,351 km^2. After rising from the Nandi Escarpment water tower, the 212-kilometer Yala River flows through the counties of Kakamega and Siaya before emptying into Lake Victoria at the Winam Gulf(J. Okungu, Adeyemo, J., & Otieno, F., (2017)). Based on data from 1950 to 2000, the river's average annual discharge over the long term is 37.6 m3 per second, which represents roughly 4.8% of Lake Victoria's surface inflow (Otiende, 2009). n the vast flat region close to Lake Victoria, the average annual rainfall is roughly 850 mm, while in the highlands, it can reach 2,000 mm. The two rainy seasons—the short and long rainy seasons—are when rainfall occurs.

With an average yearly flow of 30 m3/sec, its gross catchment area is 3,262 km^2. The Yala River Basin is a catchment area that spans the western administrative region of Kenya, including the counties of Nandi, Kakamega, Vihiga, and Siaya. Water consumption has increased at an accelerated rate, and the catchment's water resources have been steadily declining. The catchment's soil type is well-drained, deep, dark-reddish-brown humic Nitisols because of the pedoclimate and atmospheric climate fluctuations.

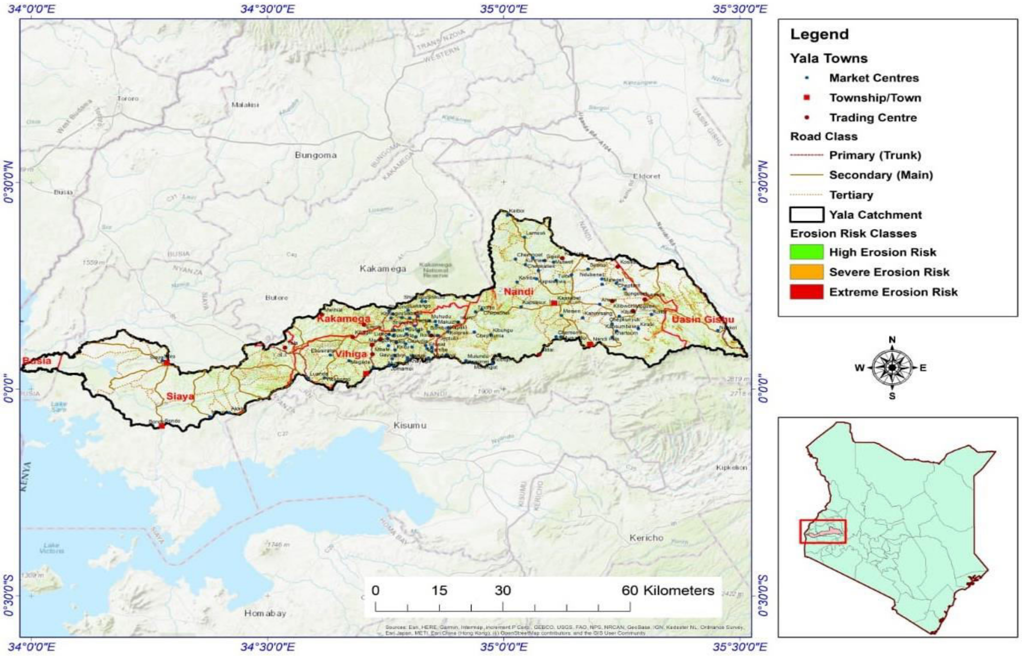

Figure 0-1: Yala Catchment Zone

Source:Author,2024

3.1.1 Climate

Yala catchment lies within the equatorial type of climate with a temperature range of 14^0C to 32^0C and an average of 23^0C. It receives between 1800mm to 200mm of rainfall annually and has a well distributed rainfall season with the long rains occur from April to June while the short rains are in September to November. Thus, there is a high potential for rainwater harvesting(J. Okungu et al., 2017)

3.1.2 Topography

The altitude of the catchment ranges between 1200masl and 1500masl, sloping gently from the East to the West with undulating hills and valleys. The terrain in the area has positive and negative implications. On the positive side, it allows free surface runoff by gravity and hence the county is not prone to flood hazards. On the negative side, it is a challenge to ground water recharge as all the surface runoff tends to discharge to the river leaving little to recharge the ground water(Wanjala et al., 2024).

3.1.3 Land Cover

Human settlements, tea and coffee plantations, and crop agriculture with isolated grazing plots are the most prevalent land cover types in the upper Yala River basin. Smallholder farms that grow maize, beans, bananas, sweet potatoes, tea, coffee, and dairy are the main producers in the mid-altitude regions.

3.1.4 Soils in the area

The catchment's hilly terrain, which is primarily made up of the rocky granite hills of Maragoli, Bunyore, and Nyangori, causes significant riverine erosion. Deep, well-drained soils classified as dystric acrisols and slightly acidic top soils from both volcanic and basement complexes with yellowish red loams derived from sediments and basements make up the majority of the catchment's upper portion(Kemunto, 2018).

3.1.5 Vegetation

Other than agriculture that is covered by crops and fodder, most part of Yala catchment is dominated by forest vegetation, the catchment is mostly green all year round, with traces of native tropical rainforests (Kibiri Forest, which is an extension of Kakamega Forest) at the far end that borders Nandi and Kakamega. Due to the extensive conversion of natural landscapes into humanized landscapes (small-scale farms and settlements), it is dominated by cultural landscapes. 40% of the land is covered by forest as a result of the recent implementation of agroforestry initiatives (Kenya Forest service Vihiga County).

3.2 Data Collection

Data collection was done between May 2023 and May 2024 in both wet and Dry seasons.The data sets collected include rainfall, temperature, soil moisture and humidity. The data sets soil moisture, temperature and humidity were simultaneously collected using oil moisture sensors whereas rainfall data was obtained as secondary data from Vihiga Meteorological Station.

3.2.1 Soil moisture

The data used in this study were collected using soil moisture sensors, which were installed in dry and wet soils regarding the rainfall seasons. The data were collected in both dry and wet seasons of the year. The data were collected in areas with eucalyptus plantations and grasslands for both rainfall season where the soil moisture content were compared.

Soil water data collection was done in four sites using TMS-4 data loggers. The parameters collected includes temperature and soil moisture. The data loggers were placed in eucalyptus tree areas and grass land. This helped to collect data at various land areas to generate averages of soil moisture in the catchment. In these study stationery soil moisture sensors were installed in secured places within eucalyptus and grassland areas in Yala catchment. The sensors were installed at 20 cm and 100 cm depth because this is the root zone of most plantations. The soil data were transmitted to the laptop for manipulation and analysis using Lolly Manager Software.

3.2.2 Soil sampling

Soil sampling was carried out from 3(three) the three study locations—grassland (Loamy, silty gravel), natural tree cover (stratified silty clay), and eucalyptus plantation (clay heavy soil) which sensors were installed within the catchments.The tree were of young stands 3-4 years The samples were collected during wet and dry seasons. Within each site (grassland, natural tree cover, and eucalyptus plantation), uniform experimental plots measuring 20 m × 20 m were established to guarantee comparability across the various land cover types. These plots were chosen to represent the predominant soil types and vegetation cover in each area(Strahler et al., 2006).

The sampling of soil was done at a depth of 15 centimeters using auger. The soil was then placed into a clean bucket or container, mixed thoroughly and take approximately 1 pint to be taken to the laboratory for soil analysis(Minase, Masafu, Geda, & Wolde, 2016). The research employed stratified random sampling, in which a basic random sample was selected from each stratum and points were allocated to predetermined groups or strata.Water retention, infiltration, and groundwater recharge are all significantly impacted by the variations in soil characteristics among locations(Owuor et al., 2016).

3.3 Modeling using HYDRUS 1D

3.3.1 Brief Description of the model

This model was used to simulate the impacts of eucalyptus, indigenous trees and grass on soil water content under varying soil water dynamics. Soil water dynamics in this study meant the following soil conditions: saturated Flow(groundwater zone), unsaturated Flow(vadose zone) and water Vapor movement saturated flow. The input data needed to run HYDRUS was managed by computer programs, which were also used for nodal discretization and editing, parameter allocation, problem execution, and result visualization.

In HYDRUS-1D (Šimůnek et al., 2008), A modified Richards' equation was used to model the uniform movement of water in one dimension through a rigid porous medium that is partially saturated. This formulation assumes that the influence of the air phase on liquid flow is negligible and that water movement caused by thermal gradients can be disregarded.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z} + 1\right)\right] - S \quad (1)$$

In this equation, h represents the water pressure head [L], θ is the volumetric water content [L^3 L^{-3}], t is time [T], and z is the spatial coordinate [L] (positive in the upward direction). The term S denotes the sink term [L^3 L^{-3} T^{-1}], which accounts for water uptake or removal, and K is the unsaturated hydraulic conductivity function [L T^{-1}], expressed as:

$$K(h, x) = K_S(z)K_r(h, z) \quad (2)$$

In this equation, K_r represents the relative hydraulic conductivity [-], and K_s is the saturated hydraulic conductivity [L T^{-1}].

3.3.2 Root Water Uptake

The amount of water drawn out of a unit volume of soil per unit time as a result of plant water uptake is known as the sink term, or S. Feddes et al. (1978) define S as follows:

$$\boldsymbol{S(h) = \alpha(h)S_p} \quad (3)$$

The root-water uptake stress response function, $\alpha(h)$, is a dimensionless function that depends on the soil water pressure head, with values ranging from 0 to 1 ($0 \leqslant \alpha \leqslant 1$). S_p is the potential water uptake rate [T^{-1}]. Water uptake is assumed to be zero when the soil is near saturation (wetter than the arbitrary "anaerobiosis point," h_1). Similarly, for $h<h_4$ (the wilting point), water uptake is also zero.

When the potential water uptake rate is non-uniformly distributed over the root zone, S_p becomes

$$S_p = b(z)T_p \tag{4}$$

Tp is the potential transpiration rate [L T^{-1}], and b(z) is a normalized water uptake distribution function [L^{-1}]. This function captures the spatial variation of the potential extraction term, Sp, within the root zone. It is determined by normalizing any measured or prescribed root distribution function, allowing for the calculation of how water uptake is distributed across the depth of the root zone.

The actual water uptake distribution is obtained by substituting (4) into (3):

$$S(h,z) = \alpha(h,z)b(z)T_p \tag{5}$$

whereas the actual transpiration rate, T_a, is obtained by integrating (5) over the rooting depth, L_R, as follows:

$$T_a = \int_{L_R} S(h,z)\partial z = T_p \int_{L_R} \alpha(h,z)b(z)\partial z \tag{6}$$

3.3.3 The Unsaturated Soil Hydraulic Properties

The unsaturated soil hydraulic properties, (h) and (h), as used in equation (1), are typically highly nonlinear functions of the pressure head. HYDRUS-1D allows for five different analytical models to describe these properties. In this study, we utilize the soil-hydraulic functions proposed by Van Genuchten (1980), who employed the statistical pore-size distribution model developed by Mualem (1976) to derive a predictive equation for unsaturated hydraulic conductivity based on soil water retention parameters. The Van Genuchten (1980) expressions are as follows:

$$\boldsymbol{\theta(h)} = \begin{cases} \boldsymbol{\theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}} & \boldsymbol{h < 0} \\ \boldsymbol{\theta_s} & \boldsymbol{h \geq 0} \end{cases} \quad (7)$$

$$\boldsymbol{K(h) = K_s S_e^1 \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2} \quad (8)$$

Where,

$$\boldsymbol{m = 1 - 1/n, \quad n > 1} \quad (9)$$

and the effective saturation Se is defined as follows:

$$\boldsymbol{S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}} \quad (10)$$

The equations mentioned above include five independent parameters: θr (residual water content), θs (saturated water content), α (related to the inverse of the air entry suction), n (a measure of pore-size distribution), and Ks (saturated hydraulic conductivity). The pore-connectivity parameter l in the hydraulic conductivity function was estimated by Mualem (1976) to be approximately 0.5 as an average value for many types of soils.

3.3.4 Initial and Boundary Conditions

The surface boundary is subjected to atmospheric conditions, where the potential fluid flux across this interface is governed solely by these external factors. However, the actual flux is influenced by the transient soil moisture conditions near the surface. The boundary condition at the soil surface can switch between a prescribed flux and a prescribed head condition. To numerically solve the governing equation, the absolute value of the surface flux is constrained by two conditions(Stark, 1975; Wright, 1959):

$$\boldsymbol{\left|-K\left(\frac{\partial h}{\partial z} + 1\right)\right| \leq E \quad at\ z = L} \quad (11)$$

And

$$h_A \leq h \leq h_S \qquad at\ z = L \tag{12}$$

Here, E represents the maximum potential rate of infiltration or evaporation based on current atmospheric conditions [L T^{-1}]. h_A and h_S are the minimum and maximum pressure heads allowed at the soil surface, respectively [L]. The value of h_A is determined from the equilibrium between soil water and atmospheric water vapor, while h_S is typically set to zero. If h_S is positive, it indicates the presence of a small water layer on the soil surface that may occur during heavy rainfall before runoff begins. HYDRUS offers the option to assume that any excess surface water above zero will be promptly removed. When the conditions defined by equation (12) are met, a prescribed head boundary condition is used to determine the actual surface flux.

3.3.5 Evaluation of Potential Evapotranspiration

The Thornthwaite method was used in this study to determine the potential evapotranspiration (PET), utilizing monthly mean temperature data. This method calculates PET by first determining a heat index, I based on the monthly mean temperatures for the location. The formula for the heat index is (Pereira & Pruitt, 2004):

$$I = \sum_{n=1}^{12} \left(\frac{T_n}{5}\right)^{1.514}$$

From the heat index, the evapotranspiration coefficient, a is derived using the equation:

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.4239$$

Once these values are obtained, the potential evapotranspiration (PET) for each month is calculated using the formula: (**Thornthwaite Equation)**

$$PET = 16 \times \left(\frac{L}{12}\right) \times \left(\frac{N}{30}\right) \times \left(\frac{10 \times T_n}{I}\right)^a$$

$$i = \sum_{n=1}^{12} \left(\frac{T_n}{5}\right)^{1.514}$$

$$a = 6.75 \times 10^7 I^3 - 7.71 \times 10^5 I^2 + 1 \cdot 792x1O^2 I + 0.49239$$

Here, L represents the average day length in hours, N is the number of days in the month, and T_n is the mean monthly temperature. This method, primarily driven by temperature, allowed for the estimation of PET in the study area, providing insight into water loss through evaporation and transpiration over the period of analysis.

3.3.6 Model Data input

The model required spatial of the following parameters: type/layer of soil, distribution of root water uptake, and initial watering conditions which were collected in the field using soil sensors and from laboratory soil analysis. Precipitation was the major input and was collected from Vihiga weather station. Model data input and output were examined using graphical tools.

A crucial consideration when choosing a model is that it should be adequate for the question being addressed without being unduly detailed. For the Eucalyptus canopy, soil moisture was obtained from TMS sensors. The main objective for the use of HYDRUS 1D model was to provide current data on the water content of the soil and potential impacts on eucalyptus on ground water quantity, to be fed with daily meteorological data. As a result, the model structure had to be water-oriented instead of crop-growth-oriented.

A simple-to-use model is necessary given the operational and applied context, which means that (i) empirical equations for hydrological processes are preferred and (ii) successful integration of remote sensing data into the model simulations should have been documented. Another crucial element that enables seamless integration on the servers taking part in the project is the availability of source code. Each of the model candidates was valued using a variety of indicators.

3.3.7 Model Evaluation

To assess the model's performance, the agreement between observed and simulated data were examined using statistical techniques. The coefficient of determination R^2, and normal root mean square error (NRMSE), were employed, which are defined as follows (Nash & Sutcliffe, 1970)

Coefficient of determination:

$$\boldsymbol{R^2} = \frac{[\sum_{i=1}^{n}(O_i-\tilde{O})(P_1-\tilde{P})]^2}{\sum_{i=0}^{n}(O_i-\tilde{O})^2\sum_{i=0}^{n}(P_1-\tilde{P})^2} \qquad (15)$$

Normal Root Mean Square Error:

$$\boldsymbol{NRMSE} = \sqrt{\frac{\sum_{i=0}^{n}(O_i-P_i)^2}{n}} * 100\% \qquad (16)$$

In these equations, Pi represents predicted values, $\bar{P}$ is the mean of predicted values, O represents observed values, and $\bar{O}$ is the mean of observed values. In the context of these statistical metrics, an optimal value for R^2 is 1, while for N$RMSE$, it is 0.

NRMSE (%) classification

≤10	Very good
10-15	Good
15 - 20	Acceptable
20 - 25	Marginal
> 25	Poor

Source: (Stöckle & Kemanian, 2020)

3.3.8 Model Calibration

It was necessary to calibrate the HYDRUS-1D model to accurately simulate soil water behaviors in the Middle Yala Catchment. The calibration procedure entailed modifying the input parameters so the model's predictions matched observed field data, demonstrating the model's capability to simulate soil moisture dynamics, depending on varying land cover. The main datasets used in the calibration included soil moisture content, rainfall, temperature and humidity were collected from field measurements and weather stations at the three study sites; Kaimosi (grassland), Shamakhokho (natural tree vegetation) and Bendera (eucalyptus plantations).

In preparation for model calibration, soil physical properties (soil texture, bulk density, and porosity) were obtained from field samples from each experimental site. Soil physical properties are essential to defining hydraulic soil properties, which are critical for water retention curves and hydrological conductivity that will serve as input parameters for the HYDRUS-1D model. There were also plant specific parameters (root water uptake and evapotranspiration) derived from dominant vegetation types used for each location (grassland, natural trees, and eucalyptus plantations).

Simulations used these input values were then compared to the simulated soil moisture data collected via Time Domain Reflectometry (TDR) sensors. The objective was to calibrate the model based on the soil moisture data that had been collected through TDR sensors. To successfully calibrate the model, identified key hydraulic parameters to be modified during the calibration process included the hydraulic parameters were the van Genuchten parameters (α, n, θr, θs) that described the soil water retention curve as well as saturated hydraulic conductivity (Ks), which also needed to adjust during the calibration process. These parameters were changed in small, real-world observed ranges until the observed soil moisture values were represented more closely to the simulations.

To calibrate the model, simulated soil moisture profiles were compared to the field data over duration of time, or during both the wet and dry season. During the calibration process throughout these time frames, performance metrics were used to quantify if the observed data matched the simulated soil moisture data closely enough through the coefficient of determination (R^2) and root mean square error (RMSE).

The final calibrated model successfully represented soil moisture dynamics for each land cover type, therefore fulfilling its purpose as a tool to assess changes in land cover on groundwater recharge in the Middle Yala Catchment area. The calibration will established that the HYDRUS-1D model was sufficiently calibrated prior to conducting further analysis or spatial scenario testing for the study.

3.3.9 Model Validation

Verifying the validity of the HYDRUS-1D model was an essential element of confirming the model's reliability and accuracy in simulating soil moisture dynamics and groundwater recharge in the Middle Yala Catchment. After calibrating the codes, the model was validated with independent data sets that did not form part of the calibration process. Validation, thus, was necessary for testing the predictive capability of the model under field conditions and to help determine the model's generalization beyond data used during the calibration period.

The validation process involved collecting additional field data on soil moisture, rainfall, and various environmental data at the same three sites (Kaimosi grassland, Shamakhokho natural tree vegetation, and Bendera eucalyptus plantations). The continuous bite of data that was used for calibration was obtained from May 2023 to May 2024, and these datasets captured both dry and wet seasonal conditions (Zhang, Chen, Yao, & Lin, 2015). The validation datasets considered data collected from different periods to ensure some understanding of temporal variability was captured. After using the input data, the calibrated hydraulic parameters and site specifics were applied to run the HYDRUS-1D model. The simulated values of soil moisture were compared to those observed an in situ during the validation time period. Performance indicators including the coefficient of determination (R^2), normalised root mean square error (NRMSE), and Nash-Sutcliffe Efficiency (NSE) were used to evaluate the performance of the model.

The model was validated satisfactorily for all sites, especially at the Kaimosi (grassland) site for which R^2 data showed a clear relationship between simulated and observed soil moisture. The data also indicated low NRMSE values (<10%) supporting the validation data, where there was little difference between the observed versus simulated based on a 100 scale. The model performance was very good, whey the validation showed adequate predictive validity with the model behaving satisfactorily during both wet and dry seasons.

3.3.10 Model Development

The vadose water flow accessible under diverse land covers in the middle Yala Catchment was analyzed and evaluated using the HYDRUS 1D model based on observed data collected from the TMS sensors installed, rainfall data collected from the Vihiga metrological station, and soil data analyzed from Masinde Muliro University of Science and Technology. The rainfall data collected from the Vihiga metrological station and soil moisture content was measured using the soil moisture sensors installed to collect 12 months of data. The data was used in the HYDRUS 1D model to simulate under the different conditions and land cover.

3.3.11 Modelling Water Demands among water users

Current and future water demands for agriculture, and environmental flow requirements were analyzed using the HYDRUS-1D model. The following steps outline the process for assessing current water demands and scenario analysis:

i. Definition of the study area and time frame:

The study area was demarcated as the middle Yala Catchment with the following coordinates 0.121596° , 34.838573° at Kaimosi Treatment Works and 0.121376° ,34.748291° Chavakali area. These areas contribute heavily of Middle Yala recharge. The collected data was analyzed and inserted in HYDRUS 1D. HYDRUS-1D can utilize spatial data for defining soil profiles and hydrological boundaries.

ii. Creation of the Current Accounts

This step involved specifying the available (existing) soil properties, climatic conditions, crop characteristics, and irrigation practices. This step was crucial as it formed the foundation of the entire modelling process and was used to calibrate the model to the existing conditions of the study area. The Current Accounts represented the basic definition of the soil-water-plant system as it currently exists, serving as the baseline for all scenario projections. Supply and demand data were specified for the first year of the study (2016) on a daily or monthly basis. All collected data on current soil moisture, groundwater levels, and crop water use were input into the Current Accounts.

iii. Creation of Scenarios

Instead of employing direct long-term observation, scenario analysis was applied to evaluate how climate change might influence soil water dynamics and water availability. Scenarios were developed based on future assumptions and projected increases in different indicators, and were central to the HYDRUS-1D modelling framework. This step allowed for the potential water resources management strategies based on the model results. Scenarios incorporated changes in climate conditions, irrigation approaches, crop varieties, and land cover.

iv. Evaluation of the Scenarios

The generated results from scenario creation were utilized within the employment of water resources planners with the intent for decision making, which is the main aim of this study. HYDRUS-1D used the scenarios to assess dynamics of moisture in soils, recharge of groundwater, and transport of nutrients under varying scenarios. All scenarios were assessed and potential answers were proposed to provide solutions for optimizing water use efficiency, avoiding degradation of soil, and increasing groundwater recharge. Balancing supply and demand was also proposed towards strategies.

3.3.12 Steps in HYDRUS-1D Model Application

i. Soil Moisture and Root Zone Dynamics

Using HYDRUS-1D to assess soil moisture and its interactions with the root zones associated with various plants and crops grown in the middle Yala Catchment. Modelling soil moisture is useful for establishing crop water requirements.

ii. Groundwater Recharge and Flow

The simulation of water flow through the vadose zone generates estimates of groundwater recharge that can be associated with different crop and rainfall information. Estimates of groundwater recharge are important in assessing water availability and sustainable land cover land cover.

iii. Climate Change Impact

HYDRUS-1D also evaluates the potential effects of changing climate conditions on moisture profiles and water percolation, which is essential in estimating future water requirements/availability and developing management challenges under climate change scenarios.

3.3.13 Integration Steps

The data collection consisted of obtaining detailed information on soil properties, climatic conditions, crop parameters, and irrigation practices relevant to the area of study. The calibration of the models involved the process of adjusting the field data of HYDRUS-1D to ensure that it would specifically capture the relationships between soil, water, and plants. After the model calibration, the simulated scenarios were completed with HYDRUS-1D under different climate and management scenarios to provide detailed simulated data on soil moisture and groundwater recharge. Data integration followed, integrating the simulation results into broader water management plans to enhance accuracy of demand and supply forecasts for water use around the world. After, the criteria for evaluation and adaptive management also took place using the outcomes from the integrated model to inform evaluation and enhance sustainable water management in all sectors. By leveraging the capacity for detailed simulations with HYDRUS-1D, a comprehensive understanding of current and future water demand was constructed to allow for better development of more effective water resource management.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

Chapter 4 reports on findings from the field study that was conducted in the Middle Yala Catchment, in relation to land cover impact on groundwater aspects, focused in terms of moisture distributions in the vadose zone and recharge from them. Three field sites were established, incorporating grassland (Kaimosi), natural trees (Shamakhokho), and eucalyptus (Bendera), to facilitate input on the importance of differences in land cover, vegetation cover, and soil strata, and how these can potentially affect moisture retention and subsequent movement.

From the collection of volumetric soil moisture content data over 2023 and 2024, dynamic patterns appear based on seasonal rainfall and practices of local land cover. Each of the three field locations exhibit variances in terms of soil profile and vegetation type that drive differing levels of moisture distributions and recharge. These findings are then further supported by modelling simulations of land cover differences and its effect on water movement within the vadose zone, for additional clarity of the intricate interactions between soil, vegetation, and climate.

The discussion addresses the fluctuations in soil moisture observations made at each station and relate them to soil hydrological processes that can drive groundwater recharge. The findings are put into context with the existing literature on soil water dynamics, to provide a solid context for understanding land cover impact on groundwater resources in the study area..

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4.2. Grassland Site

The Kaimosi region, characterized by natural grassland and stratified loamy silty gravel over cohesive red gravel, displayed significant variability in both rainfall and soil moisture. In May 2023, the region recorded the highest rainfall of 468.1 mm, leading to an MVMC of 0.439 cm^3/cm^3. However, despite subsequent rainfall drops to 199.2 mm in June and 127.1 mm in July, the MVMC values remained relatively stable at 0.404 cm^3/cm^3 and 0.398 cm^3/cm^3, respectively. This suggests that the loamy silty gravel, while allowing for good initial infiltration, likely retains moisture within the upper soil layers, limiting rapid drainage.This results are consistent with Y. Liu, Guo, Long, and Lei (2022), that surface layers (0–20 cm), with higher conductivity, lost moisture more rapidly post-rain, while deeper layers maintained higher content longer. This finding supports the idea that soil stratification—with an upper permeable layer and a denser sublayer—leads to sustained moisture retention near the surface after heavy rainfall. In addition, upper loam acts as reservoir slowing the downward movement of water thus the high MVMC throught the seasons(D. Wang et al., 2021).

By August 2023, rainfall increased slightly to 177.2 mm, but the MVMC declined to 0.339 cm^3/cm^3, possibly due to seasonal evapotranspiration or deeper percolation. Interestingly, despite moderate rainfall of 234.2 mm in October 2023, the MVMC spiked to 0.48 cm^3/cm^3, indicating delayed moisture accumulation in the soil profile. A similar trend was observed in November 2023, when rainfall reached 276.3 mm, and the MVMC rose to 0.51 cm^3/cm^3, likely due to continued soil saturation and reduced evaporation as the rainy season progressed.

In January 2024, rainfall dipped to its lowest at 70.2 mm, resulting in a corresponding MVMC drop to 0.404 cm^3/cm^3. However, even with a slight increase in February 2024 rainfall to 80.5 mm, the MVMC decreased further to 0.394 cm^3/cm^3. This period suggests a combination of low precipitation and higher evapotranspiration rates, likely due to warmer weather. By April 2024, when rainfall surged to 360.1 mm, the MVMC increased to 0.547 cm^3/cm^3, reflecting significant soil moisture recharge. The high rainfall in May 2024 (459.5 mm) maintained this moisture level, with an MVMC of 0.542 cm^3/cm^3, confirming that soil moisture retention peaked during this period of sustained heavy rainfall.

4.2.1 Natural Trees Site

Shamakhokho, characterized by natural tree vegetation and stratified loamy silty clay over fine-grained silty clay, exhibited unique moisture retention characteristics due to its dense tree cover and cohesive soil structure. In May 2023, the area received 468.1 mm of rainfall, leading to a relatively high MVMC of 0.443 cm^3/cm^3. However, the MVMC decreased significantly to 0.341 cm^3/cm^3 in June 2023 despite 199.2 mm of rainfall, indicating that evapotranspiration from the tree cover likely contributed to moisture loss.This similar with results from

Throughout the dry months of July and August 2023, with rainfall at 127.1 mm and 177.2 mm, the MVMC remained low, at 0.332 cm^3/cm^3 and 0.348 cm^3/cm^3, respectively. The fine-grained clay soil may have allowed for slower infiltration, keeping moisture locked in deeper layers. As rainfall increased to 234.2 mm in October 2023, the MVMC rose to 0.419 cm^3/cm^3, further peaking at 0.455 cm^3/cm^3 in November 2023 with 276.3 mm of rainfall, suggesting that the soil was nearing saturation.

In early 2024, rainfall dropped to 70.2 mm in January and 80.5 mm in February, with corresponding MVMC values of 0.356 cm^3/cm^3 and 0.349 cm^3/cm^3. The soil moisture content remained low despite the moderate rainfall, likely due to reduced infiltration and higher water uptake by the vegetation. However, in March 2024, when rainfall reached 112.9 mm, the MVMC jumped to 0.485 cm^3/cm^3, indicating that prior moisture retention, combined with renewed precipitation, led to a substantial increase in soil moisture. This trend continued into April 2024, when rainfall of 360.1 mm pushed the MVMC to 0.496 cm^3/cm^3, and in May 2024, it increased further to 0.509 cm^3/cm^3, reflecting sustained moisture accumulation during the wetter months.

4.2.2 Eucalyptus Plantation

The Bendera area, dominated by eucalyptus plantations and characterized by clay-heavy soil, demonstrated distinct moisture dynamics due to the high-water demand of eucalyptus trees and the clay's ability to retain water. In May 2023, rainfall of 468.1 mm resulted in an MVMC of 0.4 cm^3/cm^3. The MVMC then decreased to 0.332 cm^3/cm^3 in June 2023 despite receiving 199.2 mm of rainfall, suggesting that the eucalyptus vegetation may have absorbed much of the available moisture.

In July and August 2023, rainfall decreased further to 127.1 mm and 177.2 mm, and the MVMC dropped to 0.295 cm^3/cm^3 and 0.27 cm^3/cm^3, respectively. This indicates that the clay soil had reached near saturation, and moisture was being lost through evapotranspiration. By September 2023, with rainfall increasing to 196.5 mm, the MVMC rose slightly to 0.282 cm^3/cm^3, reflecting the soil's limited capacity to hold additional moisture after extended dry conditions.

In November 2023, rainfall increased to 276.3 mm, and the MVMC followed suit, rising to 0.421 cm^3/cm^3. However, in December 2023, despite rainfall dropping to 100.7 mm, the MVMC decreased only slightly to 0.358 cm^3/cm^3. This stability in moisture levels suggests that the clayey soil effectively retained moisture during the dry months. By

January 2024, with rainfall at its lowest point (70.2 mm), the MVMC declined further to 0.327 cm³/cm³.

Rainfall in March 2024 (112.9 mm) saw a rise in MVMC to 0.427 cm³/cm³, with further increases in April 2024 (360.1 mm) and May 2024 (459.5 mm), where the MVMC reached 0.432 cm³/cm³ and 0.441 cm³/cm³, respectively. These values indicate that the clay soil and the water-absorbing eucalyptus trees reached equilibrium, with moisture levels gradually increasing during the rainy season.

Figure 4.1 below highlights a general correspondence between higher rainfall and increased soil moisture content, although other factors, such as soil properties or prior precipitation, likely contribute to the observed moisture levels.

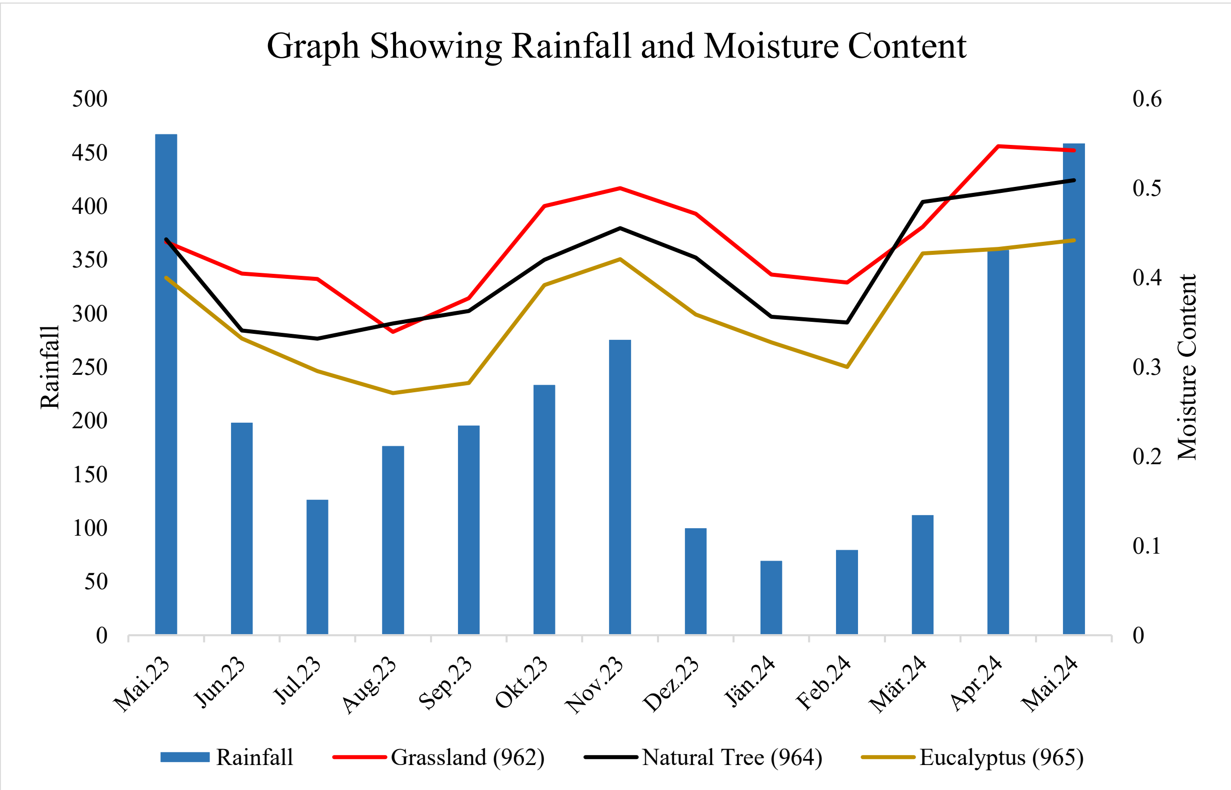

Figure 0-2: Determination of potential evapotranspiration for Natural Tree site

Evapotranspiration

The tables below show calculated evapotranspiration using Thornthwaite method

Table 0-1: Determination of actual evapotranspiration for Grassland site

GRASSLAND													
Date	**Temp**	**i(heat index)**	**PET (Not adjusted for latitude**	**b(latitude correction)**	**PET (mm/month)**	**Monthly Rainfall (mm)**	**Rainfall-PET**	**ACPWL**	**|ACPWL|**	**SM Retained**	**ΔSM**	**AET**
May-23	35.04	19.07	570.87	1.08	616.54	468.10	-148.44	-148.44	148.43	38.12	86.88	181.58
Jun-23	33.79	18.04	453.92	1.06	481.15	199.20	-281.95	-430.39	430.39	4.00	-34.13	111.14
Jul-23	29.29	14.54	185.20	1.08	200.02	127.10	-72.92	-503.30	503.30	2.23	-1.77	61.38
Aug-23	27.01	12.86	111.18	1.07	118.97	177.20	58.23	0	0	125.00	122.77	25.93
Sep-23	26.82	12.72	106.38	1.02	108.50	196.50	87.99	0	0	125.00	0	93.59
Oct-23	28.86	14.21	168.56	1.02	171.93	234.20	62.23	0	0	125.00	0	111.55
Nov-23	28.70	14.09	162.74	0.98	159.48	276.30	116.82	0	0	125.00	0	131.61
Dec-23	29.21	14.47	181.93	0.99	180.12	100.70	-79.42	-79.42	79.42	66.22	-58.78	75.96
Jan-24	30.15	15.19	222.08	1	222.08	70.20	-151.88	-231.30	231.30	19.65	-46.57	55.62
Feb-24	28.50	13.95	155.89	0.91	141.86	80.50	-61.36	-292.66	292.66	12.03	-7.62	41.97
Mar-24	30.54	15.48	240.52	1.03	247.74	112.90	-134.84	-427.50	427.50	4.089	-7.94	57.56
Apr-24	31.02	15.86	265.54	1.03	273.51	360.10	86.59	0	0	125.00	120.91	113.93
May-24	33.67	17.95	444.54	1.08	480.10	459.50	-20.60	0	0	125.00	0	218.86
	I	**198.41**				**2862.50**					**Annual**	**1280.68**

Natural Trees

Table 0-2: Determination of actual evapotranspiration for Natural Tree site

NATURAL TREES												
Date	**Temp**	**i(heat index)**	**PET (Not adjusted for latitude**	**b (latitude correction)**	**PET (mm/month)**	**Rainfall (mm)**	**Rainfall-PET**	**ACPWL**	**|ACPWL|**	**SM Retained**	**ΔSM**	**AET**
May-23	35.04	19.07	570.05	1.08	615.66	468.10	-147.56	-147.56	147.56	138.55	111.45	127.52
Jun-23	33.78	18.04	453.51	1.06	480.72	199.20	-281.52	-429.08	429.08	44.93	-93.62	78.05
Jul-23	29.29	14.54	185.43	1.08	200.26	127.10	-73.16	-502.24	502.24	33.53	-11.40	43.11
Aug-23	27.01	12.86	111.45	1.07	119.25	177.20	57.95	0	0	250	216.47	18.21
Sep-23	26.82	12.72	106.64	1.02	108.78	196.50	87.72	0	0	250	0	65.73
Oct-23	28.86	14.21	168.80	1.02	172.18	234.20	62.02	0	0	250	0	78.34
Nov-23	28.70	14.09	162.99	0.98	159.73	276.30	116.57	0	0	250	0	92.42
Dec-23	29.21	14.47	182.17	0.99	180.35	100.70	-79.65	-79.65	79.65	181.79	-68.21	53.35
Jan-24	30.15	15.19	222.26	1.00	222.26	70.20	-152.06	-231.71	231.71	98.95	-82.84	39.06
Feb-24	28.50	13.94	156.14	0.91	142.09	80.50	-61.59	-293.29	293.29	77.35	-21.61	29.48
Mar-24	30.54	15.48	240.67	1.03	247.89	112.90	-134.98	-428.28	428.28	45.08	-32.27	40.42
Apr-24	31.02	15.85	265.64	1.03	273.61	360.10	86.49	0	0	250	204.92	80.01
May-24	33.40	17.73	422.03	1.08	455.80	459.50	3.70	0	0	250	0	153.70
	I	**198.19**				**2862.50**					**Annual**	**899.40**

Eucalyptus

Table 0-3: Determination of actual evapotranspiration for Eucalyptus site

EUCALYPTUS												
Date	**Temp**	**i(heat index)**	**PET (Not adjusted for latitude**	**b(latitude correction)**	**PET (mm/month)**	**Monthly Rainfall (mm)**	**Rainfall-PET**	**ACPWL**	**|ACPWL|**	**SM Retained**	**ΔSM**	**AET**
May-23	35.04	19.06	570.05	1.08	615.66	468.10	-147.56	-147.56	147.56	229.60	120.40	230.62
Jun-23	33.79	18.04	453.51	1.06	480.72	199.20	-281.52	-429.08	429.08	102.72	-126.88	141.15
Jul-23	29.29	14.54	185.43	1.08	200.26	127.10	-73.16	-502.24	502.24	83.34	-19.38	77.96
Aug-23	27.01	12.86	111.45	1.07	119.25	177.20	57.95	0	0	350	266.66	32.93
Sep-23	26.82	12.72	106.64	1.02	108.78	**196.50**	87.72	0	0	350	0	118.87
Oct-23	28.86	14.21	168.80	1.02	172.18	234.20	62.02	0	0	350	0	141.68
Nov-23	28.70	14.09	162.99	0.98	159.73	276.30	116.57	0	0	350	0	167.15
Dec-23	29.21	14.47	182.17	0.99	180.35	100.70	-79.65	-79.65	79.65	278.77	-71.23	96.48
Jan-24	30.15	15.19	222.26	1.00	222.26	**70.20**	-152.06	-231.71	231.71	180.53	-98.23	70.64
Feb-24	28.50	13.94	156.14	0.91	142.09	**80.50**	-61.59	-293.29	293.29	151.40	-29.13	53.31
Mar-24	30.54	15.48	240.67	1.03	247.89	112.90	-134.99	-428.28	428.28	102.95	-48.45	73.1
Apr-24	31.02292	15.85502421	265.6397	1.03	273.6089	360.1	86.49106521	0	0	350	247.0469	144.7
May-24	33.4	17.73011548	422.0329	1.08	455.7956	459.5	3.704440163	0	0	350	0	277.97
	I	**198.19**				**2862.50**					**Annual**	**1626.56**

These results illustrate how different vegetation types affect water dynamics, specifically in terms of AET, soil moisture retention, and water balance. Each land cover exhibits distinct water consumption patterns, which can have significant implications for water management and ecological sustainability.

In Grassland, the annual AET was recorded at 1,280.684 mm. The Potential Evapotranspiration (PET) values range from 108.5 mm to 616.5 mm per month, with water deficits seen in several months where rainfall is insufficient to meet the evapotranspiration demand. Particularly during dry months like May and June 2023, Grassland experienced substantial negative rainfall-PET values, indicating a significant water shortfall. Soil moisture retention remains overall low throughout the duration of the year and reached maximum retention of 125 mm during a few months of the year. This indicates that Grassland has difficulty retaining water during the dry period and leads to drought-prone conditions when evapotranspiration is greater than the amount of moisture.

Natural Trees had a lower annual AET of 899.398 mm, representing their more efficient use of water compared to Grassland. The PET of Natural Trees was slightly lower than Grassland, ranging between 108.7 mm to 615.7 mm. Natural Trees managed a more stable water cycle with a positive water surplus during the wet months in August 2023 and May 2024. This vegetation type had more soil moisture retention, consistently maintaining soil moisture in amounts greater than 250 mm in a number of months, which represents their capacity to save moisture and manage a stable water cycle. From these observations, Natural Trees have lower AET and more soil moisture retention which shows the vegetation type does well in environments with water sustainability as a priority. Natural Trees can manage better during dry spells with overall better water-use efficiency.

Eucalyptus has the highest annual AET of 1,626.56 mm, indicating higher water needs. The PET values for Eucalyptus were comparable to Natural Trees, but the species consumes significantly more water overall, leading to higher evapotranspiration. Eucalyptus experienced large water deficits during dry months such as May and June 2023, as rainfall could not meet its high-water demand. Despite its high consumption, Eucalyptus retained more soil moisture than both Grassland and Natural Trees, consistently holding up to 350 mm in wetter months.This is because Clay has low infiltration but high water holding capacity therefore even if Eucalyptus consumes a lot of water the soil would retain moisture(Medeiros et al., 2025).

However, this comes at a cost; during dry periods, soil moisture levels dropped rapidly, demonstrating the species' tendency to deplete water resources quickly. While Eucalyptus may thrive in water-rich environments or where groundwater is abundant, its high water usage can lead to rapid soil moisture depletion in drier regions.

Comparing the three land covers, Natural Trees emerged as the most water-efficient, maintaining a balanced relationship between evapotranspiration and soil moisture retention. Grassland, on the other hand, exhibited poor water retention and higher vulnerability to drought, making it less suitable for areas with irregular rainfall. Eucalyptus, while retaining the most soil moisture, poses a challenge in water-scarce environments due to its high-water consumption. It can lead to significant depletion of water resources, especially in prolonged dry periods.

4.3 Recharge Rate

The graph below presents monthly groundwater recharge rates under three land cover types—grassland, natural trees, and eucalyptus—from May 2023 to May 2024, alongside the corresponding monthly rainfall. The rainfall data shows a wide variation throughout the year, with a maximum of 468.1 mm recorded in May 2023 and a minimum of 70.2 mm in January 2024. This fluctuation in rainfall directly influences groundwater recharge, though the extent of recharge varies depending on the type of land cover.

For grassland areas, the recharge rates generally follow the rainfall pattern but show notable variations. In May 2023, during a period of high rainfall, the recharge rate reaches its peak at 286.52 mm, while it drops significantly to 14.58 mm in January 2024 when rainfall is at its lowest. Grasslands tend to have a moderate capacity for recharge, as their relatively shallow, fibrous root systems allow for greater groundwater infiltration in wet months, and specifically a greater reduction in drier months.

It is consistently noted that natural tree cover has a greater capacity for recharge compared to grassland and eucalyptus cover. The highest recharge (340.58 mm) was recorded in May 2023 under natural trees, confirming their ability to retain and recharge more water due to deeper roots and greater water-holding capacity. Even in months with lower rainfall, such as January 2024, the recharge rate for natural trees is higher than grassland, indicating that natural forests provide a more stable contribution to groundwater recharge.

In contrast, eucalyptus-dominated areas exhibit the lowest recharge rates among the three land covers. While rainfall in May 2023 leads to a recharge of 237.48 mm, this is still lower than the values observed in grassland and natural trees. The eucalyptus areas show a sharp decline in recharge, particularly in drier months like January 2024, where the recharge drops to just 0.2 mm. This reflects the high water consumption typical of eucalyptus trees, which limits the amount of water available for groundwater recharge.

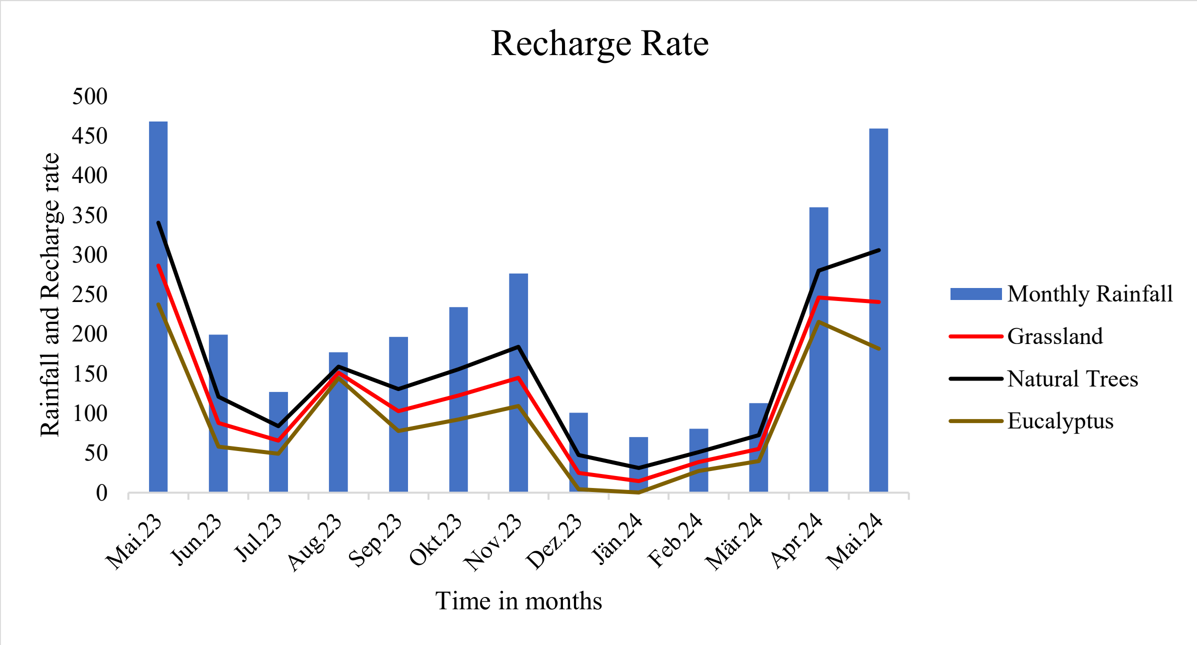

Figure 0-2: Groundwater recharge rate

4.3.1 Determination of the groundwater recharge rate in various landcovers

The natural trees site, which is represented by strong brownish-red loamy silty clay and dark brown fine-grained silty clay soil profiles, illustrates significant variability over time in moisture. The data show variability in soil moisture partly due to seasonal rainfall that can produce spikes in moisture content during wet periods and declines in moisture during drier periods. This is consistent with literature that indicates variability in recharge related to climate and seasonal variability. Smerdon (2017) notes that precise determination of recharge rates is needed to sustain groundwater, and the variability documented at the natural trees site suggests variability in recharge driven by soil properties and seasonal rainfall changes. Moeck et al. (2020) identify that natural anthropogenic factors, such as soil type and rainfall drive a recharge spectrum for evaporation, and that our results from the Shamakhokho site reflect that natural factors drive variability of recharge in each of our samples.

The grassland site also showed soil profile that had a brownish-red loamy silty gravel layer overlaid on coarse grained red gravel, and showed variation from the time series in moisture content over time. The data indicated moisture content increasing during wet conditions and declining during dry conditions, indicating that variability in recharge is also occurring at this site and is also related to variability in soil moisture as literature reflects. Seiler and Gat (2007) noted that the recharge is effectively the net infiltration after losses through processes like evapotranspiration and that recharge varied greatly depending on soil type and climatic conditions. This assessment was verified and quantified by our data collected at Amatsi, which also showed how climatic variables could change moisture content and rates of recharge. A Eucalyptus plantation which had a soil profile dominated by clay and the Eucalyptus canopy had very high variability in moisture content, with extreme peaks and valleys seen through the study period. These variation levels showed the significant issues with estimating groundwater recharge within the studies of Scanlon et al. (2006), and Hartmann et al. (2017) who also recognized the importance of subsurface variations and climatic effects within recharge estimates. Despite considering the uncertainty of many of the measurement points that recorded very high or very low moisture content at a site, the data records provided further support for models that consider climate factors and subsurface variability to expand understanding of groundwater recharge processes.

Overall, the focal areas of study fall into a lot of what we have seen reflected in the literature around groundwater recharge. The data collected indicated variability in moisture content and alignment to seasonal rainfall patterns reinforces previously mentioned literature related to influential factors involved in groundwater recharge estimates. Nevertheless, the marked variations in moisture levels at each station also underscore the difficulties related to prediction and management of groundwater recharge, in consideration of changing land cover or climate, as cited by Earman and Dettinger, 2011, Reinecke et al. 2021. Accurate recharge estimation is inherently complex due to differences in soil properties, climatic conditions, and the effects of land cover change, leaving the necessity for integrated hydrologic modeling and management of groundwater to be considered.

4.3.2 Determination of soil water distribution in the vadose zone for various land cover

A natural grassy site with two layers of soil, changing from brown reddish loam silty gravel to coarse red gravel, exhibits a considerable range of moisture from 0.322 to 0.605. As discussed by Selker et al. (1999), fluctuations in moisture content in the soil are regional to the texture of the soil. It is likely the coarse grain beneath the loamy soil facilitates drainage rates faster than the surface zone soil retains or holds moisture. These observations align with some of the principles presented by Arora et al. (2019) about how the texture and structure of soil dictate processes such as infiltration and water distribution. These significant changes in moisture content are indicative of seasonal rainfall events and soil contexts, emphasizing the complexities of soil water distribution and its role in groundwater recharge.

Another site under natural vegetative trees, with soil stratification, provides an apparent example of how soil degree of saturation or moisture is governed by soil behavior of the vadose zone. The soil profile includes loamy silty clay brownish-red from 0 to 0.5 meters, and dark brown finely grained silty clay from 0.5-1.0 meters. There was sufficient variation of soil moisture from near 0.270 and 0.548, representing the dynamic nature of moisture disappearance in vadose zone soil behavior as tabulated in Table 4.4. Such variability supports the work of Arora et al. (2019), who discuss the influence of soil texture and soil structure on water retention and transport. The finer textured soil in Shamakhokho is responsible for the differences in infiltration and retention behavior, which aligns with findings from X. Liu et al. (2019) that underscore the relationship between soil texture, water holding capacity, and permeability.

Alternatively, the planted eucalyptus vegetation site (clay-dominated soils) also presented variations in moisture content (0.202 to 0.513). The extent of variation, and extreme high and low values, suggests the influence of soil properties or vegetation on moisture content. The influence of soil on moisture retention, and particularly the high clay content existing on the eucalyptus site, supports the work of X. Liu et al. (2019) on the importance of soil texture in moisture retention and transport.

In summary, the results from the grassland, natural tree vegetation, and eucalyptus tree vegetation sites illustrate the importance of soil properties and land cover on soil moisture distribution in the vadose zone. The variability of moisture content that was demonstrated among the three sites is in agreement with the general literature, while it highlights the role of soil texture, structure, and plant cover on moisture processes. This is consistent with Arora et al. (2019) work that describes the interactions among soil properties and environmental aspects on soil water distribution for species that require a lot of water such as eucalyptus. Measurement and modeling, as shown by Simunek et al. (2005), is also an important aspect in gaining insight on how land-use factors and climate factors impact soil water dynamics and groundwater recharge. They also show how soil physical and chemical properties interact with vegetation aspect and climate factors on groundwater recharge and vadose zone moisture (X. Liu et al. 2019).

Table 4.4: Comparison between Rainfall and Volumetric moisture content in varying land covers

Date	AVERAGE MONTHLY RAINFALL	MONTHLY VOLUMETRIC MOISTURE CONTENT GRASSLAND	EUCALYPTUS	NATURAL TREE COVER
May-23	468.10	0.30	0.34	0.40
Jun-23	199.20	0.37	0.24	0.38
Jul-23	127.10	0.30	0.23	0.35
Aug-23	177.20	0.24	0.25	0.32
Sep-23	196.50	0.34	0.26	0.33
Oct-23	234.20	0.41	0.32	0.44
Nov-23	276.30	0.50	0.38	0.47
Dec-23	100.70	0.37	0.32	0.41
Jan-24	70.20	0.30	0.26	0.38
Feb-24	80.50	0.29	0.25	0.30
Mar-24	112.90	0.36	0.38	0.48
Apr-24	360.10	0.45	0.40	0.43
May-24	459.50	0.44	0.41	0.49

4.3.4 Simulation of the effects of various land cover on the water flow in the vadose zone

For all land cover types, the model validation was based on the guidelines of RSR≤0.70 suggested by Moriasi et al. (2007). In the validation period, for the eucalyptus site, the model underestimated SMC in the dry periods, while for the grassland, the model overestimated observed SMC. For both eucalyptus, natural trees and grassland sites, the May 2023-May 2024 validation period showed very limited precipitation events during the months of September to December, further reducing the soil moisture content. This consistent with Horel et al. (2022) that the eucalyptus location displayed increased soil moisture depletion.Also,Simulation of HYDRUS-1D with winter cover crops showed variable performance across plant systems, with R2 values ranging from 0.57 to 0.93 across soil depths. This reflects your model's higher accuracy in grasslands and lower accuracy under more complex vegetation (eucalyptus)(Chakraborty, Singh, Singh, & Kumar, 2022).

The best model performance was observed for the grassland SWCs, where the model nicely followed the resulting changes in SWCs from all recorded precipitation events. Simulated curves and observed curves for the three stations are as shown in figures 4.4, 4.5 and 4.6 below.

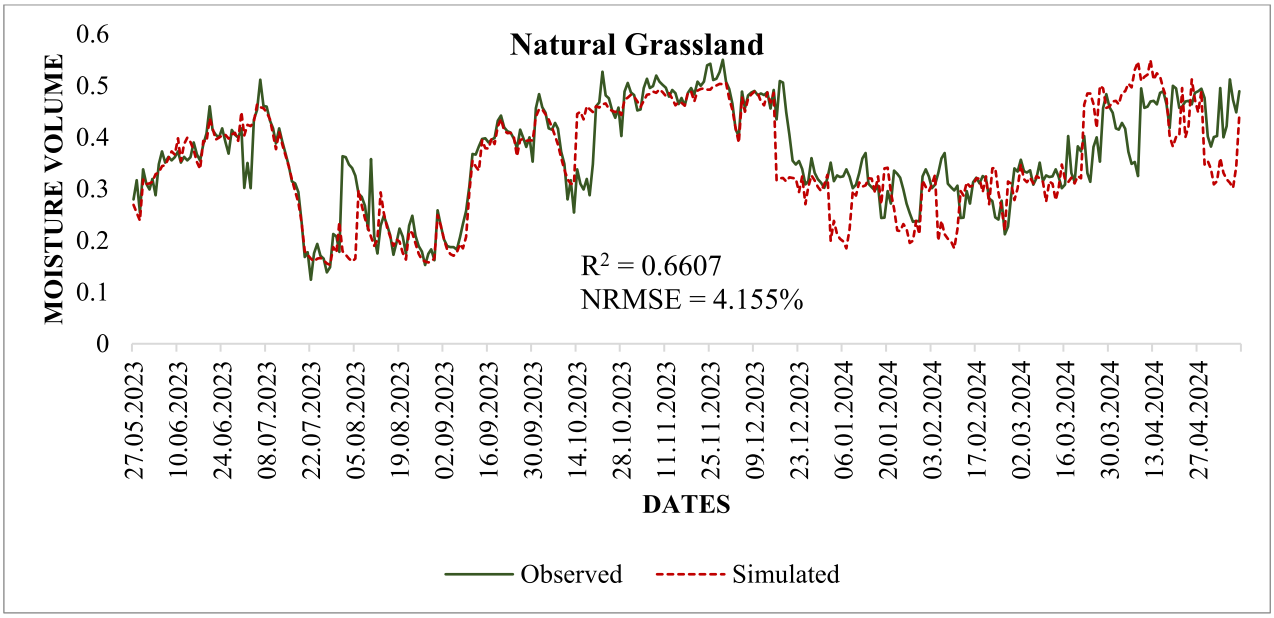

Figure 0-3: Simulated and observed VMC at station grassland site

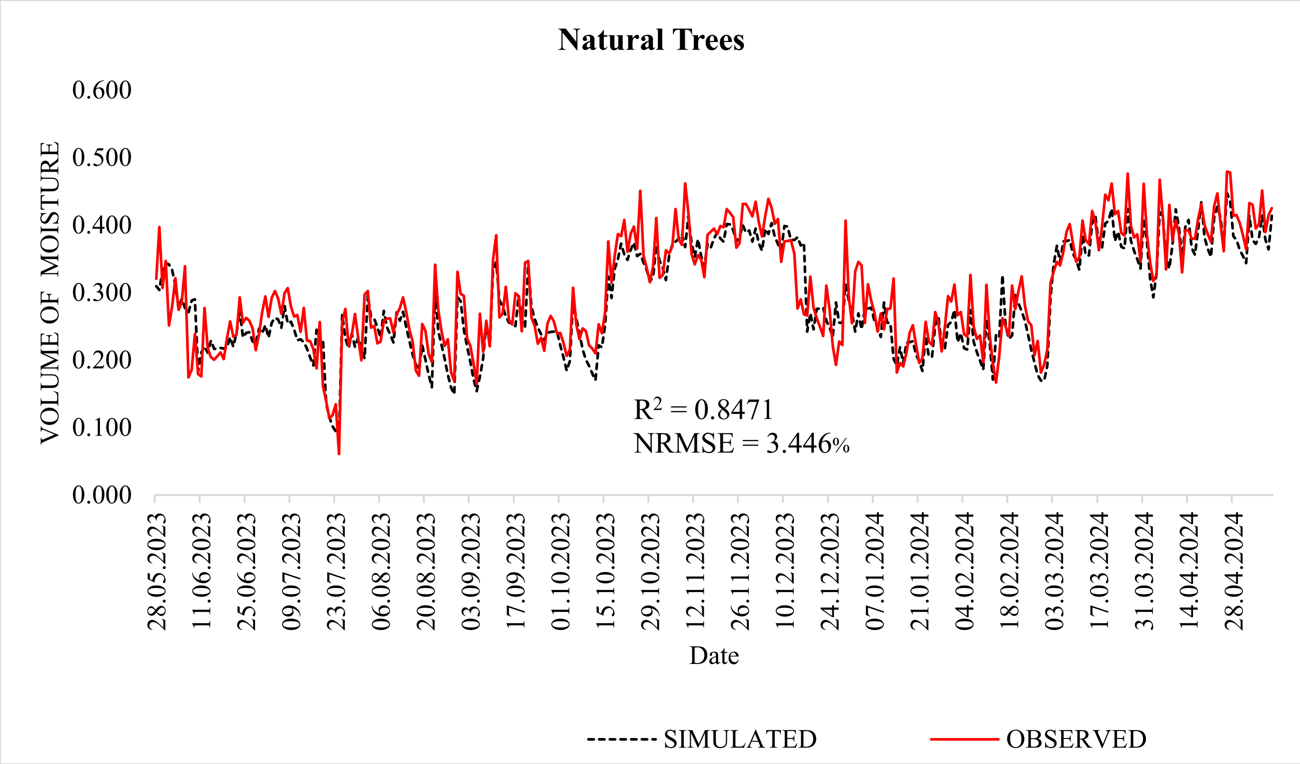

Figure 0-4: Simulated and observed VMC at natural trees site

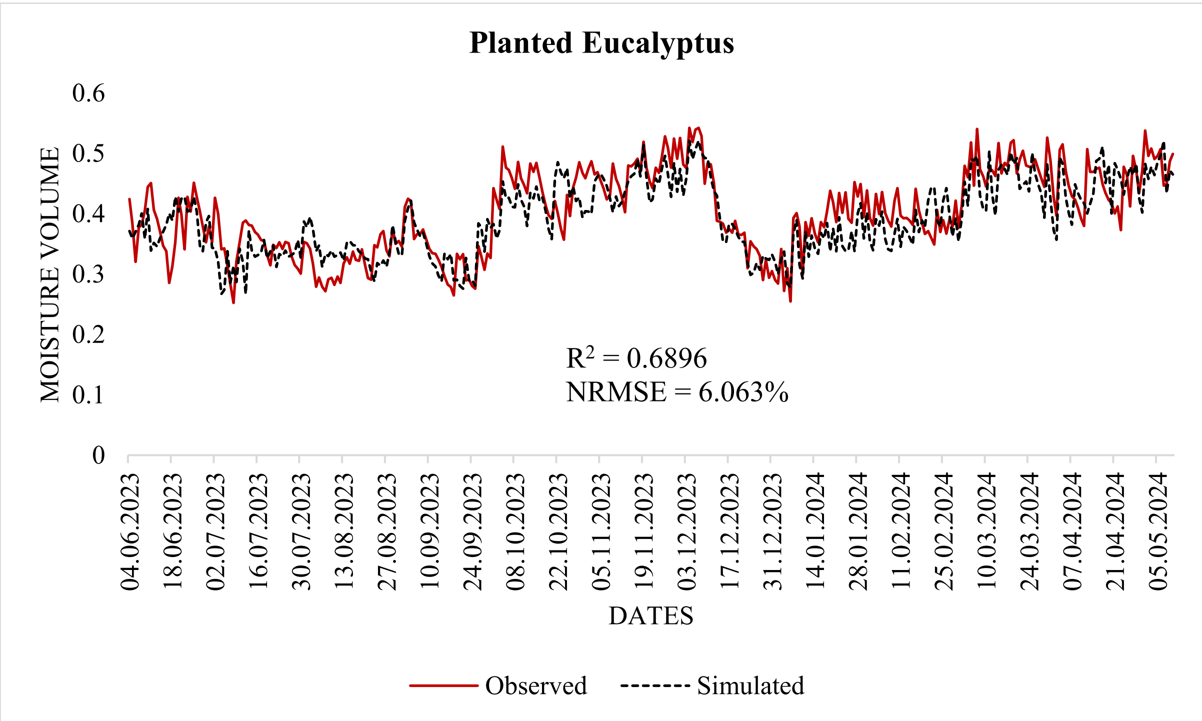

Figure 0-5: Simulated and observed VMC at Eucalyptus plantation site

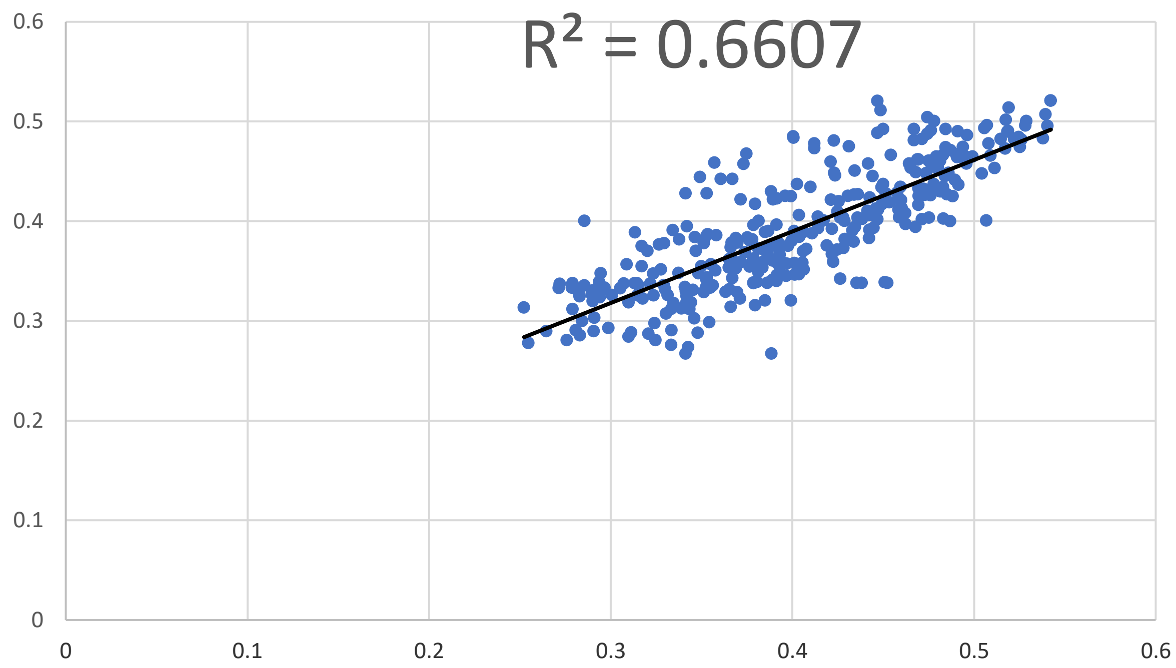

Figure 0-6: Regression plot for grassland

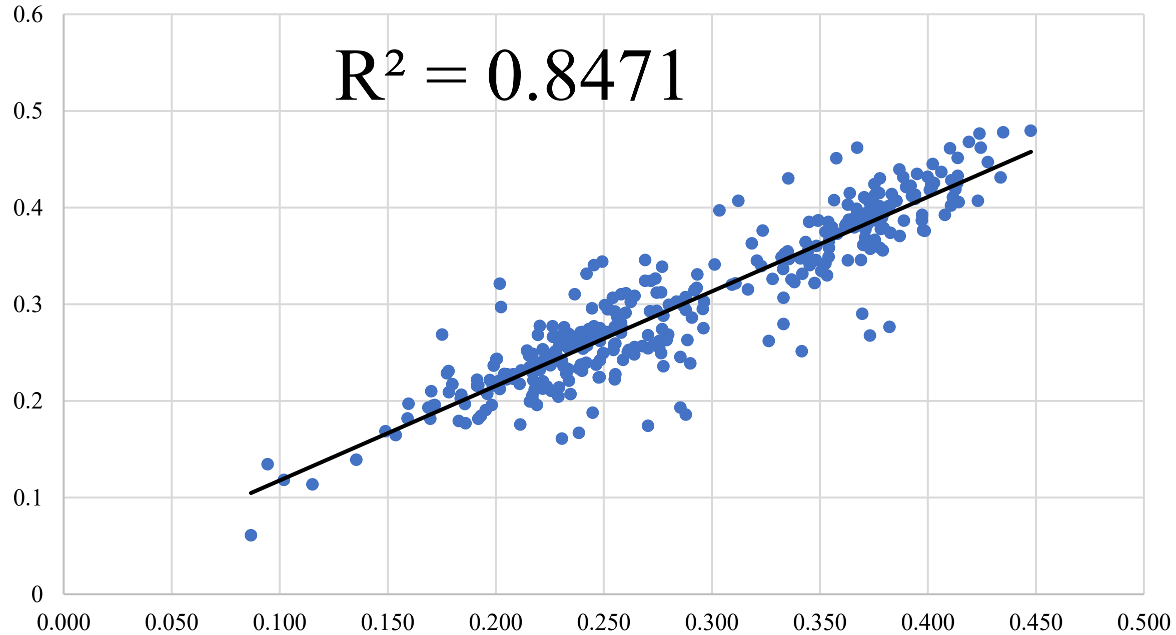

Figure 0-7: Regression plot for indigenous trees

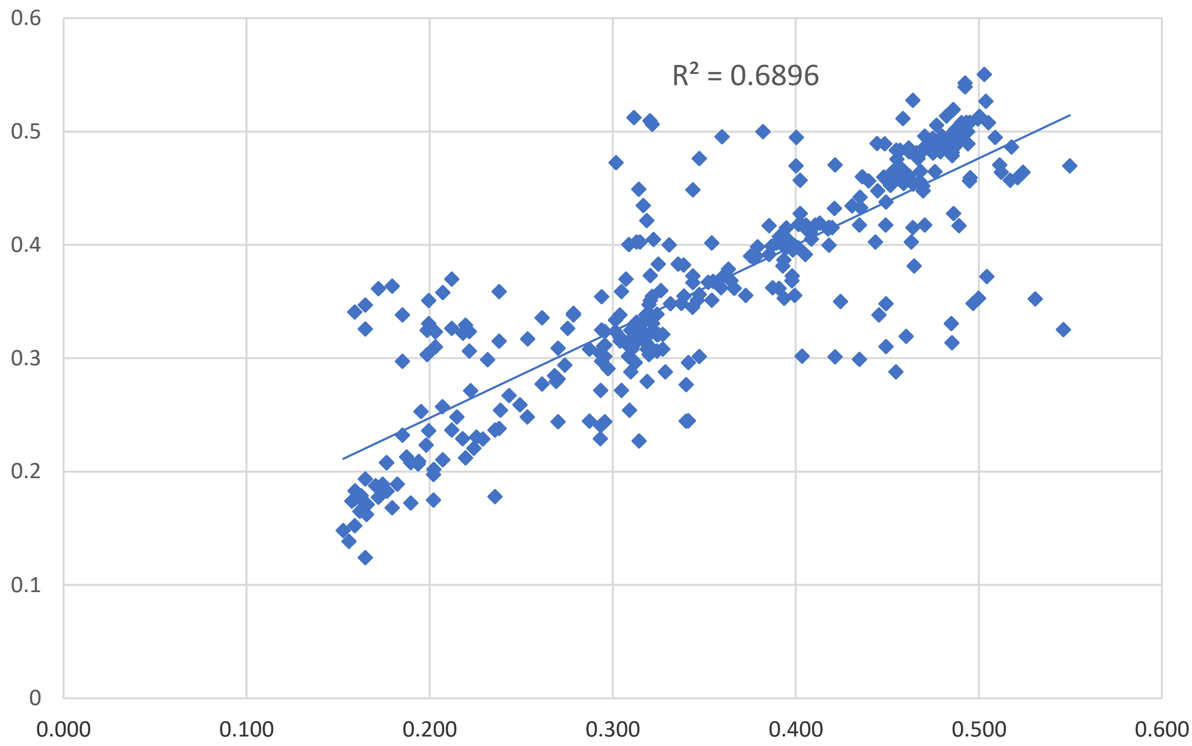

Figure 0-8: Regression plot for Exotic eucalyptus

For grassland site, the model's prediction of soil moisture demonstrated a strong correlation with observed data, with an R^2 value of 0.6607, indicating agreement between the predicted and observed moisture levels. The Normalized Root Mean Square Error (NRMSE) was relatively low, at 6.063%, suggesting minimal deviations between the model's output and actual soil moisture values. This low NRMSE indicate that the model was able to capture soil moisture fluctuations accurately, making it highly reliable for this station.

For natural vegetation site, the model exhibited a slightly lower, but still strong, correlation between predicted and observed soil moisture, with an R^2 value of 0.8471. The NRMSE was 3.446%, NRMSE indicate that the model was able to capture soil moisture fluctuations accurately, making it highly reliable for this station.

For eucalyptus plantation site, the model also performed well, with an R^2 value of 0.6896, reflecting a correlation between predicted and observed soil moisture levels. The NRMSE 4.155%, indicating lesser deviations between the predicted and observed values compared to grassland and natural trees sites. This suggests that the model effectively captures the overall trend of soil moisture at this station, there are though some significant variations in the prediction accuracy, due to local factors influencing soil moisture retention and distribution like the eucalyptus planted in that location.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study aimed to assess the effects of land cover on groundwater dynamics in the Middle Yala Catchment, with a focus on soil moisture distribution in the vadose zone and groundwater recharge rates. Through field data collection and HYDRUS-1D simulations across three distinct stations— Kaimosi (grassland), Shamakhokho (natural trees), and Bendera (eucalyptus) —we identified key relationships between land cover, vegetation cover, soil properties, and moisture movement within the vadose zone. The following were the key conclusion

5.1.1To investigate the groundwater Recharge Rates:

Variability in soil moisture and infiltration rates across the three stations directly influenced groundwater recharge rates. The grassland site demonstrated more effective recharge due to higher soil porosity and better moisture retention in the vadose zone. The eucalyptus site showed rapid soil moisture depletion, highlighting the potential negative effects of certain vegetation types on groundwater recharge, as eucalyptus trees extract large volumes of water from the soil

5.1.2. To evaluate soil water distribution in the vadose zone for various land use:

Different land covers—grassland, natural tree vegetation, and eucalyptus plantations—showed distinct soil moisture retention patterns. Grassland areas exhibited higher moisture retention and more stable moisture dynamics, while eucalyptus-dominated areas experienced more significant fluctuations, especially during wet and dry periods. Soil texture, particularly clay content, was a key factor in moisture retention, with clay-heavy soils in Bendera retaining more moisture but showing less predictable moisture behavior.

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5.1.3 To simulate the effects of various land cover on the water flow in the vadose zone:

The HYDRUS-1D model was effective at each station, with grassland having the best correlation between the simulated and observed soil moisture data ($R^2 = 0.8471$). For the eucalyptus site the model performed poorly, due to the intricate link between eucalyptus vegetation and soil moisture dynamics. Nevertheless, the model still communicated the important trends indicating that the HYDRUS-1D model is useful for simulating soil moisture conditions under various land cover within the Middle Yala Catchment.

In summary, improved groundwater management within the Middle Yala Catchment requires a nuanced understanding of land cover practices, soils, and seasonal rainfall patterns; for example, land cover practices that promote moisture retention and recharge potential would be a viable management strategy to protect sustainable groundwater within the region.

5.2 Recommendations from the Study

Drawing from the results of this study on land cover and groundwater dynamics in the Middle Yala Catchment, some significant recommendations are presented that might enhance groundwater management and land cover practices in the study area.

To begin, the adoption of land cover practices that enhance groundwater recharge should be encouraged. The study outcomes showed that different land covers produced different soil moisture retention and groundwater recharge processes. Natural grasslands and tree cover retained soil moisture better than eucalyptus plantations, which are known to have a high-water uptake. Therefore, land cover planning should focus on vegetation that enhance groundwater recharge, such as native trees and mixed agroforestry systems. Improved soil infiltration and reduced surface runoff are both positives for groundwater sustainability in relation to land use.

Second, there is a need to regulate the expansion of eucalyptus plantations. The study found that eucalyptus, particularly in eucalyptus plantation site (Bendera), negatively impacted soil moisture levels, leading to lower groundwater recharge rates. To mitigate this, it is recommended that eucalyptus planting be controlled, especially in areas critical for groundwater recharge. In existing eucalyptus plantations, water-efficient management practices or the gradual replacement of eucalyptus with less water-demanding species should be encouraged to reduce the strain on groundwater resources.

Third, sustainable water conservation efforts should be promoted in agricultural areas. In regions such as Kaimosi, where natural grasslands are prevalent, agricultural activities have altered soil moisture dynamics. Implementing sustainable agricultural practices like rainwater harvesting, soil conservation techniques, and efficient irrigation systems can enhance water use efficiency and preserve soil moisture. This will not only support agricultural productivity but also help maintain the balance between land cover and groundwater recharge.

5.3 Recommendations for Future Research

Based on the findings of this study, it is recommended that future research includes

Long-term monitoring of soil moisture and groundwater levels. While this study captured seasonal variations, extended data collection would provide more comprehensive insights into inter-annual trends and anomalies.

Further research should investigate the effects of different vegetation types such as native plant species on groundwater recharge would enhance our understanding how plant species influence soil water dynamics.

Integrating remote sensing technologies and geospatial analysis would also improve future research on land cover and groundwater recharge

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APPENDICES

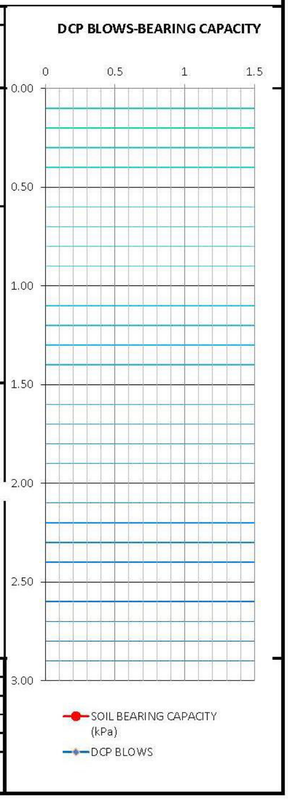
Appendix I: Soil Analysis Report

TRIAL PIT LOG

PROJECT DETAILS	
Project:	
Client:	
Location:	KAIMOSI VIHIGA COUTNY
SITE ID:	VHG001
Equipment and Method:	Pix exes and matock

FIELD DETAILS	
Trial pit No:	2
Start Date:	Saturday, May 11, 2024
End Date:	Saturday, May 11, 2024
Logged By:	Moses Toili
Elevation:	1453.03M
Max. achieved Depth:	1.50m
Coordinates S	1.11834°
Coordinates E	34.838848°

Depth scale(m)	Water	Sample No.	Sample Depth	DCP BLOWS Tested Depth	DCP BLOWS Blows	SOIL BEARING CAPACITY (kPa)	LEGEND	Change of strater (m)		Profile Description
0.50								0.00	0.50	Firm brownish red loamy silty clay soil.
1.00		B1	1.0-1.1					0.50	1.00	.Dark brown Fine grained Silty Clay soil.
		END OF TRIAL PIT								
1.50										
2.00										
2.50										
2.90										



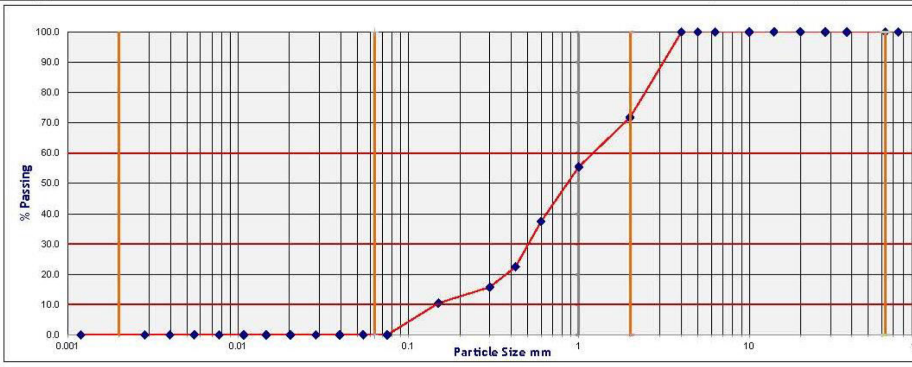
SYMBOLS AND ABBREVIATIONS	
DCP :	Dynamic Cone Penetrometer
UDS-1:	Undisturbed Sample and Number (U100)
D:	Disturbed Sample
B-1:	Bag Sample and Number
	Struck water level and Depth

TOPOGRAPHY	Hilly terrain
VEGETATION	Planted and natural shrubs
DRAINAGE	Well drained,with undulating slope
RUN OFF	Uncontrolled
COMMENTS	Already stripped surface

CLIENT:	
PROJECT	
SITE:	Sampled By:

Sample No	Depth Range 1 m	Location: TP 1	Test Date:
Grading+ Hydrometer		PARTICLE SIZE DISTRIBUTION	Tested By: Sign:
Wt. of Dry Sample	249.7 g		

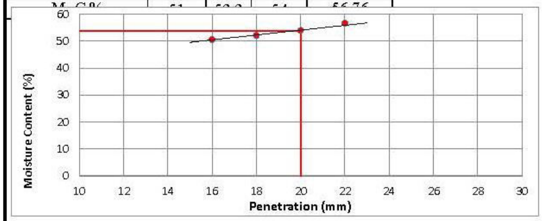
Sieve	Retained mass(g) & Hydrometer		% Passing
75			100.0
63			100.0
37.5			100.0
28			100.0
20			100.0
14			100.0
10			100.0
6.3			100.0
5			100.0
4			100.0
2	70.4		71.8
1	40.6		55.5
0.6	45.2		37.4
0.425	37.4		22.5
0.3	16.7		15.8
0.15	13.2		10.5
0.075	26.2		0.0
0.054	31	8	
0.039	30	8.5	
0.029	29	8.9	
0.020	28.5	9	
0.015	28	9.3	
0.011	27.5	9.5	
0.008	27	9.8	
0.006	26	10	
0.004	25.5	10.3	
0.003	25	10.5	
0.001	22.5	11.2	
	RH	HR	

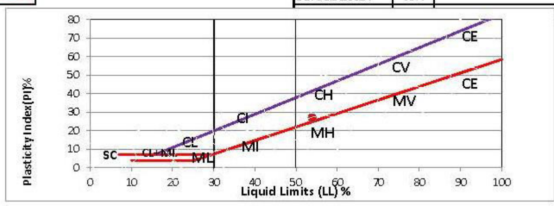


		% CLAY		% SILT				% SAND				% GRAVEL				BOULDERS	
D10			Total	Fine	Medium	Coars	Total	Fine	Medium	Coarse	Total	Fine	Medium	Coars	Total		Total
D30								15.8	21.7	34.4	71.8	28.2			28.2		
D60								SAND				very gravelly					

ATTERBERG LIMITS

	LL				PL		PI	NMC		CLAY ACTIVITY (%)	
PENETRATION	16	18	20	22	26.47	27.5	27.0	11.1		#####	#DIV/0!
M. C%	51	52.2	54	56.76	26.985			LINEAR SHRINKAGE			
								FROM LAB.	13.6	of:- 22.5	





USCS DIDACTIONS

KEY TO LABORATORY CLASSIFICATION CRITERIA

SW	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4	$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}}$ Between 1 and 3	GW	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4	$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}}$ Between 1 and 3

SP	Not meeting all gradation requirements for SW		GP	Not meeting all gradation requirements for GW	
SM	Atterberg limits below "A" Line or P.I. Less than 4	Limits plotting in shaded zone with P.I. Between 4 and 7 are borderline cases requiring use of dual symbols.	GM	Atterberg limits below "A" Line or P.I. Less than 4	Above "A" Line with P.I. Between 4 and 7 are borderline cases requiring use of dual symbols.
SC	Atterberg limits above "A" Line or P.I. greater than 7		GC	Atterberg limits above "A" Line or P.I. greater than 7	

USCS CLASSIFIED SOIL	CH	C_U	C_C	USCS POSSIBLE CLASSIFICATION	
DESCRIPTION:	Red Silty Sandy clay soil			GM/GC/SM/SC	CH
		Plasticity Modulus	605.56		

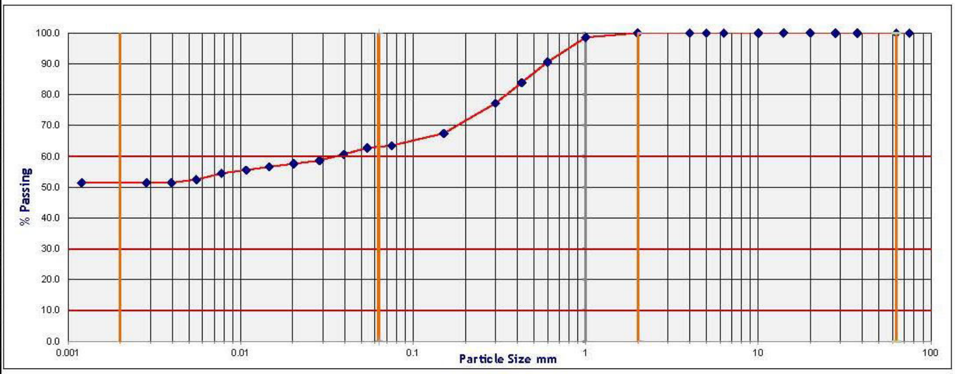
KEY

CC= Coefficient of Curvature; CU= Coefficient of Uniformity; MC= Moisture content; PL= Plastic Limit; LL= Liquid Limit
NMC = Natural Moisture Content; PI= Plastic Index

CLIENT:	
PROJECT:	
SITE:	Sampled By:

Sample No 465	Depth 1.6 m	Location: TP 2	Test Date:
Grading+ Hydrometer		PARTICLE SIZE DISTRIBUTION	Tested By:
Wt. of Dry Sample	800 g		

Sieve	Retained mass(g) & Hydrometer		% Passing
75			100.0
63			100.0
37.5			100.0
28			100.0
20			100.0
14			100.0
10			100.0
6.3			100.0
5			100.0
4			100.0
2			100.0
1	11.2		98.6
0.6	63.8		90.6
0.425	53.5		83.9
0.3	53.5		77.3
0.15	78.3		67.5
0.075	31.8		63.5
0.054	31	8	62.7
0.039	30	8.5	60.7
0.029	29	8.9	58.6
0.020	28.5	9	57.6
0.015	28	9.3	56.6
0.011	27.5	9.5	55.5
0.008	27	9.8	54.5
0.006	26	10	52.5
0.004	25.5	10.3	51.4
0.003	25	10.5	51.4
0.001	22.5	11.2	51.4
	RH	HR	

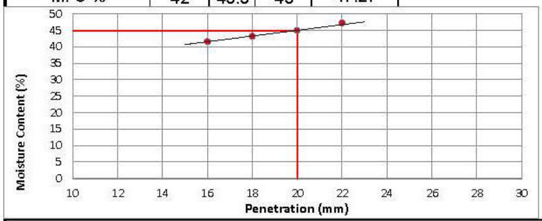


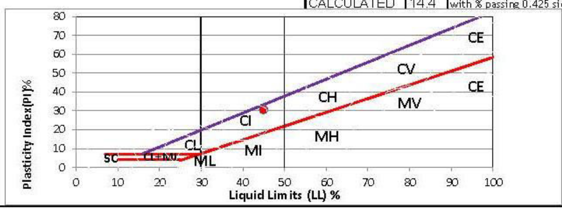
		% CLAY	% SILT				% SAND				% GRAVEL				BOULDERS
D10		Total	Fine	Medium	Coars	Total	Fine	Medium	Coarse	Total	Fine	Medium	Coars	Total	Total
D30		51.4	1.0	5.1	5.1	11.3	14.5	13.4	9.4	37.3					
D60		CLAY	silty				very sandy								

ATTERBERG LIMITS

	LL				PL		PI
PENETRATION	16	18	20	22	14.04	14.55	30.7
M. C %	42	43.3	45	47.27	14.295		

NMC	CLAY ACTIVITY (%)	
8.55	0.6	INACTIVE CLAY
LINEAR SHRINKAGE		
FROM LAB.	12.9	
CALCULATED	14.4	with % passing 0.425 sieve c 83.9





USCS DIDACTIONS

KEY TO LABORATORY CLASSIFICATION CRITERIA

SW	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4	$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}}$ Between 1 and 3	GW	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4	$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}}$ Between 1 and 3
SP	Not meeting all gradation requirements for SW		GP	Not meeting all gradation requirements for GW	
SM	Atterberg limits below "A" Line or P.I. Less than 4	Limits plotting in shaded zone with P.I. Between 4 and 7 are borderline cases requiring use of dual symbols.	GM	Atterberg limits below "A" Line or P.I. Less than 4	Above "A" Line with P.I. Between 4 and 7 are borderline cases requiring use of dual symbols.
SC	Atterberg limits above "A" Line or P.I. greater than 7		GC	Atterberg limits above "A" Line or P.I. greater than 7	

USCS CLASSIFIED SOIL	CL	C_U	C_C
DESCRIPTION:	Red Silty Sandy clay soil		
		Plasticity Modulus	2575.5

USCS POSSIBLE CLASSIFICATION: ML/CL/MH/CH | CL

KEY

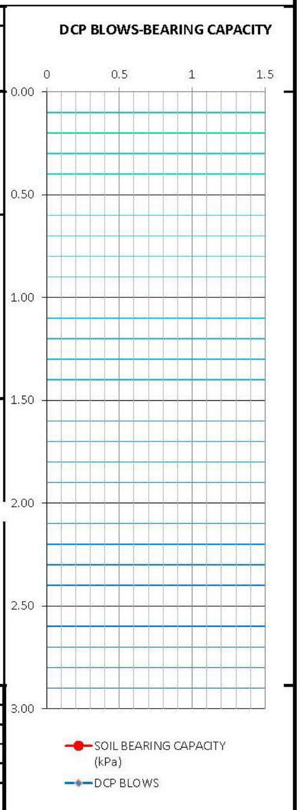
- CC= Coefficient of Curvature
- NMC = Natural Moisture Content
- CU= Coefficient of Uniformity
- PI= Plastic Index
- MC= Moisture content
- PL= Plastic Limit
- LL= Liquid Limit

TRIAL PIT LOG

PROJECT DETAILS	
Project:	
Client:	
Location:	AMATSI VIHIGA COUTNY
SITE ID:	VHG001
Equipment and Method:	Pix exes and matock

FIELD DETAILS		
Trial pit No:		1
Start Date:		Saturday, May 11, 2024
End Date:		Saturday, May 11, 2024
Logged By:		Moses Toili
Elevation:		1450.8M
Max. achieved Depth:		1.50m
Coordinates	S	1.121525°
	E	34.838578°

Depth scale(m)	Water	SAMPLES & TESTS: Sample No.	Sample Depth	DCP BLOWS: Tested Depth	DCP BLOWS: Blows	SOIL BEARING CAPACITY (kPa)	PROFILE FORMATION: LEGEND	Change of strater (m)		Profile Description
0.50								0.00	0.60	Firm brownish red loamy silty gravel.
1.00		B1	1.0-1.1							
		END OF TRIAL PIT								
1.50								0.60	1.50	Coarse grained cohessive red Gravel.
2.00										
2.50										
2.90										



SYMBOLS AND ABBREVIATIONS	
DCP :	Dynamic Cone Penetrometer
UDS-1:	Undisturbed Sample and Number (U100)
D:	Disturbed Sample
B-1:	Bag Sample and Number
(symbol)	Struck water level and Depth

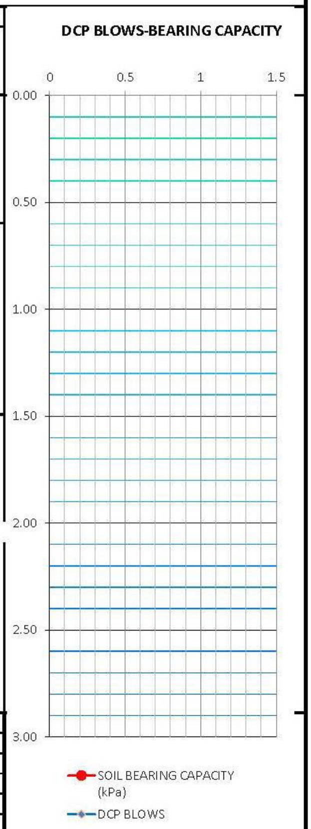
TOPOGRAPHY	Hilly terrain
VEGETATION	Planted and natural shrubs
DRAINAGE	Well drained,with undulating slope
RUN OFF	Uncontrolled
COMMENTS	Already stripped surface

TRIAL PIT LOG

PROJECT DETAILS	
Project:	
Client:	
Location:	KAIMOSI VIHIGA COUTNY
SITE ID:	VHG003
Equipment and Method:	Pix exes and matock

FIELD DETAILS	
Trial pit No:	3
Start Date:	Saturday, May 11, 2024
End Date:	Saturday, May 11, 2024
Logged By:	Moses Toili
Elevation:	1454.03M
Max. achieved Depth:	1.50m
Coordinates S	1.124014°
Coordinates E	34.845343°

Depth scale(m)	Water	SAMPLES & TESTS: Sample No.	Sample Depth	DCP BLOWS: Tested Depth	DCP BLOWS: Blows	SOIL BEARING CAPACITY (kPa)	PROFILE FORMATION: LEGEND	Change of strater (m)		Profile Description
0.50								0.00	0.50	Firm brownish red loamy silty clay soil.
1.00		B1	1.0-1.1					0.50	1.00	.Dark brown Fine grained Silty Clay soil.
		END OF TRIAL PIT								
1.50										
2.00										
2.50										
2.90										



SYMBOLS AND ABBREVIATIONS

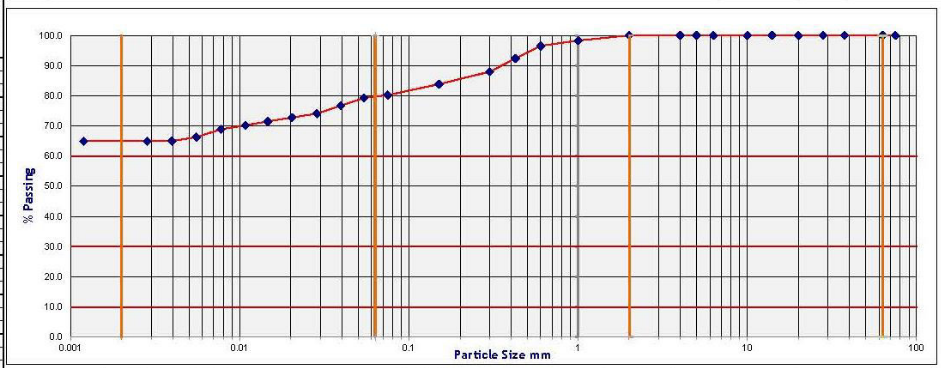
DCP :	Dynamic Cone Penetrometer
UDS-1:	Undisturbed Sample and Number (U100)
D:	Disturbed Sample
B-1:	Bag Sample and Number
(water symbol)	Struck water level and Depth

TOPOGRAPHY	Hilly terrain
VEGETATION	Planted and natural shrubs
DRAINAGE	Well drained,with undulating slope
RUN OFF	Uncontrolled
COMMENTS	Already stripped surface

CLIENT:	
PROJECT:	
SITE:	

Sample No 465	Depth 1 m	Location: TP 3	Sampled By:
Grading+ Hydrometer		PARTICLE SIZE DISTRIBUTION	Test Date:
Wt. of Dry Sample	800 g		Tested By:

Sieve	Retained mass(g) & Hydrometer		% Passing
75			100.0
63			100.0
37.5			100.0
28			100.0
20			100.0
14			100.0
10			100.0
6.3			100.0
5			100.0
4			100.0
2			100.0
1	13.7		98.3
0.6	14.2		96.5
0.425	33.6		92.3
0.3	34.7		88.0
0.15	33.2		83.8
0.075	28.9		80.2
0.054	31	8	79.3
0.039	30	8.5	76.7
0.029	29	8.9	74.1
0.020	28.5	9	72.8
0.015	28	9.3	71.5
0.011	27.5	9.5	70.2
0.008	27	9.8	68.9
0.006	26	10	66.3
0.004	25.5	10.3	65.0
0.003	25	10.5	65.0
0.001	22.5	11.2	65.0
	RH	HR	



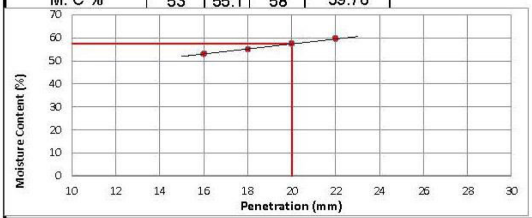
D10	
D30	
D60	

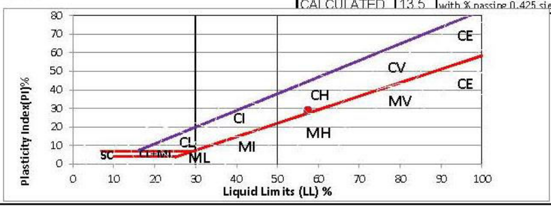
% CLAY		% SILT				% SAND				% GRAVEL				BOULDERS	
	Total	Fine	Medium	Coars	Total	Fine	Medium	Coarse	Total	Fine	Medium	Coars	Total		Total
	65.0	1.3	6.5	6.5	14.3	8.7	8.5	3.5	20.7						
CLAY		silty				very sandy									

ATTERBERG LIMITS

	LL				PL		PI	NMC	CLAY ACTIVITY (%)
PENETRATION	16	18	20	22	28.57	28.57	28.8	7.36	0.4 INACTIVE CLAY
M. C %	53	55.1	58	59.76	28.57				

LINEAR SHRINKAGE		
FROM LAB.	13.6	
CALCULATED	13.5	with % passing 0.425 sieve c 92.3





USCS DIDACTIONS

KEY TO LABORATORY CLASSIFICATION CRITERIA

SW	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4	$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}}$ Between 1 and 3	GW	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4	$C_C = \frac{D_{30}^2}{D_{10} \times D_{60}}$ Between 1 and 3
SP	Not meeting all gradation requirements for SW		GP	Not meeting all gradation requirements for GW	
SM	Atterberg limits below "A" Line or P.I. Less than 4	Limits plotting in shaded zone with P.I. Between 4 and 7 are borderline cases requiring use of dual symbols.	GM	Atterberg limits below "A" Line or P.I. Less than 4	Above "A" Line with P.I. Between 4 and 7 are borderline cases requiring use of dual symbols.
SC	Atterberg limits above "A" Line or P.I. greater than 7		GC	Atterberg limits above "A" Line or P.I. greater than 7	

USCS CLASSIFIED SOIL	CH	C_U	C_C	USCS POSSIBLE CLASSIFICATION
DESCRIPTION:	Red Silty Sandy clay soil			ML/CL/MH/CH — CH
		Plasticity Modulus	2662.8	

KEY

CC= Coefficient of Curvature; CU= Coefficient of Uniformity; MC= Moisture content; PL= Plastic Limit; LL= Liquid Limit
NMC = Natural Moisture Content; PI= Plastic Index

Appendix II: PLATES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