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Simulation of the Effects of Land Cover on Groundwater Dynamics in Yala Catchment Kenya

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ABSTRACT

Groundwater depletion is on an increasing trend due to land use changes. Soil water content is important in plant growth, nutrient transport, and oxygen balance, influencing various physiological and biochemical processes necessary for plant development and ecosystem stability. This study aimed to simulate soil water dynamics and assess the effects of land use changes on groundwater in the Middle Yala Catchment. The objectives were to determine effects of land use on moisture retention, infiltration and water availability for sustainable resource management. This was achieved through field experiments and modelling using HYDRUS-1D. Primary data, including soil moisture and groundwater levels, were collected under different environmental conditions such as tree canopy and grassland plantations. Climate data was collected from the weather station in Vihiga County. HYDRUS 1D model was used to simulate the relationship between land use scenarios under varying soil texture. The findings revealed that grassland areas maintained higher and more stable soil moisture levels than eucalyptus plantations, which experienced significant moisture fluctuations and harmed groundwater recharge. Seasonal rainfall patterns affected soil moisture in diverse ways across land uses, with eucalyptus plantations causing significant depletion due to high water uptake and evapotranspiration. The findings suggest that grasslands are more effective at retaining soil moisture, while eucalyptus plantations may contribute to water scarcity due to high water uptake and. The model accurately captured soil moisture trends in grassland but met challenges with eucalyptus interactions. The study emphasizes the importance of selecting vegetation types that enhance groundwater recharge and advocates for regulated eucalyptus expansion and sustainable agricultural practices.

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1. Introduction

Groundwater is a crucial resource, constituting 99% of Earth's freshwater, essential for human survival (Mishra, 2023). Sustainable management of this resource is increasingly important, as global water demand is projected to rise by 1% annually over the next 30 years (Boretti & Rosa, 2019). Groundwater is replenished through a process called recharge, which is significantly influenced by climate change and human activities, particularly changes in land use and land cover (LULC). LULC modifications affect groundwater recharge, surface runoff, infiltration, and soil moisture dynamics. Wang et al. (2019), reported that recharge can be greatly affected by climate change and anthropogenic activities. LULC represents the naturally and artificially distributed features on the Earth's surface, such as forest vegetation, water bodies and human structures (Siddik et al., 2023). Changes in LULC affect groundwater by modifying the pattern of water balance components (Olarinoye et al., 2023).

Plant exploitation and the constant changing of landscapes have over time produced a number of ecosystem services, but they have also had negative environmental repercussions. For instance, population growth has been enhanced by the expansion of agricultural lands and productivity over the past 200 years, but this has also resulted in widespread deforestation, soil erosion and degradation,

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desertification, biodiversity loss, and groundwater resource depletion (Adane et al., 2018).

Land-use plays a key role in controlling different patterns of soil moisture where it greatly influences the rate of infiltration surface run-off, and evapo-transpiration, especially during the growing season (Fu et al., 2000). Several studies have been carried out which mainly focused on dynamics in different agro-forestry systems, which have shown different spatial partitioning of water resources between trees and groundwater (Fernández et al., 2008). The studies majorly target the importance of available water in determining the structure of the herbaceous 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 use on water dynamics

Ecosystem sustainability, regulation of solute transport, heat transfer, and controlling regional run-off 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 (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 re-distribution is influenced by, evapo-transpiration, plant water uptake, soil surface infiltration, and precipitation.

According to Arsiso et al. (2017), changes in surface water resources and decreases in stream flow will be major threats across sub-Saharan African countries in the coming 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 use activities have negatively influenced groundwater recharge therefore, posing a forthcoming limiting factor to economic growth (Yahya et al., 2020). Additionally, there has been an accelerating growth of water consumption plus gradually deteriorating quantities water resource in the catchment. To effectively characterize and manage soil water distribution in the vadose zone, various measurement and modeling techniques are utilized. Instruments such as soil moisture sensors and neutron probes measure soil water content and monitor temporal changes. Hydrological models, like HYDRUS, simulate water flow and solute transport in the vadose zone, providing valuable insights into how different land-use scenarios and climate conditions affect soil moisture (Simunek et al., 2005). These models help predict the implications of changes in land use, climate, and soil properties on soil water dynamics, facilitating better water resource management and environmental conservation. Examples of modelling tools include soil and water assessment tool (SWAT), The Soil-Water-Atmosphere-Plant (SWAP), HYDRUS- 1D and HYDRUS 2D/3D among others. The choice of model depends on data availability, flexibility, and the specific requirements of the study area.

In Kenya, various land use activities have significantly affected groundwater flow, particularly in the context of rapid urbanization, agricultural expansion, and deforestation. Urban areas, like Nairobi and Mombasa, have experienced reduced groundwater recharge due to extensive impermeable surfaces, which have limited infiltration and increased surface runoff (Gichuhi & Gitahi, 2021). In agricultural regions, intensive farming practices and the use of irrigation have led to soil compaction and altered infiltration rates, affecting the natural recharge of groundwater (Owuor et al., 2016). Deforestation in areas such as the Mau Forest Complex has disrupted the natural water cycle, reducing soil water retention and leading to decreased groundwater recharge, which has exacerbated water scarcity in downstream areas (Rwigi, 2014). Conversely, reforestation efforts, while beneficial for soil conservation, have also altered groundwater dynamics when non-native species with high water uptake have been introduced (Reisman-Berman et al., 2019). These land use changes, compounded by climate variability, have challenged the sustainable management of groundwater resources.

It is upon this background that this study investigated the effects of land use on groundwater dynamics, by assessing the relationship between land use activities with soil properties with respect to groundwater recharge. This was achieved by carrying out a simulation of various land use practices on the water flow in the sub-surface zone. The results of this study are vital for informing land use planning decision, helping policy makers economic development with sustainable groundwater management practices. This study is crucial in informing land use planning decisions, guiding policymakers to make informed choices that balance economic development with environmental protection.

2. Materials and Methods

2.1. Description of the study area

Yala Catchment is one of the several trans-national river basins in Kenya, releasing water into Lake Victoria (Fig. 1). It covers an area of 3,351 km^2 with an elevation ranging from 1200 meters above sea level (m.a.s.l.) in the lowlands to 2200 m.a.s.l. in the highlands. The 212 km long Yala River originates from the Nandi Escarpment water tower and traverses Kakamega and Siaya counties before discharging into Lake Victoria at Winam Gulf. The river has a long-term average annual discharge (based on data from 1950 to 2000) of 37.6 m^3 per second, accounting for about 4.8% of the surface inflow into Lake Victoria. Average annual rainfall is about 850 mm in the large flat area near Lake Victoria and up to 2,000 mm in the highlands (Dida et al., 2020). Rainfall is received during two rainy seasons: i.e., short and long rainy seasons.

It has a gross catchment of 3,351 km^2 with an average annual flow of 30 m^3/sec. The Yala River Basin entails a catchment that traverses Nandi, Kakamega, Vihiga, and Siaya counties of the Kenyan western administrative region. Soil type in the catchment are well drained, deep, dark-reddish-brown humic Nitisols owing to the variations in the atmospheric climate and pedo-climate.

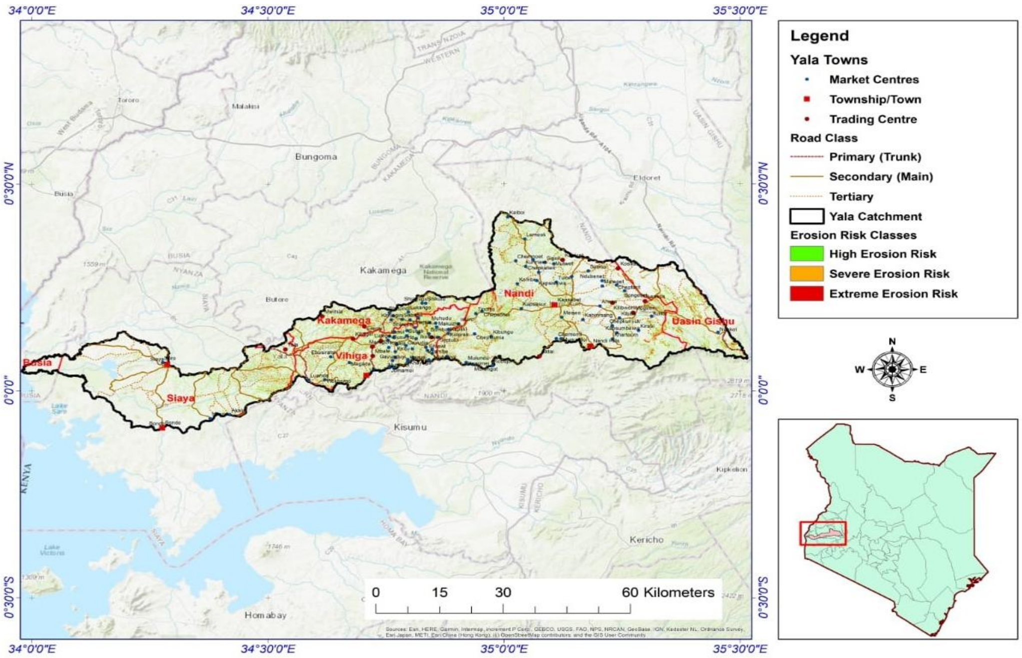

Fig. 1: The Study area

2.2. The HYDRUS 1D Model

HYDRUS ID is a simulation model used to understand soil water dynamics including groundwater recharge and root zone soil moisture distribution. It is based on Richards' Equation (Šimůnek, 2015), which describes water movement through unsaturated soils under varying environmental conditions. Model input includes maximum and minimum temperature, humidity, radiation, wind, soil moisture, plant rooting depth, albedo, leaf area index, and soil hydraulic properties among others. HYDRUS uses the Van Genuchten-Mualem hydraulic model to simulate soil water retention and hydraulic conductivity. This model characterizes how water moves through soil by describing the relationship between water content, pressure head, and conductivity. An S-shaped function is used in the model to assess how roots extract water from the soil."

2.2.1. Root Water Uptake

Root water uptake is modelled as the volume of water extracted from the soil per unit time, described by a dimensionless function that depends on the soil water pressure head. This function allows for variations in water uptake across different root zones, and it assumes that water uptake ceases when soil conditions reach saturation or the wilting point. The model uses a normalized water uptake distribution function to assess how roots take up water at different soil depths, which varies depending on soil moisture availability and root depth.

2.2.2. Unsaturated Soil Hydraulic Properties

In this study, the Van Genuchten model is applied to describe unsaturated hydraulic properties, using parameters such as soil water retention to simulate how water moves through the soil under different moisture conditions. This analytical model effectively captures the relationship between water content and hydraulic conductivity, providing critical data for simulation.

2.2.3. Initial and Boundary Conditions

The model operates under atmospheric boundary conditions, where fluid flux is influenced by environmental factors and transient soil moisture conditions. Specific conditions govern the surface flux, and the model allows for transitions between prescribed flux and pressure head conditions, ensuring accurate simulations.

2.2.4. Evaluation of Potential Evapotranspiration

The Thornthwaite method estimates potential evapotranspiration (PET) using monthly temperature data. This method is crucial for understanding water loss through evaporation and transpiration, informing the model's input parameters.

2.2.5. Model Data Input

Field-collected data, including soil type, root water uptake distribution, and initial water conditions, feed into the model. Soil moisture was obtained from TMS sensors installed in various locations as per the land use which was eucalyptus, indigenous forest and grassland plantations. Precipitation data from local weather stations serve as a primary input for simulations, while the model structure is tailored to reflect water dynamics rather than crop growth.

2.2.6. Model Calibration and Validation

Calibration of the HYDRUS 1D model is essential for accurate simulations of soil water dynamics in the Middle Yala Catchment. Input parameters are adjusted to match observed field data, ensuring the model reflects actual soil moisture behaviour across different land uses. Key hydraulic parameters are modified within realistic ranges to minimize discrepancies between simulated and observed values. Model validity check was performed by comparing measured data and HYDRUS 1D simulation outputs. Measured and simulated data from the sampling regions of the Yala Catchment.

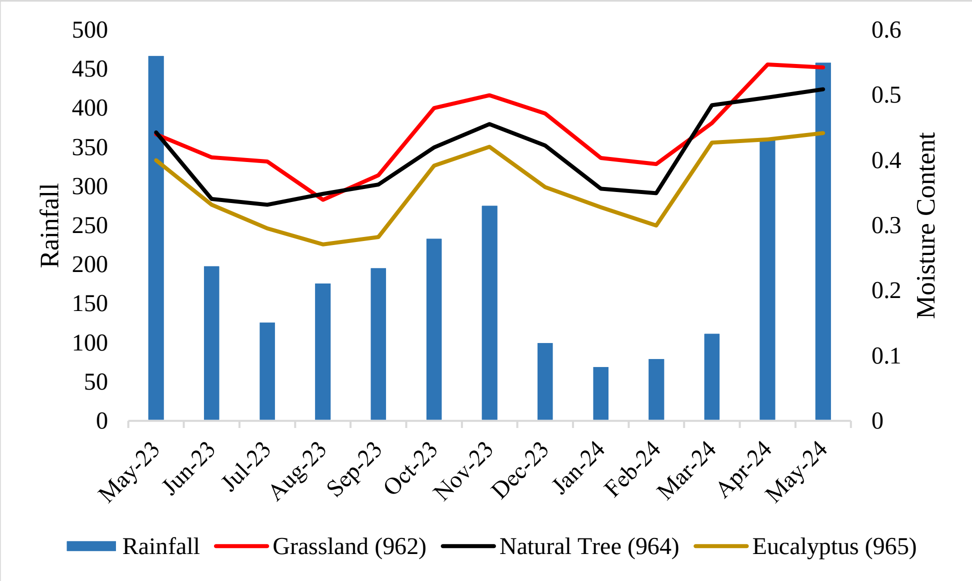

Fig. 2: Correlation between Rainfall and VMC

2.2.7. *Model Evaluation*

The model's accuracy is assessed using statistical techniques such as the coefficient of determination (R^2), modeling efficiency (EF), and normalized root mean square error (NRMSE). These metrics help quantify the degree of agreement between the simulated and observed soil moisture values, ensuring the model's reliability in capturing real-world dynamics.

3. RESULTS

3.1. Soil Moisture Dynamics

The volumetric soil moisture content (VMC) which defines the fraction of the soil's volume that is occupied by water measurements from 2023 to 2024 reveals dynamic patterns influenced by seasonal rainfall and local land use practices (Fig. 2). Each monitoring station—Kaimosi (grassland), Shamakhokho (natural trees), and Pendera (eucalyptus)—exhibits distinct soil profiles and vegetation types, which lead to varied moisture distribution and recharge rates. The findings are further supported by simulation models that explore the effects of land use on water flow within the vadose zone, providing a clearer understanding of the intricate interactions between soil, vegetation, and climate.

In the Kaimosi region, characterized by natural grassland and stratified loamy silty gravel over cohesive red gravel, significant variability in both rainfall and soil moisture was observed. In May 2023, the area recorded the highest rainfall of 468.1 mm, resulting in an VMC of 0.439 cm^3/cm^3. Despite subsequent rainfall drops to 199.2 mm in June and 127.1 mm in July, the VMC values remained relatively stable at 0.404 cm^3/cm^3 and 0.398 cm^3/cm^3, respectively, indicating that the loamy silty gravel allowed for good initial infiltration while retaining moisture within the upper soil layers. VMC peaked at 0.547 cm^3/cm^3 in April 2024, reflecting significant soil moisture recharge following a surge in rainfall (360.1 mm).

The Shamakhokho site, characterized by Indigenous 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 VMC of 0.443 cm^3/cm^3. However, the VMC decreased significantly to 0.341 cm^3/cm^3 in June, likely due to evapotranspiration from the tree cover. Throughout the dry months of July and August, the VMC remained low at 0.332 cm^3/cm^3 and 0.348 cm^3/cm^3, respectively, suggesting slower infiltration. By May 2024, the VMC increased to 0.509 cm^3/cm^3, reflecting sustained moisture accumulation during the wetter months.

In the Pendera area, dominated by eucalyptus plantations and characterized by clay-heavy soil, distinct moisture dynamics emerged due to the high-water demand for eucalyptus trees. Initially, in May 2023, rainfall of 468.1 mm resulted in a VMC of 0.4 cm^3/cm^3, but it decreased to 0.332 cm^3/cm^3 in June, suggesting substantial moisture absorption by the trees. As rainfall decreased further to 127.1 mm and 177.2 mm in July and August, respectively, the VMC dropped to 0.295 cm^3/cm^3 and 0.27 cm^3/cm^3. However, following significant rainfall in March (112.9 mm), April (360.1 mm), and May (459.5 mm), the VMC values gradually increased to 0.441 cm^3/cm^3, indicating a balance between moisture retention in the clay soil and the water-absorbing eucalyptus trees.

Overall, the findings illustrate a clear relationship between rainfall and soil moisture content while emphasizing the influence of soil properties and vegetation on moisture dynamics (Metzger et al., 2017). This research provides crucial insights into groundwater resource management and the broader implications of land use in the region, highlighting the importance of considering local conditions when assessing water dynamics in the vadose zone.

Table 1: Actual evapotranspiration for Grassland site

Date	Temp	i(heat index)	PET (Not adjusted for latitude	b (latitude correction)	PET (mm/mth)	Monthly Rainfall (mm)	Rainfall-PET	ACPWL	|ACPWL|	SM Retained	ΔSM	AET
May-23	35.040	19.065	570.866	1.080	616.536	468.100	-148.435	-148.435	148.435	38.123	86.877	181.580
Jun-23	33.785	18.041	453.916	1.060	481.151	199.200	-281.951	-430.387	430.387	3.996	-34.128	111.136
Jul-23	29.294	14.537	185.200	1.080	200.015	127.100	-72.915	-503.302	503.302	2.230	-1.766	61.382
Aug-23	27.010	12.856	111.183	1.070	118.966	177.200	58.234	0.000	0.000	125.000	122.770	25.928
Sep-23	26.821	12.719	106.376	1.020	108.504	196.500	87.996	0.000	0.000	125.000	0.000	93.593
Oct-23	28.859	14.211	168.561	1.020	171.932	234.200	62.268	0.000	0.000	125.000	0.000	111.553
Nov-23	28.698	14.091	162.739	0.980	159.484	276.300	116.816	0.000	0.000	125.000	0.000	131.607
Dec-23	29.212	14.475	181.939	0.990	180.120	100.700	-79.420	-79.420	79.420	66.218	-58.782	75.964
Jan-24	30.153	15.187	222.084	1.000	222.084	70.200	-151.884	-231.304	231.304	19.646	-46.572	55.619
Feb-24	28.502	13.946	155.886	0.910	141.856	80.500	-61.356	-292.660	292.660	12.026	-7.621	41.974
Mar-24	30.538	15.482	240.523	1.030	247.738	112.900	-134.838	-427.499	427.499	4.089	-7.936	57.556
Apr-24	31.023	15.855	265.541	1.030	273.507	360.100	86.593	0.000	0.000	125.000	120.911	113.931
May-24	33.673	17.950	444.540	1.080	480.104	459.500	-20.604	0.000	0.000	125.000	0.000	218.862
	I	**198.4141**				**2862.5**					**Annual**	**1280.6840**

3.2. Actual Evapotranspiration

The study reveals that different vegetation types significantly influence water dynamics, particularly in terms of actual evapotranspiration (AET), soil moisture retention, and water balance, which have important implications for water management and ecological sustainability.

Grassland exhibited an annual AET of 1,280.684 mm, encountering substantial water deficits during dry months (Table 1). The soil moisture retention was generally low, peaking at only 125 mm, indicating significant challenges in retaining moisture. This limitation increases the vulnerability of grassland areas to drought, making them less suitable for regions with irregular rainfall patterns.

Table 2: Actual evapotranspiration for indigenous Tree site

Date	Temp	i(heat index)	PET (Not adjusted for latitude	b (latitude correction)	PET (mm/mth)	Rainfall (mm)	Rainfall-PET	ACPWL	|ACPWL|	SM Retained	ΔSM	AET
May-23	35.040	19.065	570.054	1.080	615.658	468.100	-147.558	-147.558	147.558	138.550	111.450	127.520
Jun-23	33.785	18.041	453.514	1.060	480.725	199.200	-281.525	-429.082	429.082	44.931	-93.619	78.048
Jul-23	29.294	14.537	185.425	1.080	200.259	127.100	-73.159	-502.241	502.241	33.532	-11.399	43.108
Aug-23	27.010	12.856	111.452	1.070	119.253	177.200	57.947	0.000	0.000	250.000	216.468	18.208
Sep-23	26.821	12.719	106.645	1.020	108.777	196.500	87.723	0.000	0.000	250.000	0.000	65.729
Oct-23	28.859	14.211	168.804	1.020	172.180	234.200	62.020	0.000	0.000	250.000	0.000	78.341
Nov-23	28.698	14.091	162.986	0.980	159.727	276.300	116.573	0.000	0.000	250.000	0.000	92.425
Dec-23	29.212	14.475	182.168	0.990	180.347	100.700	-79.647	-79.647	79.647	181.794	-68.206	53.348
Jan-24	30.153	15.187	222.260	1.000	222.260	70.200	-152.060	-231.706	231.706	98.952	-82.842	39.060
Feb-24	28.502	13.946	156.139	0.910	142.086	80.500	-61.586	-293.293	293.293	77.346	-21.606	29.478
Mar-24	30.538	15.482	240.668	1.030	247.888	112.900	-134.988	-428.281	428.281	45.075	-32.271	40.420
Apr-24	31.023	15.855	265.640	1.030	273.609	360.100	86.491	0.000	0.000	250.000	204.925	80.011
May-24	33.400	17.730	422.033	1.080	455.796	459.500	3.704	0.000	0.000	250.000	0.000	153.702
	I	**198.194**				**2862.500**					**Annual**	**899.398**

In contrast, Natural Trees demonstrated a lower annual AET of 899.398 mm, reflecting more efficient water use compared to grassland (Table 2). This vegetation type maintained a more balanced water cycle, with positive water surpluses during wetter months. Additionally, Natural Trees consistently retained up to 250 mm of soil moisture, indicating a strong capacity for water conservation. This efficiency positions Natural Trees as well-suited for sustainable water management, offering resilience during dry spells and improved overall water efficiency.

Eucalyptus, on the other hand, exhibited the highest annual AET of 1,626.56 mm, signifying its greater water demand (Table 3). Although the potential evapo-transpiration (PET) values were similar to those of Natural Trees, Eucalyptus consumed significantly more water overall, leading to higher evapo-transpiration rates. Despite retaining more soil moisture than both Grassland and Natural Trees, with levels reaching up to 350 mm in wetter months, Eucalyptus faced considerable water deficits during dry periods, resulting in rapid depletion of soil moisture. While this species thrives in water-rich environments, its high-water usage poses challenges in drier regions, risking significant depletion of water resources.

In summary, Natural Trees emerged as the most water-efficient vegetation type, maintaining a balanced relationship between evapo-transpiration and soil moisture retention. Grassland displayed poor water retention and higher vulnerability to drought, while

Eucalyptus, despite its capacity to retain moisture, can lead to rapid soil moisture depletion in water-scarce environments. These findings emphasize the need for strategic vegetation management to promote ecological sustainability and effective use of water resources.

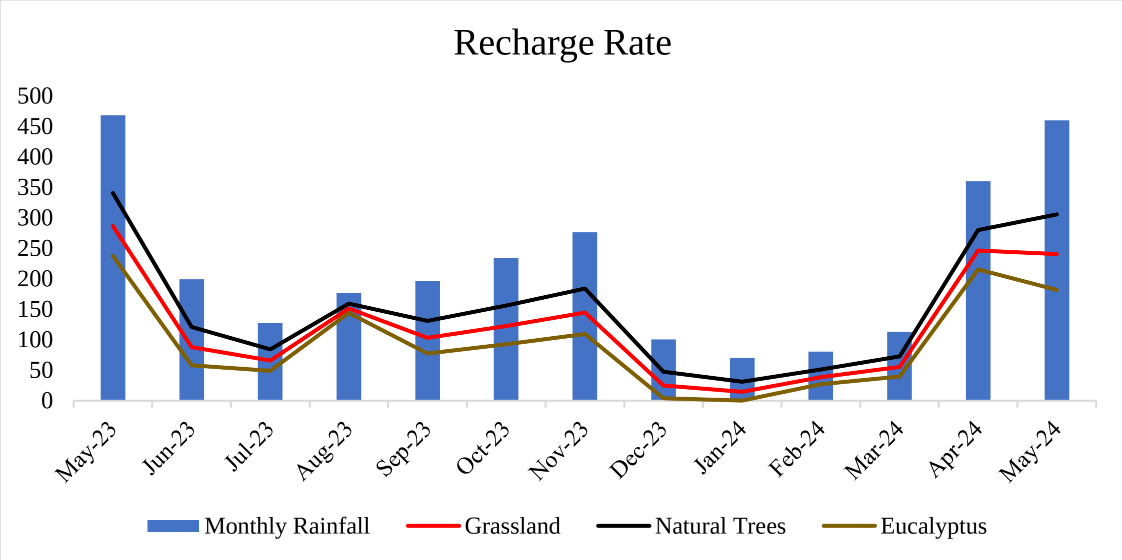

Fig. 3: Groundwater recharge rate

4. DISCUSSION

4.1. Recharge Rate

Rainfall varied significantly throughout the year, peaking at 468.1 mm in May 2023 and reaching a low of 70.2 mm in January 2024, directly impacting groundwater recharge across the different land covers (Fig. 3). For grassland areas, recharge rates generally followed the rainfall pattern but exhibited notable fluctuations. The peak recharge rate of 286.52 mm occurred in May 2023 during high rainfall, while it dropped sharply to 14.58 mm in January 2024 when rainfall was minimal. Grasslands have moderate recharge capacities, benefiting from substantial groundwater infiltration during wet months but experiencing pronounced declines in drier periods due to their relatively shallow root systems.

Table 3: Actual evapotranspiration for Eucalyptus site

Date	Temp	i(heat index)	PET (Not adjusted for latitude	b (latitude correction)	PET (mm/mnth)	Monthly Rainfall (mm)	Rainfall-PET	ACPWL	|ACPWL|	SM Retained	ΔSM	AET
May-23	35.040	19.065	570.054	1.080	615.658	468.100	-147.558	-147.558	147.558	229.600	120.400	230.620
Jun-23	33.785	18.041	453.514	1.060	480.725	199.200	-281.525	-429.082	429.082	102.718	-126.883	141.150
Jul-23	29.294	14.537	185.425	1.080	200.259	127.100	-73.159	-502.241	502.241	83.342	-19.375	77.960
Aug-23	27.010	12.856	111.452	1.070	119.253	177.200	57.947	0.000	0.000	350.000	266.658	32.930
Sep-23	26.821	12.719	106.645	1.020	108.777	196.500	87.723	0.000	0.000	350.000	0.000	118.870
Oct-23	28.859	14.211	168.804	1.020	172.180	234.200	62.020	0.000	0.000	350.000	0.000	141.680
Nov-23	28.698	14.091	162.986	0.980	159.727	276.300	116.573	0.000	0.000	350.000	0.000	167.150
Dec-23	29.212	14.475	182.168	0.990	180.347	100.700	-79.647	-79.647	79.647	278.766	-71.235	96.480
Jan-24	30.153	15.187	222.260	1.000	222.260	70.200	-152.060	-231.706	231.706	180.533	-98.232	70.640
Feb-24	28.502	13.946	156.139	0.910	142.086	80.500	-61.586	-293.293	293.293	151.404	-29.129	53.310
Mar-24	30.538	15.482	240.668	1.030	247.888	112.900	-134.988	-428.281	428.281	102.953	-48.451	73.100
Apr-24	31.023	15.855	265.640	1.030	273.609	360.100	86.491	0.000	0.000	350.000	247.047	144.700
May-24	33.400	17.730	422.033	1.080	455.796	459.500	3.704	0.000	0.000	350.000	0.000	277.970
	I	**198.194**				**2862.500**					**Annual**	**1626.560**

In contrast, natural trees consistently demonstrated higher groundwater recharge rates compared to grassland and eucalyptus. The maximum recharge of 340.58 mm in May 2023 underscores their superior ability to retain and recharge water, attributed to their deeper root systems and better water retention capabilities. Even during low rainfall months, such as January 2024, natural trees maintained a recharge rate that exceeded that of grassland, indicating their more stable contribution to groundwater resources due to factors such as evapotranspiration that affect the grassland (Adane et al., 2018).

Eucalyptus-dominated areas, however, showed the lowest recharge rates among the three land uses. Although rainfall in May 2023 resulted in a recharge of 237.48 mm, this was still lower than the figures for grassland (Table 1) and natural trees (Table 4). The recharge rate sharply declined during drier months, dropping to just 0.2 mm in January 2024, highlighting the high-water consumption of eucalyptus trees, which limits the availability of water for groundwater recharge. Overall, the data suggests that natural trees are the most effective land cover for groundwater recharge, while grasslands show moderate capacities and eucalyptus areas tend to deplete groundwater resources due to high consumption.

The natural tree site features a soil profile comprising brownish-red loamy silty clay and dark brown fine-grained silty clay, exhibiting considerable variability in soil moisture over time. This variability, influenced by seasonal rainfall, reveals notable moisture peaks during wet periods and declines in drier spells. This observation aligns with the literature indicating that climate and seasonal variability significantly impact groundwater recharge rates. According to Smerdon (2017) accurately assessing these rates is essential for groundwater sustainability, a finding echoed by Reinecke et al. (2021) who highlight how factors like soil type and rainfall contribute to recharge variability, consistent with the data from the natural tree site.

Table 4: Comparison between Rainfall and Volumetric moisture content in varying land

		MONTHLY VOLUMETRIC MOISTURE CONTENT		
Date	AVERAGE MONTHLY RAINFALL	GRASSLAND	EUCALYPTUS	NATURAL TREE COVER
May-23	468.1	0.29980701	0.342769093	0.4
Jun-23	199.2	0.37523626	0.240807434	0.382005003
Jul-23	127.1	0.29834923	0.231738908	0.345512871
Aug-23	177.2	0.23931882	0.248628847	0.320858497
Sep-23	196.5	0.33708305	0.262788791	0.332149195
Oct-23	234.2	0.40779518	0.319809244	0.441593204
Nov-23	276.3	0.49826347	0.385439535	0.470727244
Dec-23	100.7	0.37159612	0.322513191	0.408825622
Jan-24	70.2	0.30353554	0.256162177	0.377706124
Feb-24	80.5	0.29441451	0.249652441	0.3
Mar-24	112.9	0.35685306	0.384560941	0.47718205
Apr-24	360.1	0.44702957	0.39638463	0.432
May-24	459.5	0.44242828	0.408994402	0.491785437

Similarly, the grassland site, characterized by brownish-red loamy silty gravel transitioning to coarse-grained red gravel, shows moisture content fluctuations influenced by seasonal rainfall and land use changes. The increase in moisture during wet periods followed by declines in drier phases aligns with findings by Seiler and Gat (2007) who discuss how recharge, defined as net infiltration after losses like evapotranspiration, can vary significantly across different soil types and climatic conditions. The data from sensors installed in grassland at Kaimosi supports this notion, illustrating the direct impact of climatic factors on moisture content and recharge rates.

In contrast, the eucalyptus plantation site features a clay-heavy soil profile, exhibiting significant fluctuations in soil moisture content. This variability reflects challenges in estimating groundwater recharge, as discussed by Hartmann et al. (2017) and Scanlon et al. (2006). Both studies emphasize the importance of accounting for subsurface variability and climatic influences in recharge estimates. The data from the eucalyptus site, with its pronounced peaks and troughs in moisture content, underscores the necessity for accurate modeling that considers both climatic and subsurface factors to better understand groundwater recharge processes.

Overall, the findings from all study areas reflect established knowledge on groundwater recharge. The variability in soil moisture content correlating with seasonal rainfall patterns supports existing literature. However, the significant fluctuations observed at each site also highlight the challenges in predicting and managing groundwater recharge, especially amid changing land use and climate conditions, as noted by Earman & Dettinger (2011 and Reinecke et al. (2021). The complexity of accurately estimating recharge rates is reinforced by the variability in soil properties, climatic conditions, and land use changes, underscoring the need for comprehensive hydrologic modeling and effective groundwater management strategies.

4.2. Soil Water Distribution in the Vadose Zone for Various Land Uses

The natural grassland site, with soil layers transitioning from brownish-red loamy silty gravel to coarse-grained red gravel, exhibits significant moisture variability ranging from 0.322 to 0.605. This variation reflects the influence of soil texture on moisture dynamics, as discussed by Mittelbach & Seneviratne (2012). The coarse-grained lower layer facilitates faster drainage, while the upper layer retains more moisture. These observations are consistent with Arora et al. (2019), who describe how soil texture and structure impact water infiltration and distribution. The fluctuations in moisture content, driven by seasonal rainfall and soil properties, highlight the complexity of soil water distribution and its implications for groundwater recharge.

The natural tree vegetation site, featuring a soil profile of brownish-red loamy silty clay from 0 to 0.5 meters and dark brown fine-grained silty clay from 0.5 to 1.0 meters, demonstrates significant moisture variations ranging from 0.270 to 0.548 (Table 4). These fluctuations reflect the dynamic nature of soil water distribution in the vadose zone and align with Arora et al. (2019), who emphasize the influence of soil texture and structure on water retention and movement. The finer soil texture at this site contributes to varied infiltration and retention patterns, consistent with findings by (Peng et al. 2019), which highlight the effects of soil texture on water holding capacity and permeability.

The eucalyptus plantation site, characterized by clay-heavy soil, shows moisture content variations from 0.202 to 0.513. The significant fluctuations in moisture content reflect the influence of soil characteristics and vegetation on soil water dynamics. The impact of high clay content on moisture retention aligns with the work of (Peng et al. 2019), emphasizing the role of soil texture in determining water holding capacity and permeability.

Overall, the data from grassland, natural tree vegetation, and eucalyptus vegetation sites demonstrate the significant influence of soil properties and land use on soil water distribution in the vadose zone. The variability in moisture content observed across these sites supports literature emphasizing the importance of soil texture, structure, and vegetation in determining moisture dynamics. The findings align with Arora et al. (2019), who highlight the interplay between soil characteristics and environmental factors in shaping soil water distribution. Additionally, the application of measurement and modeling techniques, as discussed by Simunek et al. (2005), offers valuable insights into how land use and climatic conditions affect soil water dynamics and groundwater recharge.

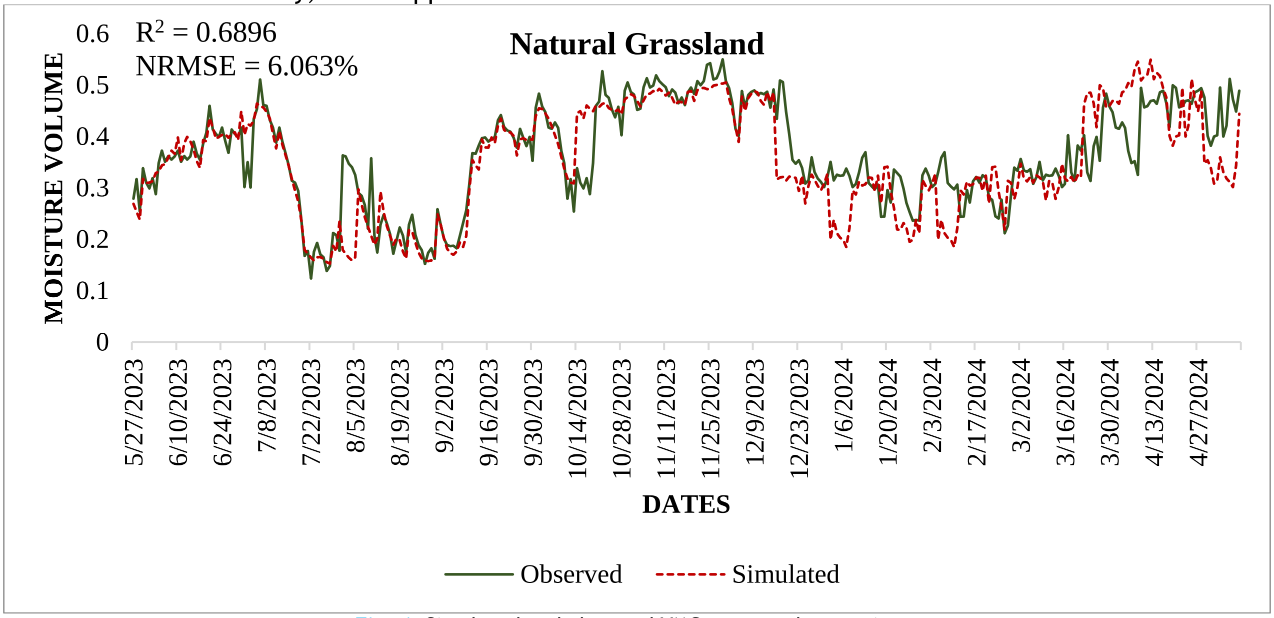

Fig. 4: Simulated and observed VMC at natural trees site

4.3. Simulation of the effects of various land use on the water flow in the vadose zone.

For all land use types, the model validation was based on the guidelines of $R^2 \leq 0.70$ 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. 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 Fig. 4, 5 and 6.

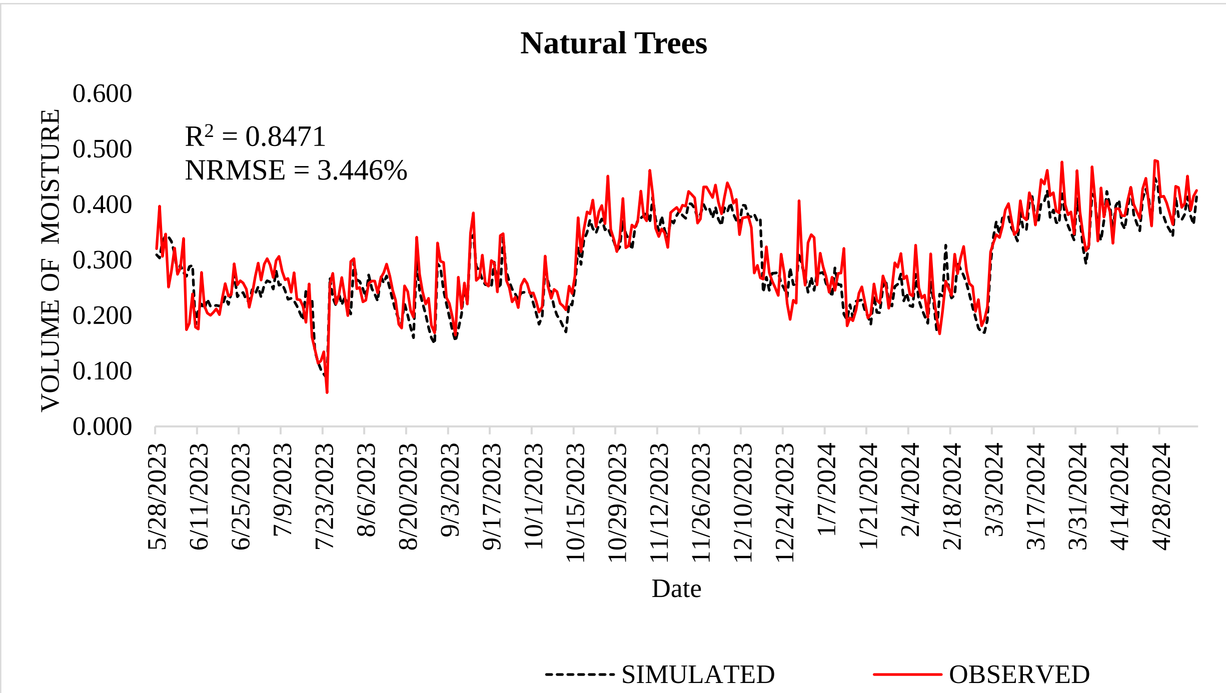

Fig. 5: Simulated and observed VMC at natural trees site

The model's performance in predicting soil moisture across different sites yielded varying degrees of accuracy. For the grassland site, the model demonstrated a strong correlation with observed soil moisture, achieving an R^2 value of 0.6896, which indicates excellent agreement between predicted and actual values. R^2 values close to 1 represent a perfect model. The NRMSE was low at 6.063% (<10%), suggesting minimal deviations and affirming the model's reliability for this location.

At the natural trees site, the model still showed a strong correlation, albeit slightly lower, with an R^2 value of 0.8471. The NRMSE was even better at 3.446%, indicating moderate discrepancies between predictions and actual observations, thus reflecting a robust performance in capturing soil moisture dynamics. For the eucalyptus plantation site, the model performance was good with a R^2 value of 0.6607 and NRMSE of 4.15%.

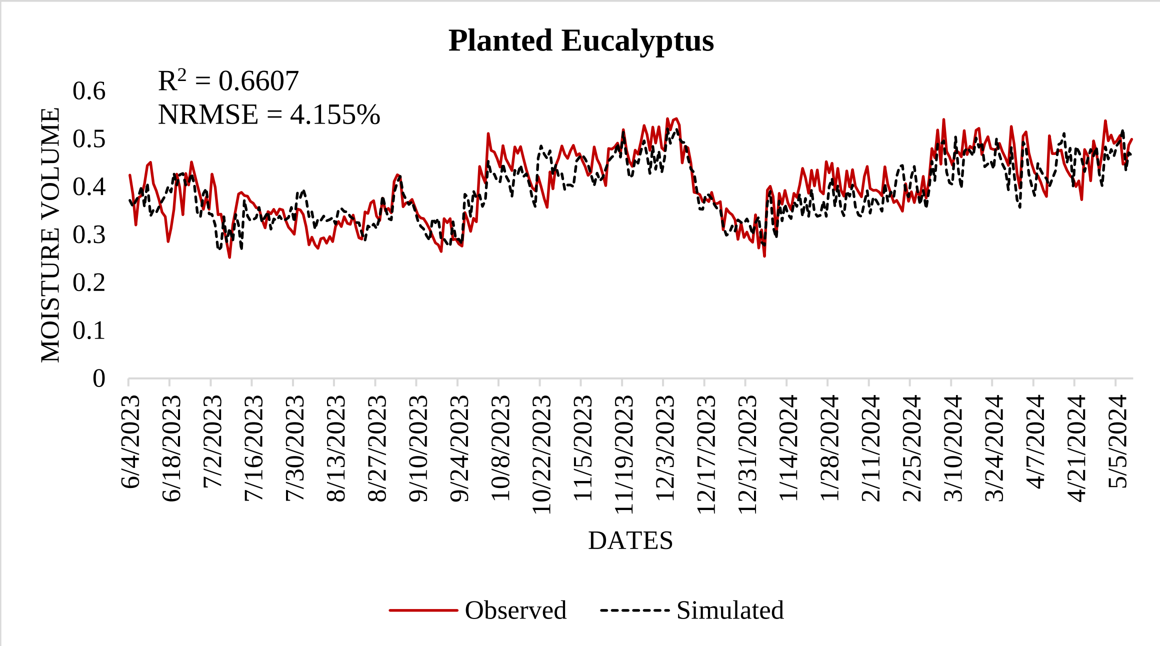

Fig. 6: Simulated and observed VMC at Eucalyptus plantation site

5. CONCLUSION

The study investigates the effects of land use on groundwater dynamics in the Middle Yala Catchment, focusing on soil moisture distribution in the vadose zone and groundwater recharge rates. Data was collected from three distinct stations—Kaimosi (grassland), Shamakhokho (natural or indigenous trees), and Pendera (eucalyptus)—and analyzed using HYDRUS-1D simulations, leading to several key conclusions. Firstly, different land uses showed distinct patterns of soil moisture retention. Grassland areas demonstrated higher and more stable moisture retention, while eucalyptus-dominated sites exhibited greater fluctuations in soil moisture, particularly during wet and dry periods. The study highlighted soil texture, especially clay content, as a significant factor in moisture retention, with Pendera's clay-heavy soils retaining more moisture but displaying unpredictable behaviour. Secondly, all stations exhibited a correlation between seasonal rainfall and soil moisture, although the strength of this relationship varied. Kaimosi showed consistent moisture levels despite rainfall variability, whereas Shamakhokho had discrepancies likely due to higher evapotranspiration and root water uptake by trees. Eucalyptus vegetation at Pendera led to notable moisture depletion, especially during dry periods. Thirdly, variability in soil moisture and infiltration rates impacted groundwater recharge rates. The grassland site demonstrated effective recharge due to higher soil porosity and moisture retention in the vadose zone, while the eucalyptus site showed rapid soil moisture depletion, indicating potential negative effects on groundwater recharge.

The HYDRUS-1D model performed well overall, with the highest accuracy observed at the grassland site (R^2 = 0.8471), where the simpler dynamics of soil moisture allowed for better predictions. For the eucalyptus site, the model's performance was lower (R^2 = 0.6607), possibly due to the complex interactions between eucalyptus trees' high-water consumption and soil moisture fluctuations, which the model struggled to capture accurately. The study's findings emphasize the critical influence of land use on groundwater recharge in the Middle Yala Catchment, highlighting the need to consider vegetation type, soil properties, and rainfall patterns in groundwater management strategies. The selection of vegetation types, such as eucalyptus, can significantly impact soil water retention and recharge potential, affecting long-term groundwater sustainability. The findings from this study contribute to practical application in groundwater management and land use planning by providing information to assist policymakers in regulating land use practices to improve groundwater recharge. Also, to farmers by encouraging them to plant native trees that have low water demand thus practicing long-term soil and water conservation. Furthermore, the insights in the study provide potential further research to examine the potential effects of climate change on soil moisture and groundwater water availability. In conclusion, this study highlights the need for a nuanced understanding of how land use practices, soil characteristics, and seasonal rainfall patterns interact to shape groundwater dynamics in the Middle Yala Catchment. For the long-term health of the area's groundwater supplies, the knowledge gathered from this study will help develop more efficient groundwater management plans that balance land use, safeguard water supplies, and encourage sustainable land practices.

The study suggests that to enhance sustainable groundwater management and land use planning in the Yala Catchment, policymakers prioritize grasslands and native tree cover over eucalyptus plantations. Grasslands and native trees are better suited for sustainable water management because of their higher moisture retention and superior groundwater recharge rates. For long-term groundwater sustainability creating policies that promote sustainable land-use practices and offer financial incentives to farmers and landowners who choose water-efficient vegetation types is recommended Also, predicting soil moisture and recharge under various land-use scenarios can be made more accurate by bolstering groundwater monitoring and modelling with technologies like HYDRUS-1D. Local communities will be empowered to embrace sustainable practices if they are involved in training and awareness initiatives about how land use affects groundwater dynamics.

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