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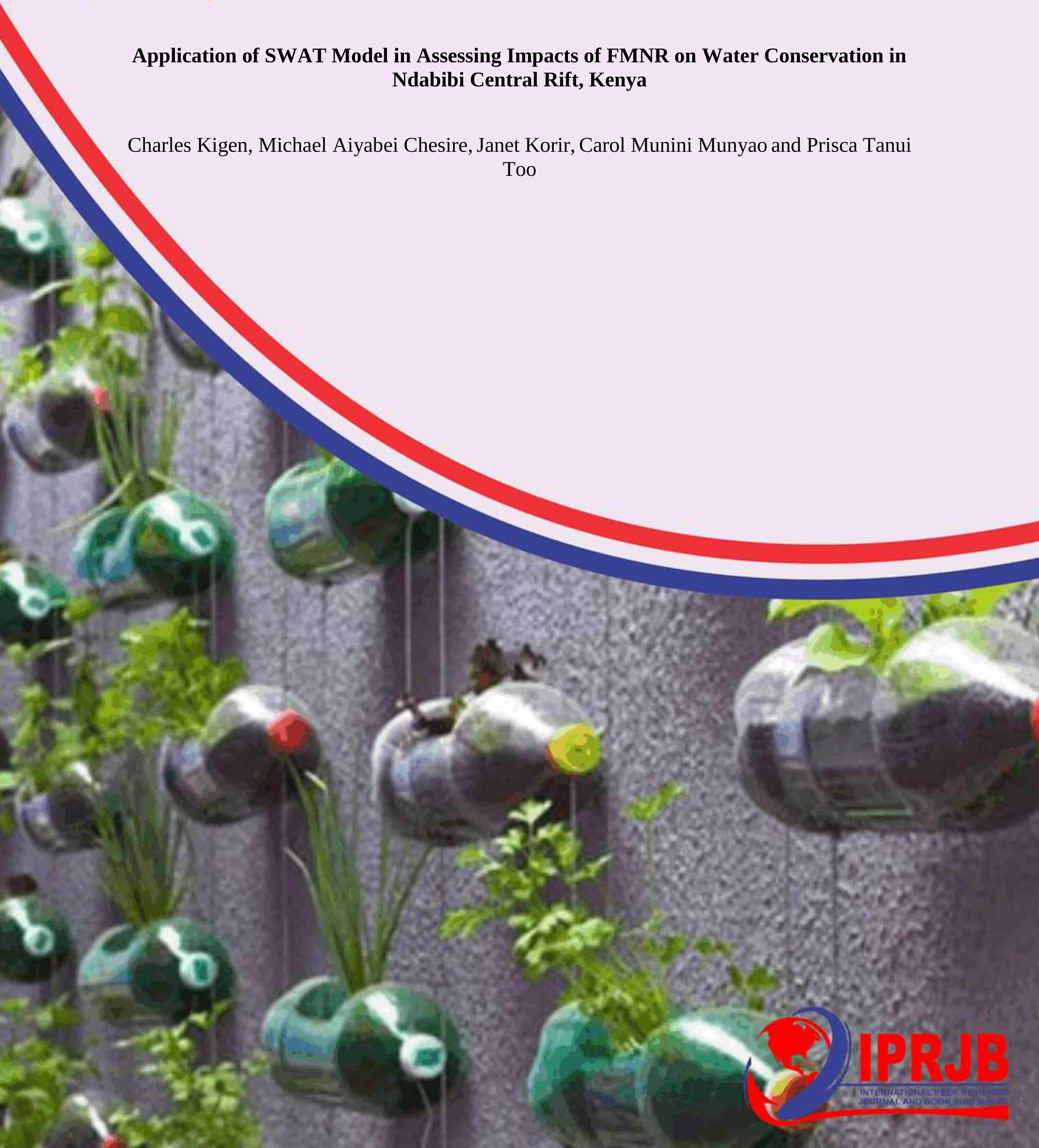

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Application of SWAT Model in Assessing Impacts of FMNR on Water Conservation in Ndabibi Central Rift, Kenya

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Abstract

Purpose: The Ndabibi watershed is predominantly agricultural that impacts its hydrological functions and water balance. This manifest through reduced watershed sponge effect, increased surface runoff during wet season and decreased surface runoff during the dry season, a situation that can be reversed by Farmer Managed Natural Regeneration (FMNR). FMNR is a conservation technique where trees/shrubs/ and other woody plants are allowed to grow naturally with minimal management by a farmer. Its application increases vegetation cover thereby reducing surface runoff. This study sought to establish the impact of FMNR on water conservation.

Methodology: The impact of this technique on surface runoff was quantified using SWAT (Soil and Water Assessment Tools) model. The watershed is ungauged and relied on regionalization with an assumed adoption of 20% FMNR in the watershed. The SWAT model under FMNR was calibrated with coefficient of variation (R^2) of 0.95 for 20% and Nash-Sutcliffe of 0.88 on monthly time scale.

Findings: The monthly streamflow analysis showed that there is a significant change in surface runoff ranging from -21.2% to 24.07% during the wet and dry seasons respectively.

Unique Contribution to Theory, Practice and Policy: The study concludes that there is significant benefit of FMNR in regulating water balance in a given watershed and recommends its widespread adoption.

Keywords: *FMNR, SWAT, Infiltration, Surface Runoff, Streamflow*

INTRODUCTION

A pristine landscape has its ecosystem processes and functions in a dynamic balance. Natural vegetation plays an important role in hydrological balance and also has multiple benefits in agriculture and economy through soil and water conservation and timber provision among others (Garrity et al., 2010). The need for agricultural land has led to significant landscape modifications and rapid loss of vegetative cover; reduced cover along with soil compaction and other contributing factors have reduced rainfall infiltration and increased soil movement, necessitating application of soil and water conservation measures. Soil and water conservation seeks to prevent soil erosion by deploying various strategies, including contour farming, terracing, and no-till farming, among others (FAO, 2015). The arid and semi-arid lands (ASALs) are fragile ecosystems making them more vulnerable to landscape degradation and soil erosion. In water-scarce landscapes, soil and water conservation is more challenging since biomass production is very slow. In such regions, the management of natural vegetation, including trees and shrubs is crucial for the restoration and maintenance of soil and water resources apart from other ecosystem services benefits. In balancing agriculture and natural vegetation, a technique known as Farmer Managed Natural Regeneration (FMNR) has been proven to be working by (Leaky and Tchoundjeu, 2012; Bayala et al., 2014; Nair, 2014; World Vison Australia 2018; and Chomba et al. 2020). The FMNR involves promoting the natural regeneration of trees, shrubs (Bayala et al., 2014). This technique has multiple benefits, including increased food production, improved soil fertility, carbon sequestration, and climate change mitigation (Garrity et al., 2010).

Farmer Managed Natural Regeneration is particularly applicable in dry areas classified as ASALs such as Ndabibi in Kenya, where it has been promoted by World Vision Kenya since 2018. A significant number of farmers in Ndabibi have adopted FMNR practices, with a combined land area of 164.72 acres under FMNR representing 12.64% of the total area by the end of the first phase of the Central Rift Farmer Managed Natural Regeneration Scale-Up (CRIFSUP) Project in 2021 (World Vision Kenya, 2021). Several studies have been conducted to assess its effectiveness in restoring degraded land and conserving soil and water resources. Leaky and Tchoundjeu (2012) described the benefits of FMNR as an approach to sustainable food security while Nair (2014) studied the benefits of FMNR as an adaptation measure to climate change.

The restoration of degraded land is a major challenge in the ASLAs where soil degradation, water scarcity, and climate change issues are prevalent (Moustapha, 2014). Land degradation has been documented to cause decline in soil fertility, loss of vegetation cover, and a reduction in the availability of water resources. In such regions, the restoration of natural vegetation is crucial for the conservation of soil (FAO, 2001) and water resources (Ilestd et al, 2016). FMNR is a low-cost and sustainable method for restoring degraded land and promoting the regeneration of natural vegetation, including trees and shrubs, and grasses.

FMNR involves selecting and protecting living tree stumps or roots, allowing new shoots to grow, which with regular pruning eventually develop into mature trees. The technique has been shown to have multiple direct and indirect benefits on livelihoods of farmers, including increased food production, improved soil fertility, carbon sequestration, and climate change mitigation (Garrity et al., 2010). FMNR is particularly effective in arid and semi-arid regions where natural vegetation regeneration is challenging due to limited rainfall, high temperatures, and soil degradation. Agroforestry models show that FMNR, through protective tree coverage, has a positive and stabilising effect on staple food production and on forage grass in drought years, making farmers more drought-tolerant and capable of a more rapid recovery once rains return (van Schoubroeck, 2018 and World Vision Australia, 2018).

In addition to the environmental benefits, FMNR has also been shown to have positive socio-economic impacts. A study conducted by the World Agroforestry Centre in Niger found that households practicing FMNR had a 69% increase in income compared to non-practicing households (Garrity et al., 2010). This income increase was largely attributed to the production of non-timber forest products such as fruits, nuts, and medicinal plants which is the same case in Baringo Kenya (World Vision Australia, 2018).

Given its multiple benefits, FMNR has been gaining popularity as a method for soil and water conservation in various parts of the world. In Kenya, FMNR is being promoted by World Vision Kenya (WVK) through projects like CRIFSUP (2018-2021). The CRIFSUP was designed to introduce farming households in the Central Rift Valley region to FMNR and other climate-smart practices such as conservation agriculture and agroforestry. One of the target areas, Ndabibi, had a number of farmers who adopted FMNR though at different levels.

Despite self-determining evidence and increasing uptake of FMNR by farmers as a method of soil and water conservation, little has been done to quantify its water conservation benefits through change in landscape hydrological characteristics. The Ndabibi watershed is one such area where FMNR was initiated in 2019 and provides an opportunity to analyse its benefits over a given period. This study therefore sought to analyze changes in Ndabibi watershed water movement with the introduction of FMNR. The study applied the Soil and Water Assessment Tool (SWAT) hydrological model to simulate impacts of FMNR on the watershed water movement. This research contributed to the understanding of the potential of FMNR in water conservation thereby aiding decision making on integrated watershed management objectives.

METHODOLOGY

Study Area

Ndabibi watershed is located in the Central Rift Valley region of Kenya, near the town of Naivasha within latitudes -0.8118 and -0.9118 and longitudes 36.1149 and 36.209 decimal degrees (Figure 1) with an area of 36.95 km^2. The climate is classified as a subtropical highland climate, which experiences a cool and temperate climate throughout the year due to its high altitude of 2436m, with mean monthly temperatures ranging from 10°C to 30°C depending on the season. The area receives an average annual rainfall of about 850-1100 mm per year, with peaks occurring during two rainy seasons: the long rains, which last from March to May, and the short rains, which last from October to December.

The climate is suitable for agriculture, with a variety of crops grown in the area, including maize, wheat, vegetables, flowers, and fruits. However, farmers in the region face challenges such as soil degradation and water scarcity, which negatively impacts agricultural production. To address these challenges, FMNR was introduced and promoted by WVK.

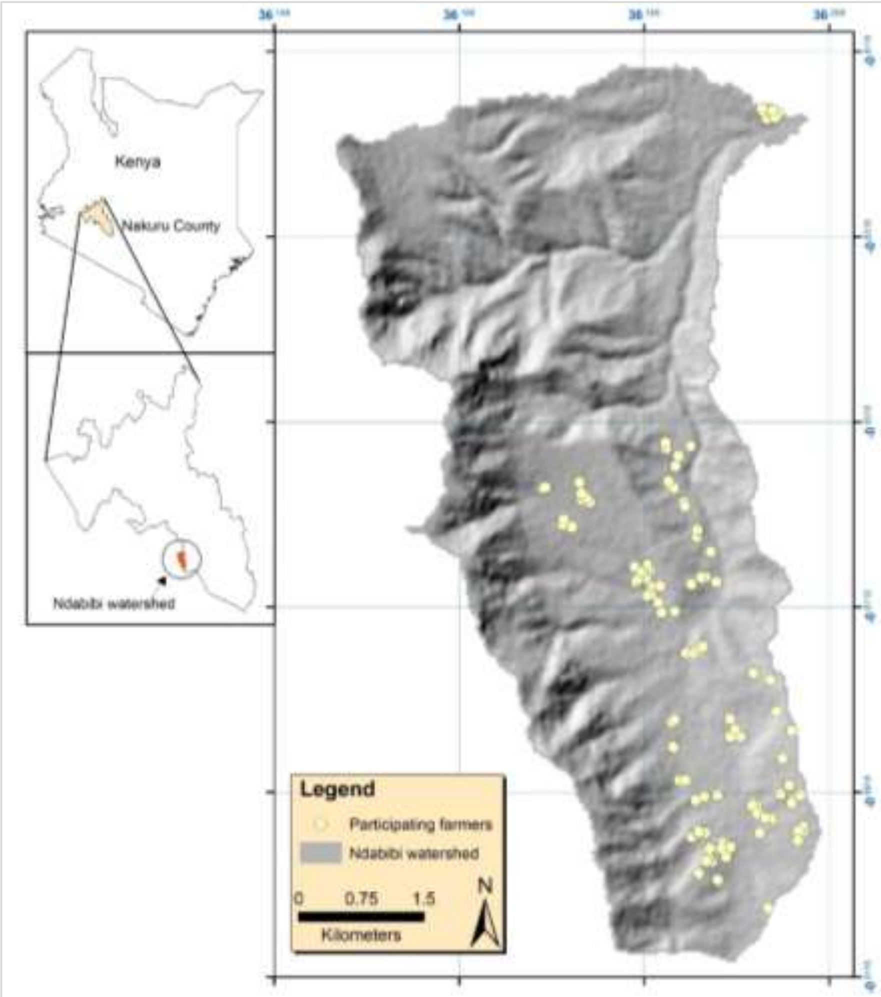

Figure 1: The Location of Ndabibi Watershed

SWAT Model and SWAT-CUP Description

The Soil and Water Assessment Tool (SWAT) is a widely used hydrological model in watershed analysis. It is a process based distributed model designed to assess the impacts of land management practices on water and soil in a watershed (Abbaspour et al., 2007). The model simulates processes on a daily time scale, including hydrology, soil erosion, crop development, and biogeochemical cycles on the land and in the stream network (Abbaspour, et al., 2004). The model processes are performed within a geographical unit called hydrologic response units (HRUs) (Neitsch et al., 2011). The HRUs are the smallest units with similar soil type, land use, and slopes in the SWAT model. The water budget equation served as the fundamental equation for the hydrologic cycle in the SWAT Model. The SWAT model is described by the water budget equation (1).

$$SW_t = SWo + \sum_1^t (R_{day} - Q_S - E_a - W_S - Q_{gw}) \quad \text{…………..} \text{ (Equation 1)}$$

Where SW_t represents the water content of soil in (mm), SWo represents the initial water content in soil (mm), *t* the time (day), R_{day} is the daily rainfall in (mm), *Qs* represents the surface runoff (mm), *Ea* is the evapotranspiration (mm), *Ws* represents the water stored in vadose (mm), and *Qg* The amount of water returning from the ground to the surface (mm) (Neitsch et al., 2011).

The assessment of SWAT model performance is done among other tools SWAT-CUP (Soil and Water Assessment Tool – Calibration Uncertainty Procedures) (Abbaspour et al., 2007). SWAT-CUP is a software for running automatic calibration, validation and uncertainty and sensitivity analysis in the SWAT model. The SWAT-CUP includes Sequential Uncertainty Fitting Version 2 (SUFI-2) which is a multi-site, semi-automated inverse modelling routine (Faramarzi, 2009). SUFI-2 improves the accuracy of SWAT model by iteratively adjusting the model parameters to minimize the difference between the observed and simulated data (Abbaspour et al., 2007). The model is run several times sequentially with different parameters combinations to find the best-fit parameter values. In SUFI-2, parameters uncertainty is expressed as 95% probability distributions and propagation is conducted using Latin hypercube sampling expressed as 95% prediction uncertainty (95PPU) (Abbaspour et al., 2007). The model strength of calibration or uncertainty analysis include r-factor which is the average thickness of the 95PPU band divided by the standard deviation of the measured data (Faramarzi, 2009). Calibration and prediction uncertainty is judged on the basis of the closeness of the p-factor to 100% and the r-factor to 1.

Data Collection, Processing and Analysis

The constructed SWAT model made use of LULC, elevation, soil and climate data (Figure 2). The LULC was processed from satellite imageries obtained from the United States Geological Survey's (USGS) Earth Explorer website, available at https://earthexplorer.usgs.gov. This platform provides a comprehensive collection of satellite imagery that can be used for various applications, including land-use studies, resource management, and environmental monitoring. Using the end of project evaluation report by World Vison (2021) of FMNR adoption level of 12.6%, a new LULC dataset incorporating a 20% FMNR adoption level was generated for 2022. The elevation data of 30 m resolution was sourced from the USGS Earth Explorer website and was used to generate the slope dataset. Soil data, which is another essential component of the SWAT simulation, was downloaded from the SWAT website, available at https://swat.tamu.edu/media/116406/af_soil.zip/. This dataset contains soil information for various African countries, including Kenya. The soils are classified into four hydrological groups of A (high infiltration), B (moderate infiltration), C (slow infiltration) and D (very slow infiltration). Based on this hydrological classification, the soils in the study area are in class D (very slow infiltration).

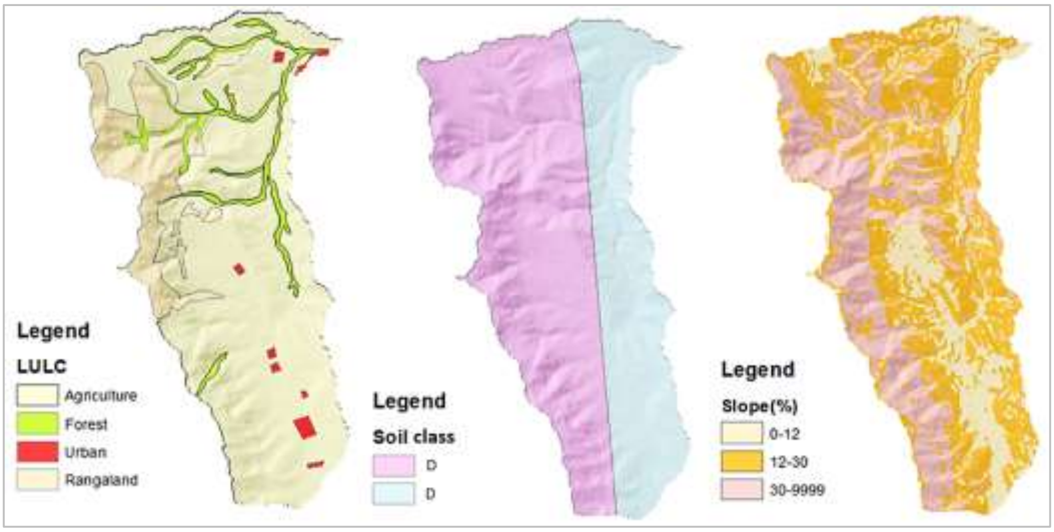

Figure 2: The Spatial Datasets Used in the Model

The climate data from 2003 to 2021 was obtained from the University of Guelph's Watershed Web Services (W3S) platform at https://www.uoguelph.ca/watershed/w3s/. This platform provides access to various weather data sets used to drive hydrological models like SWAT. All the climate datasets constituted precipitation, minimum and maximum temperature on daily basis. The combination of these data allowed for a comprehensive analysis of the potential impact of FMNR on streamflow and soil movement, which is critical in developing sustainable management strategies that promote environmental conservation and sustainable development.

SWAT Model Set Up

The Ndabib watershed SWAT model was built using elevation, LULC and soil spatial datasets. The model generated three sub-watersheds measuring 4.90 km^2, 7.98 km^2 and 24.07 km^2 (Figure 3). A total of 53 HRUs were generated depicting the watershed heterogeneities in soil, land use, and slope. The model was run from 1st Jan 2003 – 31st Dec 2021 with the first two years being a warm-up period.

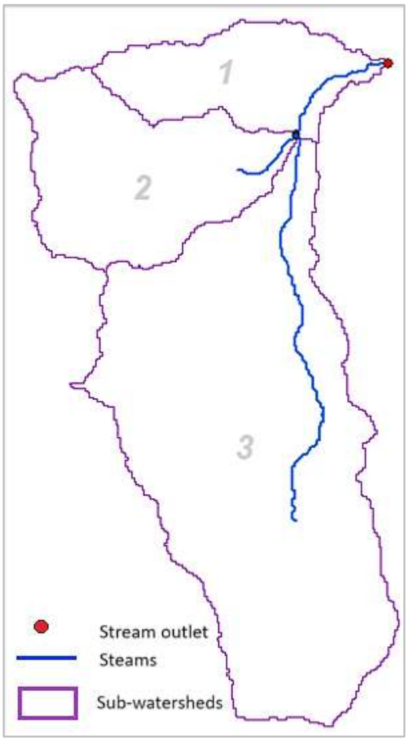

Figure 3: The Extracted Ndabibi Watershed and its Three Sub-Watersheds

Model Calibration, Validation and Evaluation

The Ndabibi watershed is ungauged meaning it does not have any river streamflow measurements. Therefore, the Ndabibi watershed calibration was done using the regionalization method. Regionalization is based on the concept that watersheds with similar characteristics show similar hydrological treatments and therefore the hydrological parameters can be transferred from the same watersheds. A number of studies using different methods of regionalization have been conducted by Santhi et al. (2001) (physical similarity method), Moriasi et at (2007) (regression methods) and Tolson and Shoemaker (2004) (spatial proximity method). This study regionalization used River Malewa watershed parameters from Abbassi et. al (2019) located within the larger Lake Naivasha watershed with their physical characteristics presented in Table 1.

Table 1: Properties of the Donor and Recipient Watersheds

Watershed	Annual rainfall (mm)	Area (km^2)	Mean Slope (%)	Elevation (m)	Soil hydrology class	LULC (Major)
Ndabibi (Recipient)	1046	36.95	68.65	2464	D	Agriculture
River Malewa (Donor)	1100	1600	49.21	2217	D	Agriculture

The calibrated parameters by Abbassi et al. (2019) were transferred into the initial model using the manual calibration helper. The model calibration, validation and uncertainty analysis were done in SUFI-2 in SWAT-CUP with 100 simulations. SUFI-2 uncertainties are represented in model output by r-factor and p-factor. The model attempts to bracket maximum data (P-factor

= 1) within a narrow band (R-factor = 0) while balancing between the two. To provide for the measure and significance of parameter sensitivity, t-test and p-values were used, respectively.

The SWAT model consisted of 23 parameters but sensitivity analysis narrowed down to the parameters that are most sensitive. Model evaluation was done using Nash-Sutcliffe efficiency (NSE) and coefficient of determination (R^2). The NSE measures the variation of measured data versus simulated data in comparison to a 1:1 best fit line. It varies from any negative value to 1, with any NSE values higher than or equal to 0 indicating that the simulated value predicted the component of consideration more accurately than the mean measured value, and an NSE value of 1 indicating ideal modelling. Moriasi et al. (2007) classified NSE into "Unsatisfactory" (below 0.5), "Satisfactory" (0.5 - 0.65"), "Good" (0.65 - 0.75) and "Very good" (0.75 - 1). The coefficient of determination (R^2) shows how well the model was able to predict events based on how much of the total variation it explained. The R^2 values vary from 0 to 1, with improved model performance as the value approaches 1.

RESULTS AND DISCUSSION

Calibration and Validation

The SWAT-CUP (SWAT-Calibration and Uncertainty Program) was used in SWAT model calibration and validation. The sensitivity of Ndabibi watershed parameters analysis is presented in Table 2 for current LULC and 20% FMNR LULC. In the current LULC, of the initial 12, only 7 parameters were sensitive and ranked from the most to the least sensitive. The most sensitive parameter was the CN2.mgt, and the least sensitive one was the GW_REVAP.gw.

Table 2: The Parameter Sensitivity of Streamflow Simulation

Parameter	Description	Fitted value	Range	Rank	t-Stat	P-value
Current LULC						
CN2.mgt	Initial Soil Conservation Service SCS runoff curve number for moisture condition II	-0.17	35 – 98	1	-9.2448	0.0000
SOL_AWC.sol	Available water capacity of first soil layer (mm/mm)	0.855	0 – 1	2	6.3901	0.0000
GW_DELAY.gw	Groundwater delay (days)	40.5	0 – 500	3	-3.8612	0.0002
SURLAG.bsn	Surface runoff lag time (days)	23.64075	0 – 24	4	-2.3253	0.0222
ALPHA_BF.gw	Baseflow alpha factor (days)	0.735	0 – 1	5	1.1670	0.2462
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm H2O)	442.5	0 – 1000	6	-0.2565	0.7982
GW_REVAP.gw	Groundwater "revap" coefficient	0.1219	0 – 1	7	-0.1118	0.9112
20% FMNR LULC						
GW_DELAY.gw	Groundwater delay (days)	32.1	0 – 500	1	-6.3495	0.0000
ALPHA_BF.gw	Baseflow alpha factor (days)	0.795	0 – 1	2	3.8635	0.0002
SOL_AWC.sol	Available water capacity of first soil layer (mm/mm)	0.445	0 – 1	3	3.5438	0.0006
GW_REVAP.gw	Groundwater "revap" coefficient	0.1307	0 – 500	4	0.6233	0.5347
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm H2O)	407.5	0 – 1000	5	-0.5407	0.5900
CN2.mgt	Initial Soil Conservation Service SCS runoff curve number for moisture condition II	0.09	35 – 98	6	0.2751	0.7838
SURLAG.bsn	Surface runoff lag time (days)	11.18675	0 - 24	7	0.2263	0.8214

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For the 20% FMNR LULC, GW_DELAY was the most sensitive with SURLAG being the least sensitive. The calibration period was 2003 – 2021 while validation was from 2012 – 2021. The results of calibration for daily simulation were R^2 of 0.79 and NSE of 0.61 and R^2 of 0.95 and NSE of 0.88 for the current and 20% FNMR LULC respectively (Figure 4). These values according to Moriasi et al. (2015) were satisfactory with very good outputs. Generally, the results showed that the output of the models were satisfactory. Further, the uncertainty analysis results showed more than 50 percent of the streamflow variations is explained by the model indication a good SWAT model performance (Moriasi et al., 2007) and Chen et. al, 2017).

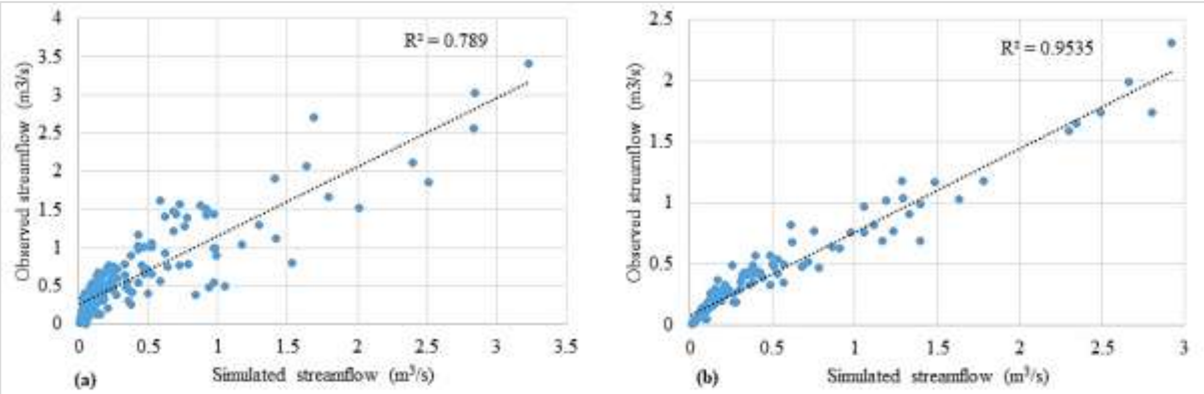

Figure 4: Observed and Simulated Streamflow for (a) LULC in 2021 and (b) LULC with 20% FMNR

Calibration hydrographs for both LULC scenarios in Ndabibi watershed (Figures 5, 6) show large differences between the simulated and observed river streamflow. The differences are more pronounced during peak periods with overestimation of baseflows for the current LULC. There is more agreement between the simulated and observed streamflow for 20% FMNR LULC scenario though the peaks are overestimated. The periods of rising and fall of the water are poorly taken into account, and the model overestimates the high values and flows. However, the general pattern of the calculated hydrograph is reproduced.

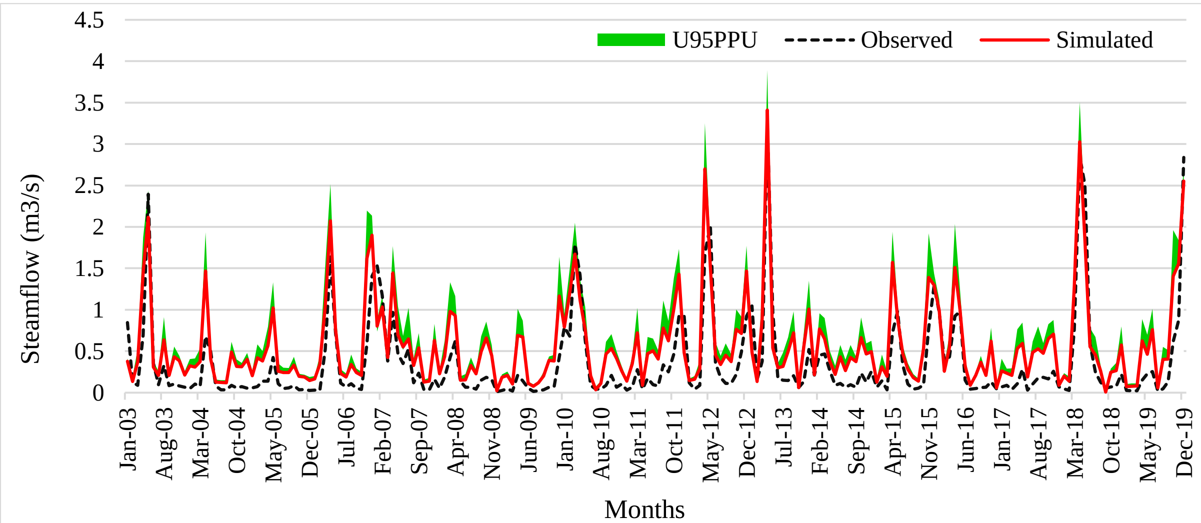

Figure 5: Monthly Streamflow Calibration for Current LULC

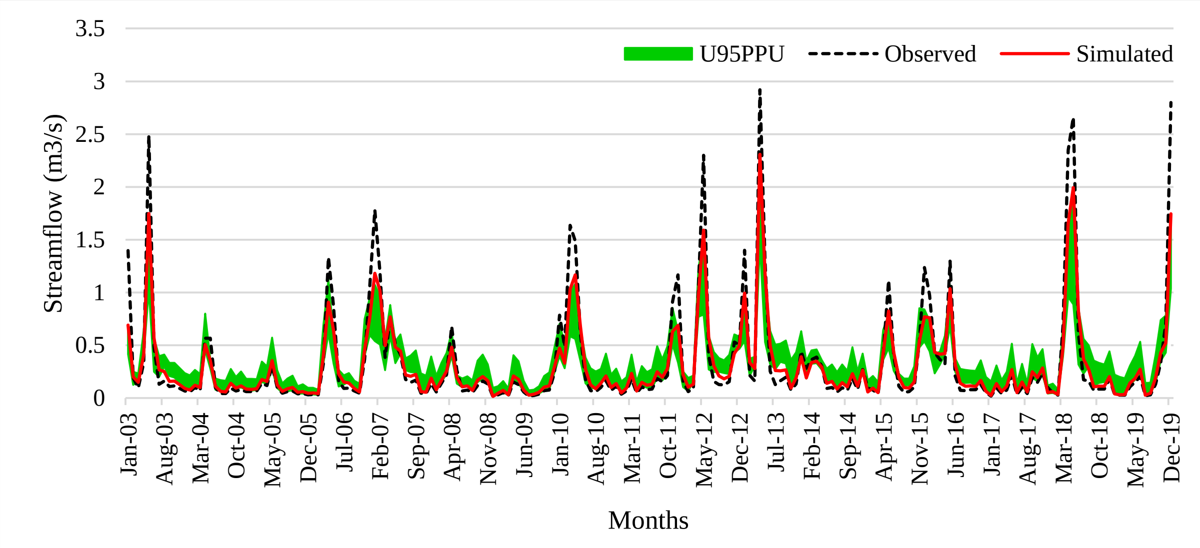

Figure 6: Monthly Streamflow Calibration For 20% FMNR LULC

Impact of FMNR on Streamflow

According to the Universal Soil Loss Equation, vegetation cover, soil erodibility (or type) and slope steepness are important factors affecting surface runoff (Moriasi et al. 2007). The results of the hydrological model show that the introduction of FMNR regulates the quantity of surface runoff in Ndabibi watershed. The monthly average river streamflow fluctuates with rainfall (Figure 7). The rainfall peaks in April and November and influences the streamflow in the same time. The same pattern is observed with low rainfall in both LULC scenarios.

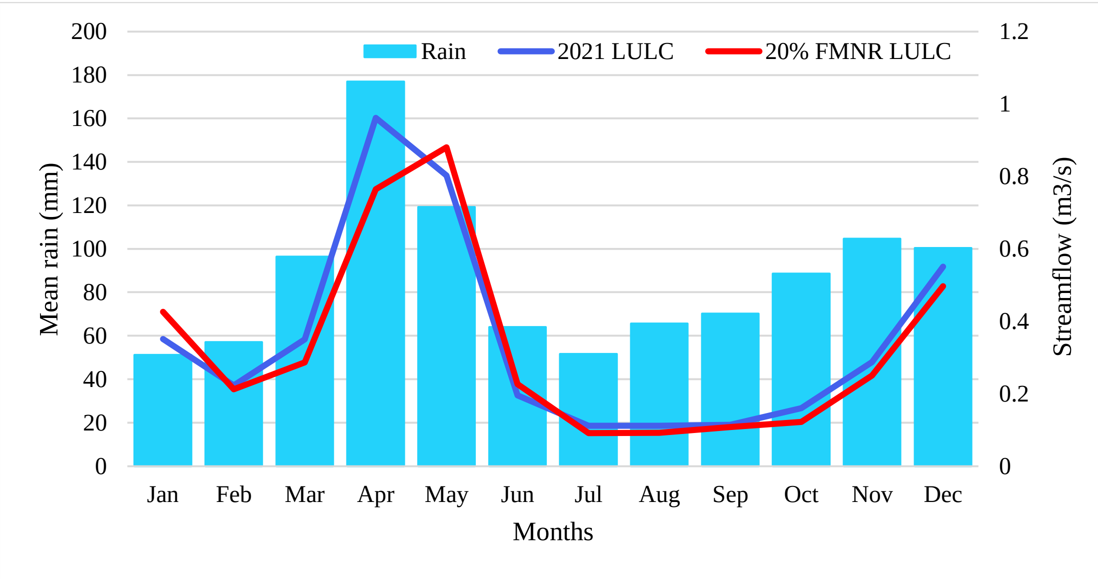

Figure 7: Mean Monthly Rainfall and Streamflow of Ndabibi Watershed

The quantities of streamflow are different in the two LULC scenarios. With introduction of 20% FMNR LULC, the river streamflow changed by 21.2 % and -24.07% in January and October respectively (Figure 8). The results suggest that the increased vegetative cover under FMNR significantly increases surface water retention time, thereby regulating streamflow over the year. The observed pattern of increased and reduced streamflow during the lower and higher rainfall months respectively indicates the hydrological impact of 20% FMNR adoption by the farmers.

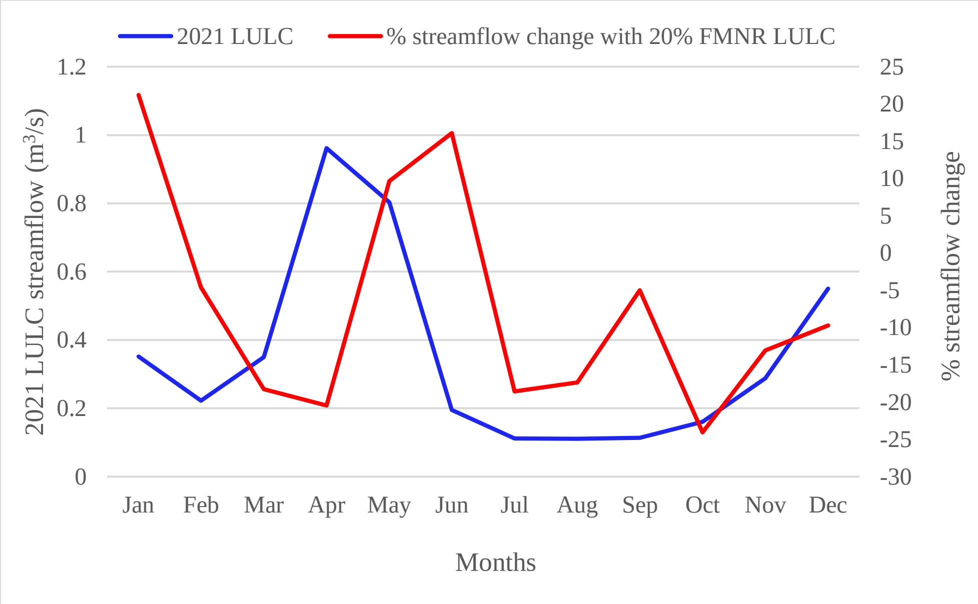

Figure 8: Change of Streamflow under 20% FMNR LULC from the Current LULC

CONCLUSION AND RECOMMENDATIONS

This study applied the SWAT hydrological model to demonstrate that widespread adoption of FMNR practices leads to increased vegetation cover. This rise in vegetation has a positive impact on water conservation by enhancing infiltration rates. In essence, FMNR promotes a natural feedback loop where more vegetation equates to more water retention in the soil. These findings highlight the potential of FMNR as a sustainable strategy for water resource management in similar ecosystems.

Acknowledgement

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