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Hydrological modeling of the Enguli ephemeral sand river basin using HEC-HMS for sustainable water management in Kenya's ASALs

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ABSTRACT

This research aimed to characterize the hydrological behavior of the Enguli ephemeral sand river in Makueni, Kenya, using simulation modeling to aid sustainable water management in arid and semi-arid areas. The specific objectives were to analyze streamflow patterns and infiltration rates within the basin employing Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). The Soil Conservation Service Curve Number (SCS-CN) method was used for streamflow simulation, and infiltration modeling was performed using the Green–Ampt method. Model performance for streamflow simulation during calibration was Nash-Sutcliffe Efficiency (NSE) = 0.78, Percent Bias (PBIAS) = 19.83%, and coefficient of determination (R^2) = 0.76, while during validation it was NSE = 0.81, PBIAS = -29.28%, and R^2 = 0.78. In infiltration simulation, model efficiency was NSE = 0.58, PBIAS = -14.32%, and R^2 = 0.6 after calibration and validation using field measurements from five sampling locations across the study area. Infiltration in the study area was significant, which points towards the reliability of alluvial aquifers as a water source during dry seasons. The study demonstrates the applicability of employing hydrological models in determining the potential of sand rivers as natural water storage reservoirs in arid and semi-arid lands. It forms part of enhanced water resource management approaches and informs climate-resilient, farmer-led irrigation systems.

Contribution/Originality: This study contributes to the hydrology literature by exploring streamflow and infiltration simulation modeling in ephemeral sand river systems. This research offers insights into the role and impact of sand rivers as natural aquifers, enhancing understanding of their potential to support climate-resilient and farmer-led irrigation systems.

1. INTRODUCTION

Sand rivers are seasonal streams with surface runoff during rainy periods and are usually dry with either no or minimal flow during dry periods [1]. Sand rivers are predominant in the African drylands, especially in ASAL areas. Despite the absence of surface water runoff during dry periods, groundwater is present in the underlying alluvial aquifer in the sand riverbeds [2]. In ASAL areas where dependable surface water is limited, shallow aquifers in the sand rivers constitute a potential source of water during dry periods [3]. Sand river aquifers are rapidly recharged during storm rains, even to saturation within a matter of hours, and stored water normally recedes slowly over a few months, subject to demand [1]. Consequently, sand rivers can be impactful in supporting irrigation and household water demands in large regions within ASAL areas [4].

Hydrological modeling is essential in the management of water resources in arid and semi-arid regions (ASALs), where hydrological data is sparse and highly variable. HEC-HMS is a physically based, semi-distributed model developed by the USACE to simulate major hydrological processes within the watershed system [5]. HEC-HMS model has been effectively applied for streamflow simulation and prediction across various climatic conditions, including humid, tropical, subtropical, and arid regions [6]. HEC-HMS captures key hydrological processes such as infiltration, evaporation loss, and surface runoff. When dividing a catchment into smaller sub-basins assumed to be homogeneous regarding land use and soil conditions, HEC-HMS offers various model options focused on generating runoff hydrographs and routing them from individual sub-basins to basin outlets [6].

ASAL areas are characterized by serious water resource management problems due to rainfall inconsistency and extended dry seasons [7]. Climate variability and water scarcity are major issues that have resulted in increased drought frequencies. This leads to food security issues since rain-fed agriculture is the main source of livelihood for most communities in the regions. Sand rivers provide a natural option where water is stored in their alluvial aquifers and can be utilized to meet irrigation demands. Limited knowledge and research on water flow and infiltration into alluvial aquifers make water resource management in these regions challenging [8]. Soil properties, topography, and heterogeneity of land use in such catchments make it even more challenging to estimate water availability precisely, particularly in areas such as Makueni, Kenya, with limited detailed hydrological observations.

Various studies have been conducted on the potential of rivers for water supply [7], but there is limited research on hydrological characterization in the ASALs, such as in Makueni, Kenya. Sand rivers in ASALs, such as the Enguli River in Makueni, Kenya, with potential for sustainable water supply, have been inadequately researched [9]. Previous research has shown that sand rivers can be used to support farmer-led irrigation systems, which are more adaptable and responsive than government-managed projects [10]. However, there is limited extensive research on infiltration rates and rainfall-runoff relationships in these ASAL regions [11]. This study aimed to bridge such gaps by using the HEC-HMS hydrological model in intensively analyzing the hydrologic processes of the Enguli River with an aim to have more efficient water management practices in the region. Applying an event-based rainfall and runoff modeling approach, this research targets its analysis especially towards the two rainy seasons' rainfall, addressing a gap of unknown hydrological behavior characteristic of Kenya ASALs' ephemeral rivers.

Kenya's ASAL areas are characterized by distinctive water resource management challenges, which have led the government to take steps towards improving climate change resilience and food security. National policies also focus on adopting sustainable water management practices, encouraging rainwater harvesting, improving water storage infrastructure, and adopting effective irrigation practices. They are formulated to mitigate the limited and unpredictable rainfall in ASAL regions, assist people in adapting to climatic variations, and provide water supplies to agriculture and domestic consumption, which is important in sustaining the livelihoods of the communities in these regions [12]. The research outcome on the hydrological nature of sand rivers presents valuable lessons for policymakers and development practitioners that can be used to design more equitable and sustainable water management systems. This research aligns with the global goal towards capitalizing on nature-based solutions in addressing climate adaptation challenges in ASAL areas where resilient water management has the potential to enhance resilience and facilitate local development. By studying sand river hydrology, this research aims to create knowledge that enhances water availability for agriculture and other uses, and hence improves livelihoods in vulnerable and resource-scarce areas.

The main objective of this study is to evaluate the potential of the Enguli ephemeral sand river in sustaining water supply to the local community within ASAL areas. The study is driven by the need to provide scientific insights into the hydrology of the Enguli sand river and its potential to provide water security and enhance food production in ASAL areas. Through the study of the Enguli River, this research demonstrates how hydrological models can be employed to model water availability, predict seasonal variability, and inform irrigation management. Insights from this research can inform local development in Makueni and make contributions towards an initiative to advocate for sustainable agricultural practices in ASAL areas, eventually improving food security and enhancing community resilience.

This study aimed to:

i. Analyze the streamflow pattern of the Enguli River using the HEC-HMS model.

ii. Assess infiltration rates across the Enguli basin using the Green–Ampt infiltration model within HEC-HMS.

2. METHODOLOGY

2.1. Study Area

Makueni County, situated in the southern region of Kenya in East Africa, is one of the country's 47 counties. It spans an area of approximately 8,176.7 km², lying between latitudes 1°35' and 2°59' south and longitudes 37°10' and 38°30' east. Makueni experiences two climate zones, predominantly ASALs, characterized by relatively low rainfall and extended dry seasons [13]. The Enguli River watershed, which serves as the study area, covers an area of 46.774 km², as shown in Figure 1.

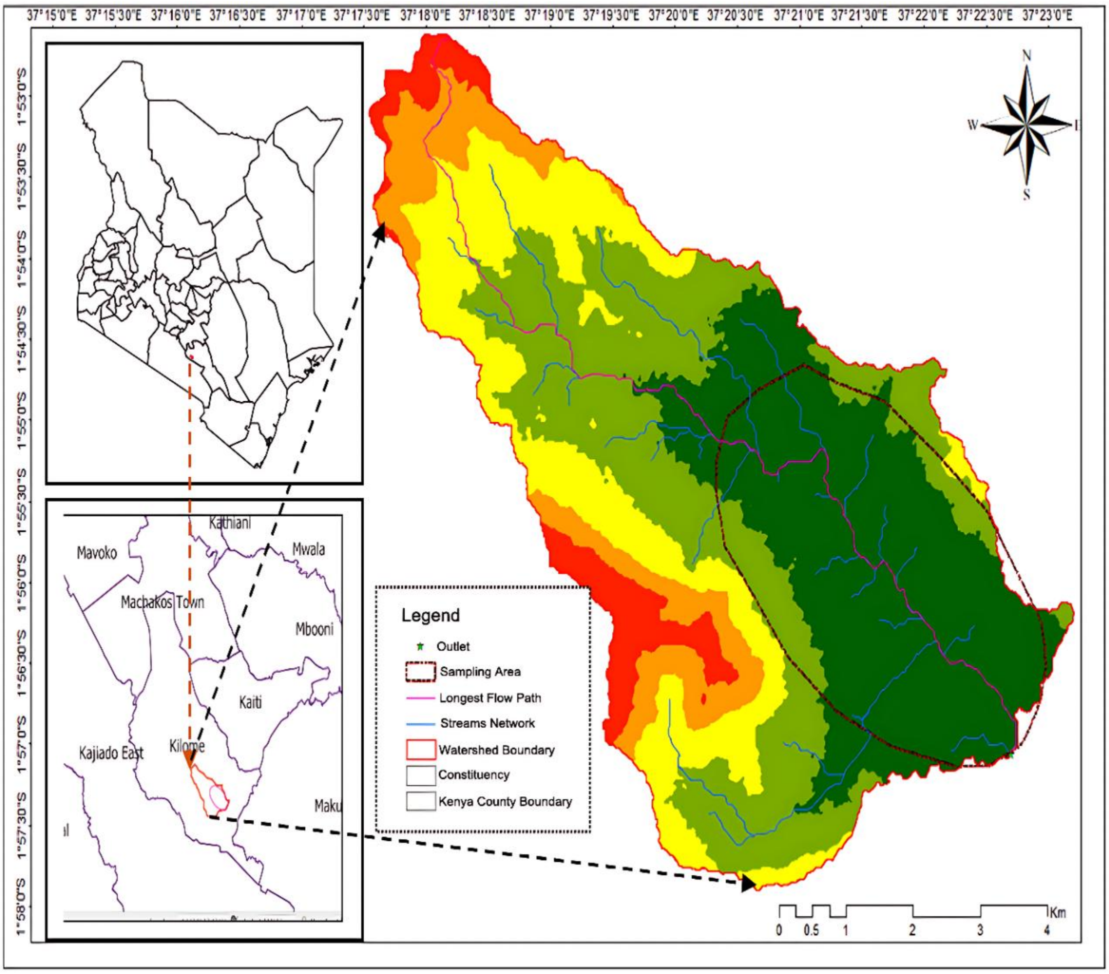

Figure 1. Enguli River Basin.

2.2. Input Data Sets

In this study, HEC-HMS 4.12 was applied to simulate rainfall-runoff and infiltration processes specific to the Enguli Sand River. Rainfall–runoff simulation data input into the HEC-HMS model requires a Digital Elevation Model (DEM) to define basin and sub-basin characteristics. Land Use Land Cover (LULC) and soil data sourced from the Soil and Terrain Database for Kenya (KENSOTER) informed parameters related to vegetation and impervious surfaces, affecting infiltration and runoff rates. Rainfall data from 2010 to 2024, sourced from the Kenya Meteorological Department (KMD) and Trans-African Hydro-Meteorological Observatory (TAHMO), was used to drive the simulations. Infiltration modeling using the Green–Ampt method in HEC-HMS requires data on soil hydraulic properties, including initial moisture content, saturated hydraulic conductivity, and wetting front suction head. These parameters were derived from field measurements and soil classification data for the Enguli Sand River basin. Table 1 shows the source of the data, specifications, and corresponding figures.

Table 1. Input datasets.

Data	Source	Specification	Figure
DEM	Alos Palsar	12.5m spatial resolution	Figure 2
LULC	Sentinel-2	10m spatial resolution	Figure 3
Soil data	KENSOTER	-	Figure 4
Rainfall data 2010-2024	KMD and TAHMO	Daily temporal resolution	-
Streamflow data 2018 - 2023	Water Resources Authority (WRA)	Daily temporal resolution	-
Soil hydraulic properties	Field measurements	-	-
Infiltration data	Field measurements	-	-

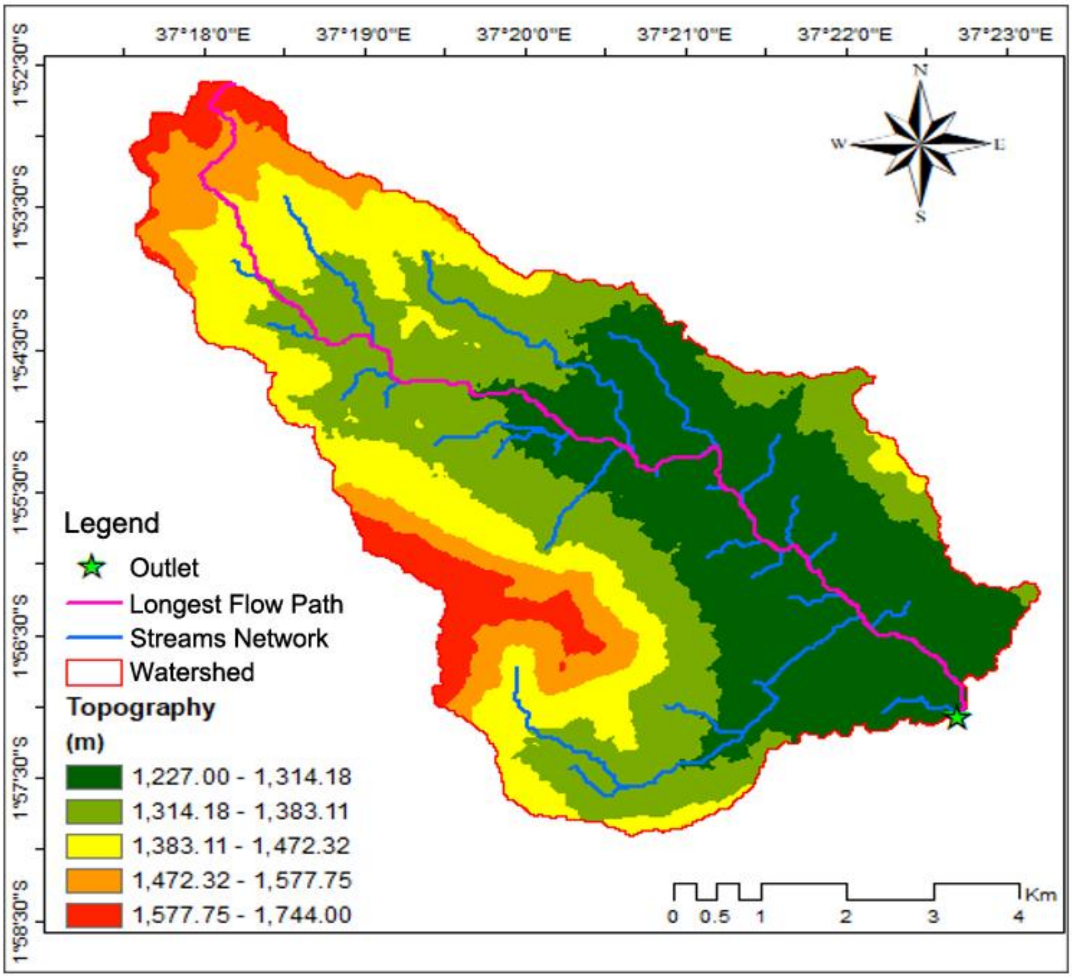

Figure 2. Digital elevation model.

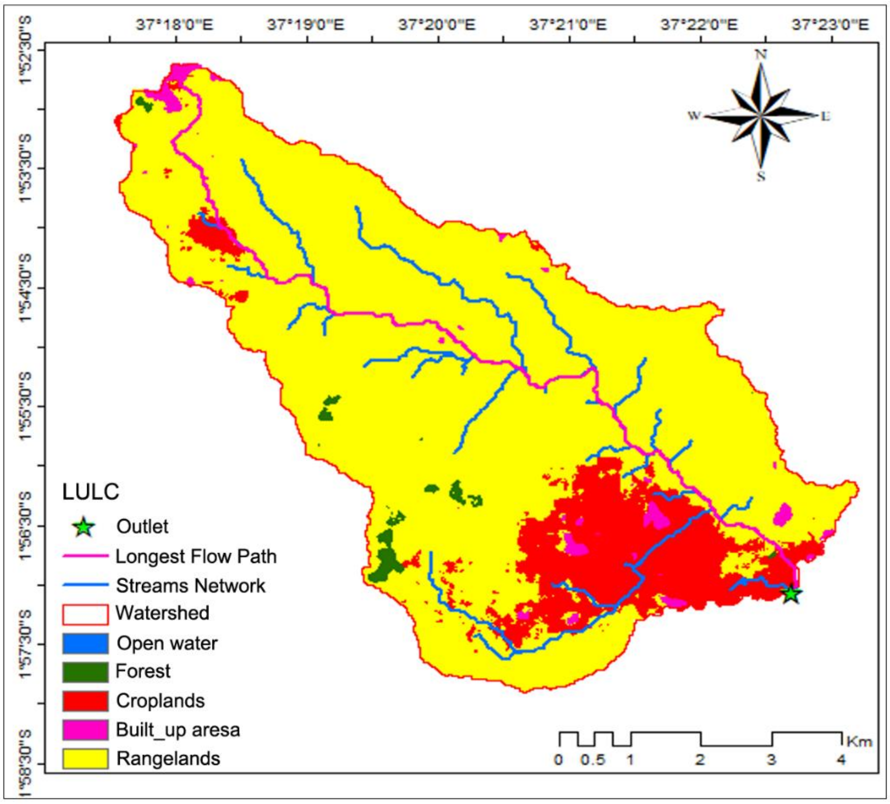

Figure 3. Land use land cover.

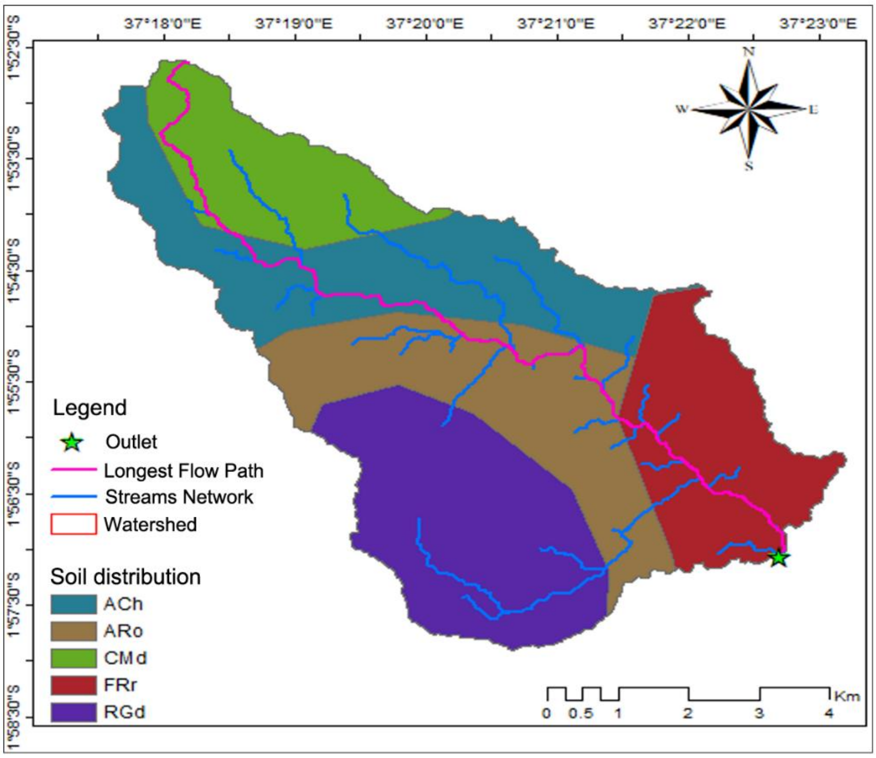

Figure 4. Soil Map of the study area.

2.3. Data Collection

2.3.1. Infiltration Data

Soil hydraulic properties were measured to determine porosity, permeability, and soil infiltration capacity within the Enguli sand river basin. Field infiltration data were supplemented with data from local agricultural and geological survey databases. Soil infiltration rates were determined using a double-ring infiltrometer, following the ASTM D3385-03 standard testing procedure. The infiltrometer setup involved two concentric metal rings inserted into the soil, with water introduced to initiate infiltration measurement. The standard ASTM specified 30 cm and 60 cm diameters for the inner and outer rings, respectively, as shown in Figure 5.

Figure 5. Double-ring infiltrometer.

Water was introduced into the inner ring, and the volume of infiltrated water over time was recorded. The outer ring helped prevent lateral flow of water. The decrease in water level within the inner ring was used to calculate the infiltration rate, defined as the amount of water that penetrated the soil per unit area and time [14]. The results of the field infiltration tests are presented in Table 2.

Table 2. Measured infiltration rate and saturated hydraulic conductivity.

S. No	Sampling location	Soil texture classification according to soil particle distribution.	Suction head, cm. According to soil texture from FAO guidelines.	Infiltration rate (cm/hr.)	Saturated Hydraulic Conductivity (cm/hr.)
1	River bed	Sandy	6	20	7.83
2	Musaani Shopping Centre	Clayey	40	0.4	0.16
3	Enguli Market Centre	Sandy Loam	15	6	2.35
4	Enguli Secondary School	Loamy sand	18	8	3.13
5	Enguli Secondary (Red Soil)	Clay Loam	42	1	0.39

2.3.2. Soil Hydraulic Conductivity

Soil hydraulic conductivity was determined using the same experimental approach as the infiltration test, following the ASTM D3385-03 standard procedure. The saturated hydraulic conductivity values obtained from the field tests are presented in Table 2. To calculate the saturated hydraulic conductivity (K_{sat}), the steady-state infiltration rate (I_{steady}) was first obtained by measuring the depth of water infiltrated over time. Darcy's equation for Saturated Flow, K_{sat} was used to computed as follows.

$$K_{sat} = \frac{I_{steady} \times H}{t} \quad (1)$$

Where:

K_{sat} - Saturated hydraulic conductivity (cm/hr).

I_{steady} – Steady-state infiltration rate (cm/hr).

H – Water depth maintained in the ring (cm).

T - Time taken for infiltration (minutes).

This provided an approximation of the capacity for water infiltrated into the soil when saturated, which was essential in quantifying infiltration dynamics in the Enguli sand river basin.

2.3.3. Soil Moisture Content

Soil moisture content was measured by laboratory testing to determine the soil's water-holding capacity, which is one of the required input parameters of the Green-Ampt infiltration model in HEC-HMS. This data was essential for estimating the initial soil moisture deficit shown in Table 3, a critical parameter in modeling infiltration in the Enguli sand river basin.

Table 3. Soil moisture data.

	Sampling location	Initial soil moisture content (%)	Saturated soil moisture content (%)	Soil moisture deficit to saturation (%)
1	River bed	9.24	40	30.76
2	Musaani Shopping Centre	11.61	48	36.39
3	Enguli Market	7.7	44	36.30
4	Enguli Secondary	12.68	44	31.32
5	Enguli Secondary (red soil)	11.51	48	36.49

2.4. HEC-HMS Model Setup

In HEC-HMS, the SCS-CN method was applied to estimate direct runoff. This approach calculated runoff based on the Curve Number (CN) as shown in Table 4, which varies according to soil type and LULC [15], also shown in Figure 6. The SCS-CN method operates on the principle that accumulated rainfall excess is influenced by total rainfall, soil characteristics, land use, and antecedent moisture conditions, estimated as.

$$P_e = \frac{(P-I_a)^2}{P-I_a+S} \quad (2)$$

Where;

I_a - the initial abstraction (mm) = 0.2S.

S - the potential maximum retention (mm).

P_e – cumulated rainfall excess at time t (mm).

P - the accumulated precipitation depth at time t (mm).

The maximum retention, S, and watershed characteristics are related through an intermediate dimensionless parameter, the curve number (CN).

$$S = 25400 - \frac{254 \times CN}{CN} \quad (3)$$

Table 4. Weighted curve number.

	Sub basin 1	Sub basin 2	Sub basin 3	Sub basin 4	Sub basin 5
Mean	72.888	71.453	57.118	65.369	67.255

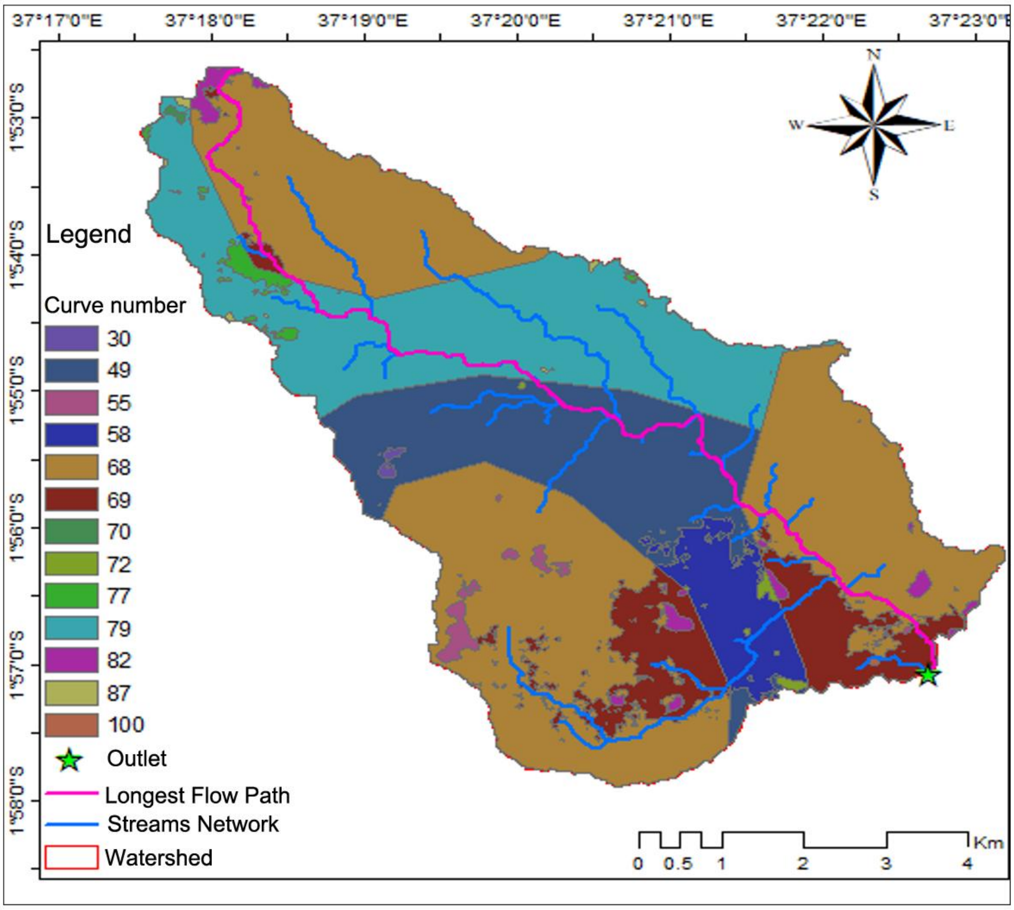

Figure 6. Curve Number distribution across the study area.

The Soil Conservation Service Unit Hydrograph (SCS-UH) model in HEC-HMS was used to convert excess rainfall into runoff. In this method, lag time (T_{lag}) was the primary input. It represented the duration from the midpoint of excess rainfall to the peak of the hydrograph and was calculated for each watershed using the concentration time T_c, as follows.

$$T_{lag} = 0.6T_c \quad (4)$$

Where T_{lag} and T_c are in minutes.

The concentration time was calculated by Kirpich formula given by.

$$T_c = KL^{0.77}S^{-0.385} \quad (5)$$

Where: S – Slope and L – Length.

Routing was used to simulate the channel flow from the upper catchment down to the basin outlet. The HEC-HMS Muskingum routing method was applied for this purpose. This method required two parameters: the flood wave's travel time through the routing reach and a dimensionless weighting factor representing the degree of flood wave attenuation as it progresses downstream [16]. Typically, these routing parameters were calibrated against observed discharge hydrographs.

$$S = K(XI + (1 - X)Q) \quad (6)$$

Where KQ is the prism storage, KX(I-Q) is equal to volume of the wedge storage, K is proportionality coefficient and X weighing factor ranging 0-0.5.

The Green and Ampt infiltration model requires hydraulic conductivity, suction head, moisture deficit, percent imperviousness, and initial loss. This infiltration method will describe the infiltration rate for the soil type around Enguli River. It is computed as.

$$F(t) = \sqrt{2 \times K \times \varphi \times \Delta\theta \times t} \quad (7)$$

Where:

K - Saturated hydraulic conductivity (cm/hr.), φ - is the wetting front soil suction head (cm), $\Delta\theta$ - moisture content deficit, t – daily time (24 hours).

Cumulative infiltration was then calculated from the measurement soil and infiltration parameters. The calculated cumulative infiltration (mm/day) and simulated infiltration (mm/day) from model is as shown Table 5. The simulated infiltration across the sub-basins in the study area shows significant spatial variability, reflecting differences in hydrologic response and possibly land use or soil type. This is shown in Figure 7.

Table 5. Observed and simulated infiltration rate (mm/day).

Sub basin	Observed (mm/day)	Simulated (mm/day)
Musaani shopping center	105.7	110.798
Enguli Market Centre	247.8	165.09
Enguli Market (RS)	169.2	158
River Bed	263.4	250
Enguli Secondary School	291	239.01

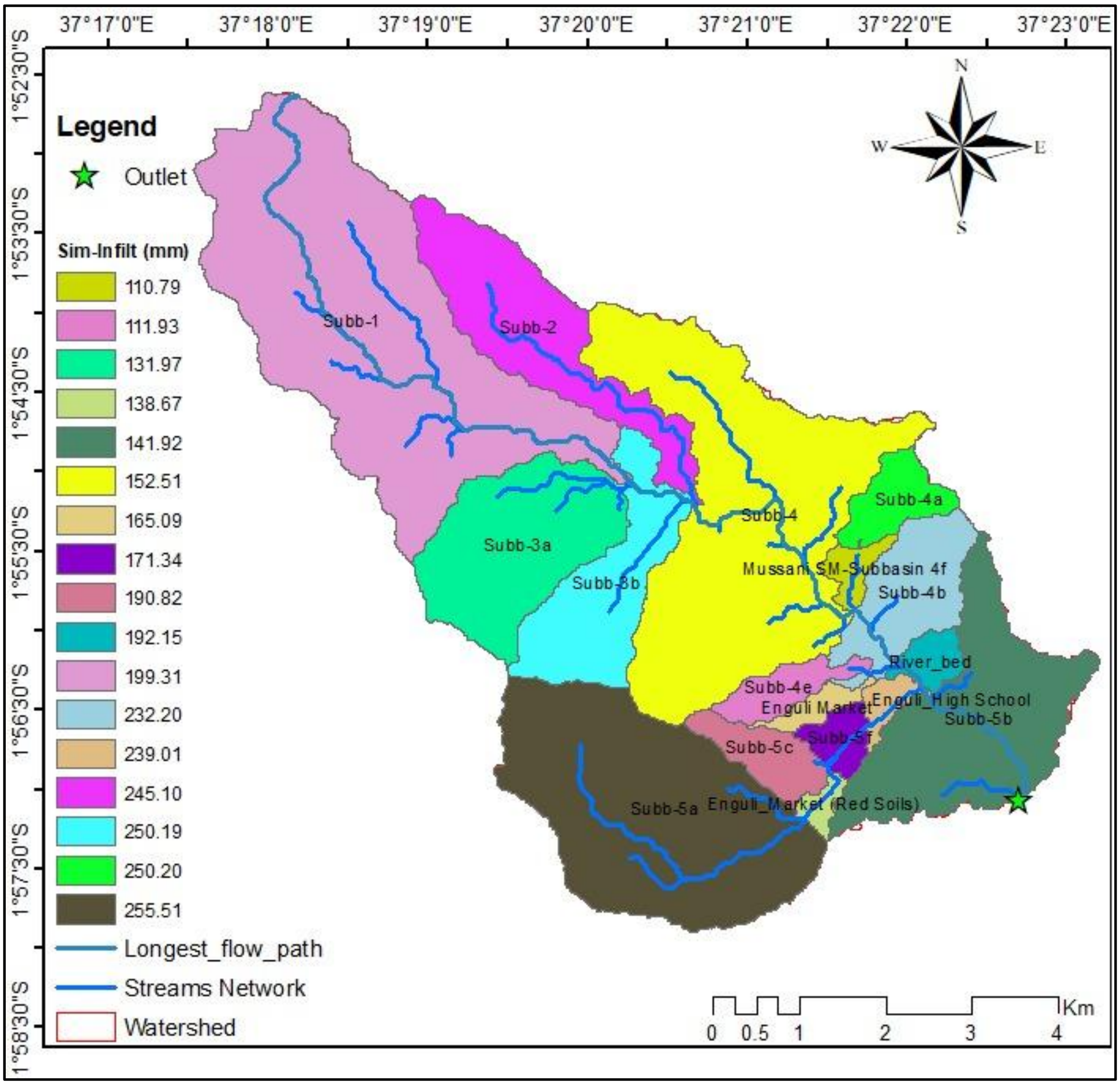

Figure 7. Spatial infiltration rate variability.

2.5. Model Calibration and Validation

In HEC-HMS, the Nelder-Mead and Univariate Gradient algorithms are available for optimizing the objective function. The model calibration employed the Univariate Gradient optimization method, paired with the Peak-Weighted Root Mean Square Error (PWRMSE) objective function, selected for their simplicity and effective performance. For validation, the model's predicted data were compared to observed data, applying statistical error functions to assess accuracy. Calibration entailed adjusting model parameters to minimize discrepancies between simulated and observed values. For this study, streamflow data from March 27, 2018, to December 31, 2021, were utilized for calibration, while data from January 1, 2022, to December 31, 2023, were employed for validation. This is shown in Figure 8.

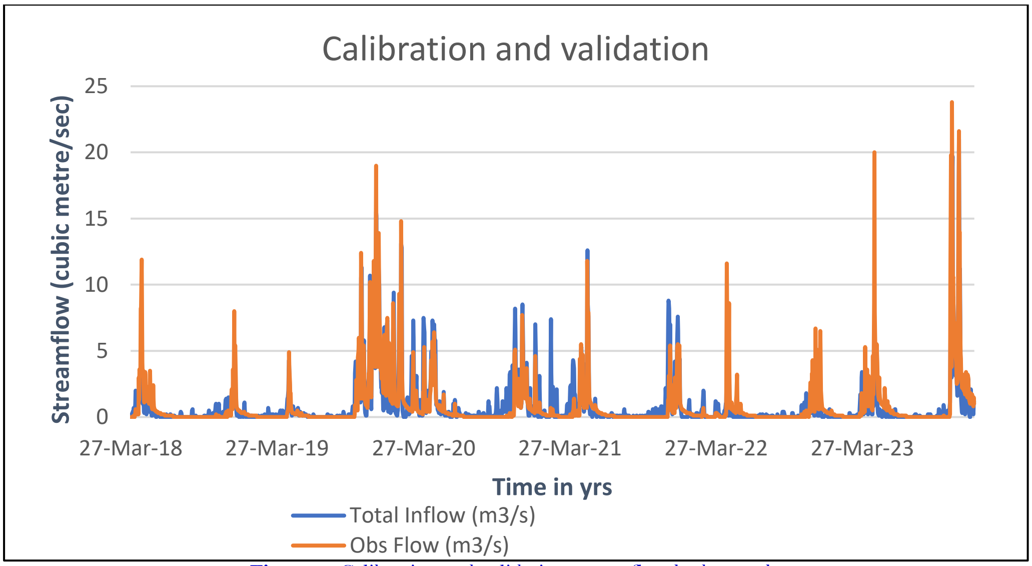

Figure 8. Calibration and validation streamflow hydrograph.

The field-measured infiltration rates were used to calibrate and validate the model-simulated infiltration outputs. A graphical representation of the comparison between observed and simulated infiltration rates is presented in Figure 9.

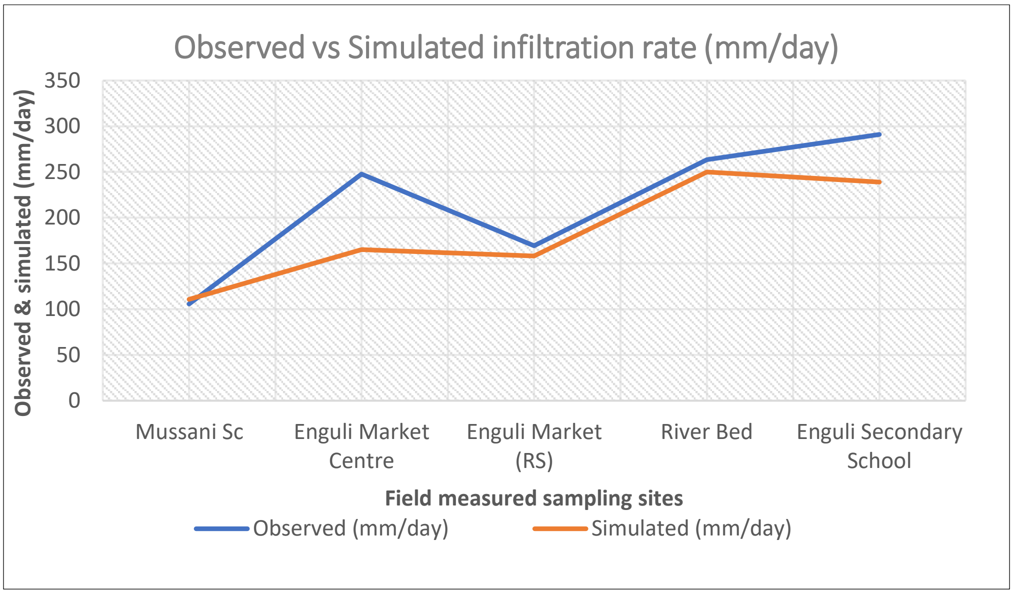

Figure 9. Observed vs simulated infiltration rate (mm/day).

2.6. Model Evaluation

The performance of the HEC-HMS model was evaluated using the Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and the coefficient of determination (R^2).

2.6.1. Nash-Sutcliffe Efficiency (NSE)

The NSE was used to evaluate the forecasting efficiency of hydrological models. NSE was calculated as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i}-X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i}-\overline{X_{obs}})^2} \quad (8)$$

Where:

$X_{obs,i}$ is observed data, X_{model} is the computed values and $\overline{X_{obs}}$ is the mean of observed discharge values at time/place i.

2.6.2. Percent Bias (PBIAS)

PBIAS measures the overall tendency of the simulated data to be either higher or lower than the observed values. An ideal PBIAS value is 0.0, with lower values indicating a more accurate model simulation. Positive PBIAS values suggest an underestimation, while negative values indicate an overestimation bias. PBIAS was calculated as follows:

$$PBIAS = \frac{\sum_{i=1}^{n}(X_{obs,i}-X_{sim,i})(100)}{\sum_{i=1}^{n}(X_{obs,i})} \quad (9)$$

Where:

$X_{obs,i}$ is observed data, $X_{sim,i}$ is simulated values at time/place i.

2.6.3. Coefficient of Determination (R^2)

R-squared is a statistical measure that evaluates the proportion of variance in the dependent variable that can be predicted from the independent variables. It provides insight into the goodness of fit of the model, indicating how well the observed outcomes are replicated by the model.

$$R^2 = 1 - \frac{\left[\sqrt{\sum_{i=1}^{n}(X_{obs,i}-X_{sim,i})^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(X_{obs,i}-\overline{X_{obs}})^2}\right]} \quad (10)$$

Where:

$X_{obs,i}$ is observed data, $X_{sim,i}$ is simulated values, and $\overline{X_{obs}}$ is the mean of observed discharge values at time/place i.

3. RESULTS AND DISCUSSION

3.1. Streamflow Simulation

Streamflow simulation was carried out using the HEC-HMS model with the Soil Conservation Service Curve Number (SCS-CN) method to represent direct runoff processes. The model was set up to simulate hydrologic responses to rainfall events during the long (March–May) and short (October–December) rainy seasons from 2010 to 2024, in line with the event-based modeling approach adopted in this study.

Model performance was evaluated using the Nash–Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and the Coefficient of Determination (R^2) for both calibration and validation periods. During the calibration phase, spanning from 27th March 2018 to 31st December 2021, the model achieved an NSE of 0.78, PBIAS of 19.83%, and R^2 of 0.76. In the validation phase (1st January 2022 to 31st December 2023), the model showed improved performance, with NSE = 0.81, PBIAS = -29.28%, and R^2 = 0.78.

According to commonly used hydrologic model performance benchmarks, an NSE between 0.65 and 1.00 indicates very good performance, while a PBIAS within ±30% is considered satisfactory. These results demonstrate that the HEC-HMS model performed well in simulating streamflow for the Enguli River basin.

The simulated streamflow hydrograph effectively captured the timing and magnitude of discharge events, reflecting the basin's hydrological response to rainfall. The hydrograph highlights distinct peak flows during rainfall events and aligns closely with observed discharge data, enabling a reliable assessment of runoff generation and water availability. This analysis is essential for informing water resources planning and for understanding flow variability within the ephemeral river system.

From the simulation, it was observed that significant streamflow events were concentrated during the rainy seasons, specifically March–May and October–December. Minimal or no discharge was recorded in the other months, confirming the ephemeral nature of the Enguli River. The hydrograph displays rapid rises and short-lived peaks, indicative of quick surface runoff typical in semi-arid catchments with sandy soils and limited vegetation cover.

The HEC-HMS-generated hydrographs for the basin outlet are presented in Figure 10 and Figure 11. These represent streamflow for the two main rainfall periods, respectively. The results provide insights into discharge magnitude, event timing, and runoff volume generated during peak rainfall events.

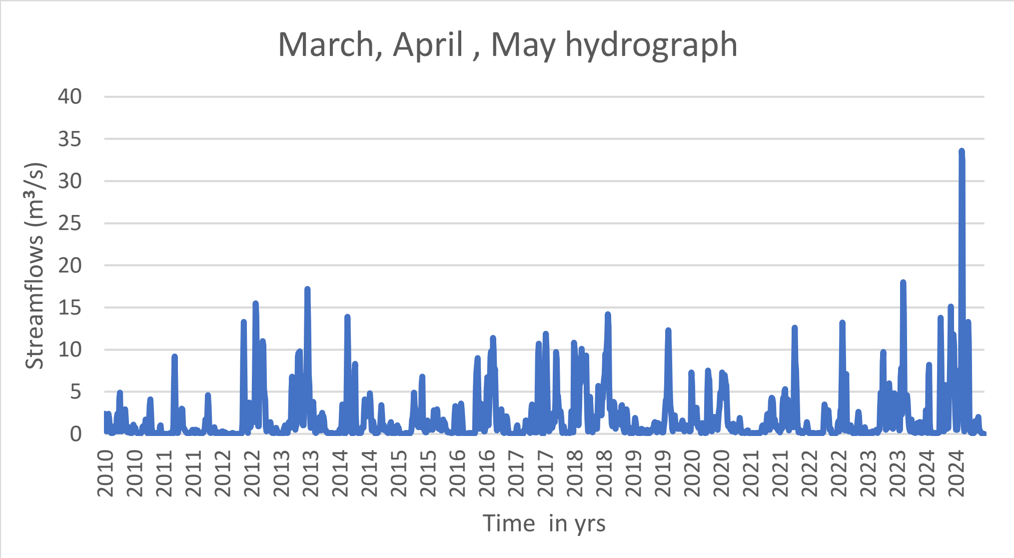

Figure 10. Simulated Streamflow Hydrograph – March–May Events.

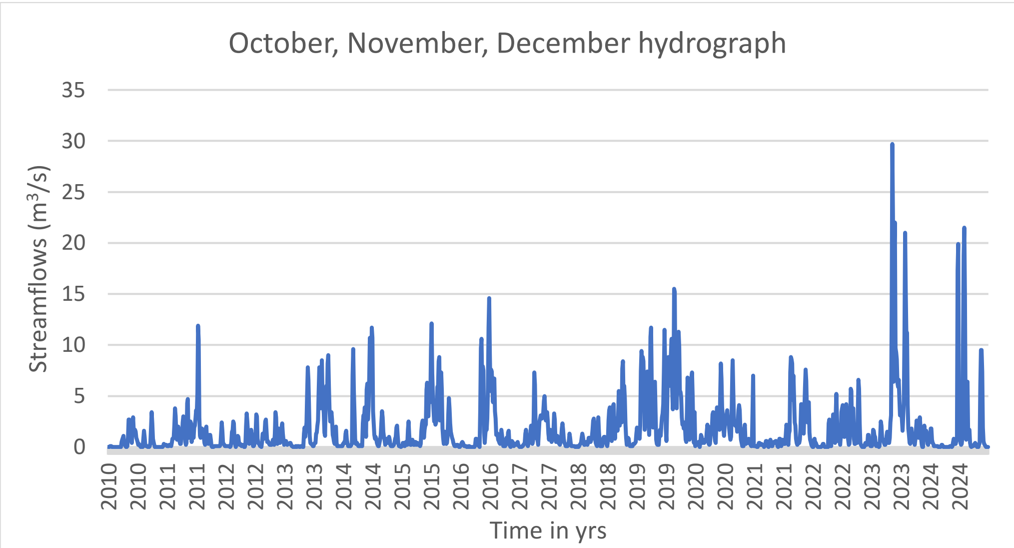

Figure 11. Simulated Streamflow Hydrograph – October–December Events.

This analysis illustrates the seasonal variations in streamflow within the Enguli Sand River Basin and provides critical insights for guiding water resource management practices, particularly in optimizing the timing and design of water storage in underlying alluvial aquifers.

3.2. Infiltration Simulation

Infiltration modeling was conducted using the Green–Ampt method in HEC-HMS to simulate infiltration across the Enguli Sand River watershed. The model parameters were field data collected from five sampling sites. Infiltration rate was measured using a double ring infiltrometer; suction head, depending on soil texture, was determined from FAO guidelines, and saturated hydraulic conductivity was calculated from these measured parameters. Soil moisture content analysis was conducted to estimate the soil moisture deficit a key input into the Green–Ampt method.

The model was calibrated and validated using field-measured infiltration data. The model's performance was evaluated using the Nash–Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Coefficient of Determination (R^2). The results showed NSE = 0.58, PBIAS = -14.32%, and R^2 = 0.60. These values indicate a moderately good model fit, with the model capturing some variability in observed infiltration rates. The positive PBIAS value suggests that the model tended to slightly underestimate actual infiltration. This level of accuracy is considered acceptable for hydrological models applied in data-scarce regions, though further refinement of spatial parameters could enhance model reliability. The model revealed significant spatial variability in infiltration rates across the sub-basins. Monthly average infiltration values over the 2010–2024 period ranged from approximately 110.79 mm/day to 255.51 mm/day. Sub-basin 1 in the northwest side of the study area showed relatively low infiltration of 110.79 mm/day, potentially due to compacted soils or steeper terrain. In contrast to sub-basins in the central and southeastern sides, particularly Sub-basin 4f and Sub-basin 5a, which recorded the highest infiltration rates, reaching up to 255.51 mm/day. These high values may be attributed to flatter topography, sandy soils, and more permeable geological layers, which enhance infiltration and groundwater recharge. The infiltration map shown above in Figure depicts this spatial heterogeneity, which attributes to the heterogeneous composition of land cover, types of soil, and land use activities across the water basin. This heterogeneity has significant effects on the hydrological response of the Enguli river system and on the significance of localized parameterization in infiltration modeling.

Different locations across the study area exhibit distinct infiltration characteristics. In the Musaani area Sub basin 4f, moderately high infiltration, 110.79 mm/day, suggests the presence of porous soils or well-managed land cover, supporting reduced runoff. Enguli Market Centre Sub basin 4d exhibited high infiltration rates, 247.8 mm/day, likely driven by sandy soils and low surface sealing, although future land use changes may influence these rates. Nearby, Enguli High School Sub basin 5e recorded consistently high infiltration, greater than 290 mm/day, indicating effective drainage and strong groundwater recharge potential. In Sub basin 4c along the Riverbed, infiltration was more variable, 291 mm/day, reflecting localized saturation or compacted riparian conditions that may limit further infiltration during peak events. These site-specific insights reflect the hydrologic complexity of the basin and reinforce the importance of spatially distributed analysis in infiltration modeling.

Despite achieving a satisfactory level of performance, some limitations were noted in the infiltration modeling process. The temporal limitation of field observations, with tests conducted on a single day, restricts the ability to capture seasonal or event-based variability. The spatial extrapolation of point-based infiltration measurements across the entire sub-basin introduces uncertainty, as local heterogeneity may not be fully represented.

4. CONCLUSION AND RECOMMENDATION

4.1. Conclusion

This research effectively characterizes the hydrological behavior of the Enguli ephemeral sand river in Makueni, Kenya. The study focuses on streamflow and infiltration modeling using the HEC-HMS model, applying the Soil Conservation Service Curve Number (SCS-CN) method for runoff and the Green–Ampt method for infiltration simulation. The model achieved good performance in simulating seasonal streamflow patterns and captured spatial variation in infiltration in the Enguli basin. The results demonstrate the potential of event-based modeling in ASALs, where sand river hydrological processes are heavily reliant on seasonal rainfall events. The study addresses a significant knowledge gap in hydrological sand river characterization in dryland areas, where field data and monitoring are sparse, limiting sustainable water planning.

One of the key contributions of this study is the collection of field-based infiltration data and their input into a calibrated hydrological model, a significant step toward understanding the groundwater recharge potential for sand river basins. The results are particularly valuable for application in informing farmer-led irrigation systems and nature-based solutions that take into account seasonal runoff and infiltration in attaining increased water security.

This study contributes towards Sustainable Development Goals (SDGs), SDG 6 (Clean Water and Sanitation), SDG 2 (Zero Hunger), and SDG 13 (Climate Action) since it informs sustainable management of water resources, increases agricultural resilience in the ASALs, and promotes climate-adaptive water storage technologies.

In summary, this research enhances the theoretical and practical understanding of sand rivers and explores their potential in sustaining livelihoods in Kenya's ASAL areas.

4.2. Recommendation

Water resource planners should prioritize high-infiltration sub-basins such as Sub basin 5a and Sub basin 4f for groundwater recharge protection and seasonal water storage initiatives. County governments and NGOs working in ASAL regions are encouraged to support infrastructure development for sand dams or infiltration galleries in areas with high recharge potential, especially where communities rely on dry-season water extraction. Data generated from this study can inform integrated watershed management plans, particularly for adapting to rainfall variability and enhancing dry-season resilience. Community-based water committees and farmers can also apply the findings to better time planting and irrigation practices in alignment with seasonal streamflow and infiltration trends.

Future studies should incorporate long-term infiltration monitoring to better understand seasonal and annual variability in infiltration rates. The use of higher-resolution rainfall data, such as hourly observations, is recommended to better capture short-duration storm events that influence infiltration and peak flow dynamics. Comparative hydrological studies across multiple sand river systems within Kenya and other dryland regions would enhance regional water resource strategies. Additionally, the integration of land use change, sediment transport, and groundwater monitoring into hydrological models will provide a more comprehensive picture of the basin's behavior and sustainability. Expanding this research to include climate change scenarios would further support the design of adaptive water management interventions in ASAL zones.

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