



Rainfall-runoff modelling to determine continuous time series of daily streamflow in the Umba River, Kenya

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ABSTRACT

Long time series of streamflow data are required to understand the flow characteristics of a river that could be applied for various watershed and water resource management plans. A reliable estimate of river flows generated from catchments are commonly obtained by water level observations from in situ gauging stations. However, sufficient streamflow observations are not available due to missing flow records and limited observation periods in the Umba River, a transboundary river basin shared between Kenya and Tanzania. Hence, it was necessary to undertake a study on hydrological simulation by developing an appropriate model to the watershed. A rainfall-runoff model was developed using the Hydrologic Engineering Center - Hydrologic Modelling System (HEC-HMS). The model was simulated to generate a continuous time series of daily streamflow for the last 30 years (1988 to 2017). The computed streamflow results were then used to infill the missing records and to extend the flow data of the river. The study is expected to inform management decisions for efficient water resource allocation in the basin. Hence, a continuous collection of data on hydrology is recommended to ensure the provision of sustainable water flows in the river.

Key words: HEC-HMS, rainfall-runoff modelling, simulation; streamflow, time series, Umba River, watershed

RÉSUMÉ

De longues séries chronologiques de données des débits fluviaux sont nécessaires pour comprendre les caractéristiques d'écoulement d'une rivière qui pourraient être appliquées dans divers plans de gestion des bassins versants et des ressources en eau. Une estimation fiable des débits fluviaux générés par les bassins versants est généralement obtenue par des observations de niveau d'eau à partir de stations de jaugeage in situ. Néanmoins, il n'y a pas suffisamment de données d'observations d'écoulement disponibles, en raison des manquements dans les enregistrements de débit et des courtes durées d'observation dans la rivière Umba, un bassin fluvial transfrontalier partagé entre le Kenya et la Tanzanie. Il était donc nécessaire d'entreprendre une étude sur la simulation hydrologique en développant un modèle adapté au bassin versant. Un modèle pluviométrie-écoulement a été développé à l'aide du Système de Modélisation Hydrologique du Centre d'Ingénierie Hydrologique (HEC-

HMS). Le modèle a été simulé pour générer une série chronologique continue du débit quotidien des 30 dernières années (1988 à 2017). Les résultats de l'écoulement fluvial calculés ont ensuite été utilisés pour remplir les enregistrements manquants et pour étendre les données d'écoulement de la rivière. L'étude devrait aider à la prise des décisions de gestion pour l'allocation efficace des ressources en eau dans le bassin. Par conséquent, une collecte continue de données sur l'hydrologie est recommandée pour assurer la fourniture de débits d'eau durables dans la rivière.

Mots clés : HEC-HMS, modélisation précipitation-écoulement, simulation, débit, séries chronologiques, rivière Umba, bassin versant

INTRODUCTION

Surface runoff plays an important role in balancing the hydrologic cycle by returning the excess precipitation into oceans and controlling the streamflows. It has also key roles in soil erosion, flooding, and resource distribution. The amount of streamflow from a watershed mainly depends on catchment characteristics (drainage area, soil properties, land cover, topography, and vegetation), storm properties (rainfall amount, duration and intensity), characteristics of groundwater aquifer, and other climatic conditions. Hence, accurate streamflow estimation is essential for efficient management of watersheds and water resources, flood regulation, and understanding ecological relationships of the river environment (Sitterson *et al.*, 2012; Tiwari *et al.*, 2013; Devia *et al.*, 2015).

A reliable estimate of river flows generated from catchments are commonly obtained by water level observations from *in situ* gauging stations. The water level records are then converted to their corresponding discharges using stage-flow rating curves. However, sufficient observations may not be found due to missing records, lack of gauging stations, or limited observation periods (Elshorbagy *et al.*, 2000; Vaze *et al.*, 2012). These gaps and discontinuities, lead to problems in planning water development schemes, design of hydraulic structures, and in management of water resources.

Hydrological researchers have developed models and techniques to estimate missing flow data and to reconstruct the time series (Elshorbagy *et al.*, 2000; Tencaliec *et al.*, 2015). Various methods have been adopted for infilling streamflow data gaps which range from basic interpolations to complex statistical analyses (Mwale *et al.*, 2012). Hydrological models with different characteristics and applications have also been developed to simulate the hydrologic processes of basins and to estimate the responses to various watershed management practices (Tiwari *et al.*, 2013; Choudhari *et al.*, 2014). These models are necessary tools for the management of water resources, climate change studies, flood prediction, and environmental flow assessments (Vaze *et al.*, 2012; Devia *et al.*, 2015).

The Umba River basin is a transboundary river catchment shared between Kenya and Tanzania. Freshwater input from the river is a major factor controlling the productivity of the riverine ecosystems and the livelihoods they support. The river has one flow gauging station (3kg01) located near the town of Lunga-Lunga. The stage (water level) of the river has been measured from the station since 1966. The majority of available records cover the periods from 1966 to 1987. In addition to the data gaps existing within the observation periods, there is a large period (1988 to 2017) with missing flow data. These gaps and discontinuities present problems in planning

water development projects and managing water resources to meet developmental and environmental needs. In view of the planned future developments in the Umba River, it was necessary to undertake a study on hydrological simulation by developing an appropriate model to the watershed. The overall objective of this study was, therefore, to simulate the rainfall-runoff process of the Umba River basin using HEC-HMS and generate continuous time series data of daily streamflow for the years 1988 to 2017.

MATERIALS AND METHODS

Description of the study area. The Umba River Basin (Figure 1) extends between 3.83 and 4.91 Latitudes, South and between 37.94 and 39.25 Longitudes, East. It covers a total area of 8,070 km² of which about 5,510 km² is in Tanzania and the remaining 2,560 km² lies in Kenya. Originating from the Usambara Mountains in Tanzania, the river's main catchment lies in the Tanga region. The river is made up of three main tributaries: Bombo, Mbalamo, and Umba. The combined river drains southeast, crosses the Tanzania-Kenya border, and enters the Indian Ocean through a huge mangrove forest at Vanga town of Kenya. The river flows across areas of widely diverse climate, topography, and land use (IUCN Eastern Africa Programme, 2003; Lerise, 2005).

The topography of the Umba River Basin ranges from sea level at the Indian Ocean to about 2,760 m above sea level at the Usambara Mountains. It comprises five Agro-Ecological Zones (AEZs) namely the coastal plain, the foot plateau, the coastal uplands, the Nyika plateau, and the Usambara Mountains. The basin covers humid areas near the Usambara Mountains, sub-humid coastal plains near the Indian Ocean, and semi-arid lands in the north-western part of the basin. The average annual temperature in the study area is 24 °C and the rainfall ranges between 500 mm and 1500 mm. High mean temperatures are experienced in the months of November

and April while the coolest period is between June and August (CWSB, 2013; Kwale, 2013; MoALF, 2016).

According to the Köppen–Geiger climate classification system, the basin includes tropical monsoon (Am), tropical savannah with dry summer (As), and tropical savannah with dry winter (Aw). The basin is mainly characterized by tropical climate controlled by the large-scale pressure systems of the Western Indian Ocean in combination with orographic effects of the coastal hills and convection over the hot and dry hinterland of the northwest. These result in two distinct monsoon periods, with the long rainy season occurring from March to June and the short rainy season occurring between October and January (Wang'ondou *et al.*, 2010; CWSB, 2013; VAJIKI PFMP, 2017).

The land cover (Figure 2) of the basin is dominated by Mosaic Vegetation and Cropland which covers about 45% of the basin followed by Grassland constituting 20% of the area. The main land uses in the northern part of the basin are irrigation and wildlife conservation, while cattle grazing and irrigation are the main activities in the southern areas (IUCN Eastern Africa Programme, 2003). The water in the Umba River is a critical resource to the livelihoods of the communities living around it for its use in domestic water supply, large scale irrigation, the environment, and other uses. Modern irrigation, which is practiced on the lower parts of the river has a potential for expansion (Lerise, 2005).

Hydrological modelling. Hydrological models provide a simplified representation of actual hydrologic systems using several equations based on empirical relationships, physical laws, or conceptual operations. They help to study the functioning of watersheds and their response to various inputs, and thereby give a better understanding of the hydrologic processes (Tiwari *et al.*, 2013; Gao *et al.*, 2018). The two classical types of hydrological models are

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Deterministic that use direct data and Stochastic that use statistical data. Deterministic hydrology models can be classified as Dynamic, which include time, and Static, that excludes time factor. Dynamic models are subdivided into event-based models that produce output for

only specific time periods and continuous models that simulate for a longer duration. Commonly used Stochastic models are regression, transfer functions, neural networks and system identification (Moradkhani and Sorooshian, 2009; Nandalal and Ratmayake,

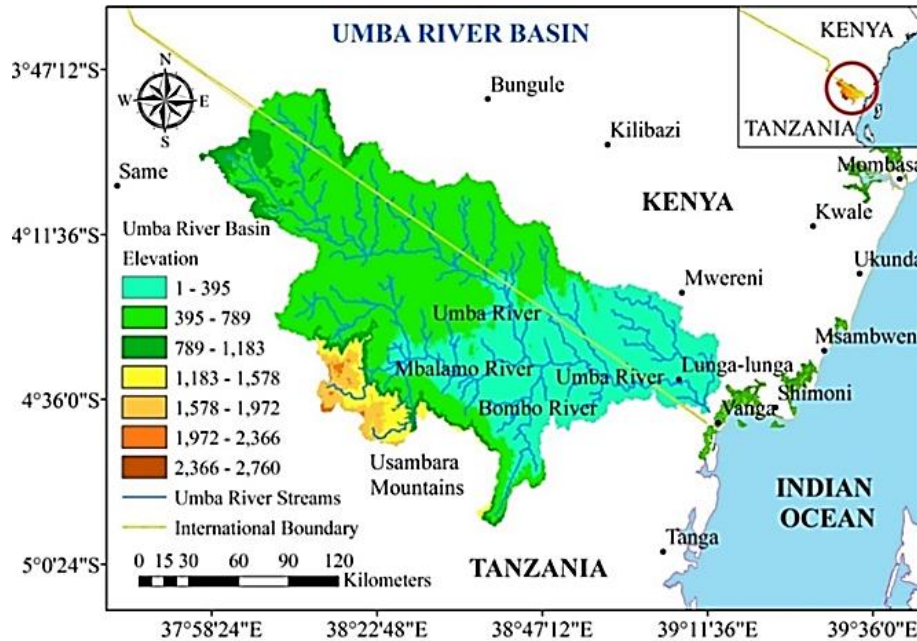


Figure 1. Location map showing the Umba River Basin in Kenya and Tanzania

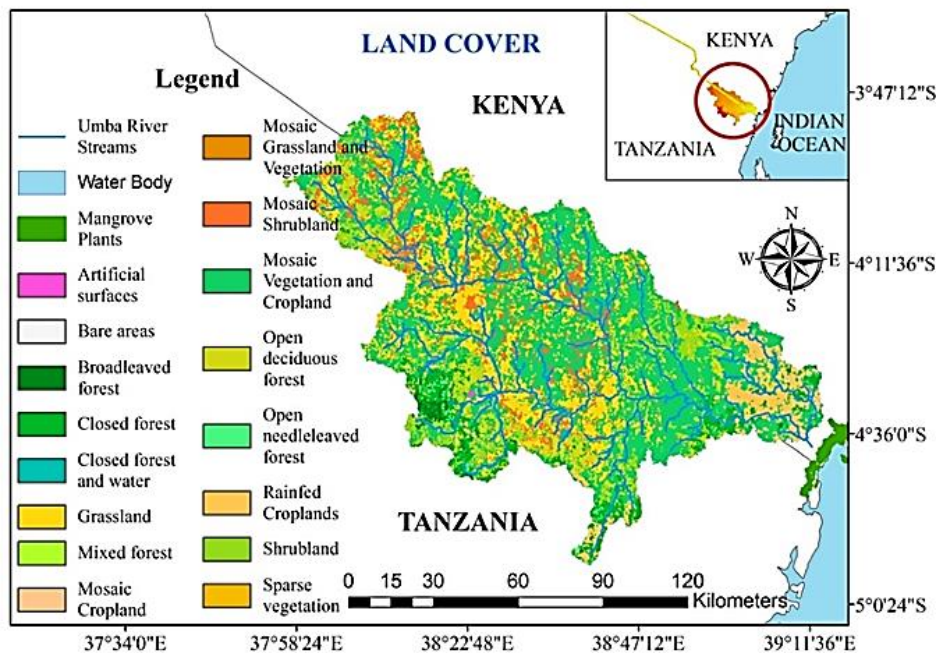


Figure 2. Land cover of the Umba River Basin

2010). Hydrologic models have been developed and used to fulfil various desirable needs with the purpose of managing water resources and watersheds (Sok and Oeurng, 2016).

Rainfall–runoff modelling. Rainfall–runoff modelling describes complex surface and subsurface processes of the hydrologic cycle (Moradkhani and Sorooshian, 2009; Kherde, 2016). It involves various parameters that define the characteristics of a watershed and its climatic conditions (Rathod *et al.*, 2015) and sets of equations that describe those processes to estimate the surface runoff generated from the watershed (Devia *et al.*, 2015; Ramly and Tahir, 2016). The various components synthesised are infiltration, soil-moisture storage, groundwater percolation, evapotranspiration, surface runoff, and sub-surface flow. Outflow from a sub-basin is computed from rainfall data by subtracting losses, transforming excess precipitations into the surface runoff, and adding base flows (Tahmasbinejad *et al.*, 2012).

Rainfall-runoff models are generally classified as empirical, conceptual, and physically based models on the basis of the hydrological processes and model input parameters. According to the spatial structure and the extent of physical principles applied to the models, they are categorized as lumped, distributed and semi-distributed models (Beven, 2012; Sitterson *et al.*, 2012; Devia *et al.*, 2015; Sintayehu, 2015).

Empirical or data-driven models. These are observation oriented models that depend on input data accuracy from statistical relationships between inputs and outputs without considering the features and processes of the hydrological system. On the other hand, conceptual or parametric models describe the hydrological processes using simplified components and equations. Physical based (process-based or mechanistic) models use principles of physics and a large number of parameters to describe the

physical characteristics of the system. Lumped models do not consider spatial variability of parameters and the entire river basin is taken as one unit. In semi-distributed models, parameters are processed by dividing the catchment into smaller areas. However, distributed models process the spatial variability by using parameters incorporated in high resolution grid cells (Beven, 2012; Sitterson *et al.*, 2012; Vaze *et al.*, 2012; Devia *et al.*, 2015; Kherde, 2016).

Rainfall-runoff modelling may be applied for a variety of design purposes and for providing information to support decision making in water and land management (Mokhtari *et al.*, 2016). It helps to assess the spatial and temporal catchment yields, to understand the response to climate variability and land use, to interpret water availability and seasonal flow characteristics, to estimate and forecast flows, to supplement streamflow data, to infill data gaps, and to assess environmental flows (Moradkhani and Sorooshian, 2009; Devia *et al.*, 2015; Kherde, 2016). Rainfall-runoff modelling involves calibration and validation for simulating streamflows. Calibration is the process of adjusting model parameters to reduce the error between the simulated streamflow and the observed flow record. Model validation uses the calibrated model parameters to estimate runoff for periods outside the calibration period (Vaze *et al.*, 2012).

In addition to good input data, selection of an appropriate hydrologic model is important for a good estimation of streamflow from a watershed. With increased understanding of the hydrological processes and computational technique, rainfall-runoff models have become more advanced. The choice of an appropriate model, therefore, depends on the purpose of the modelling, nature of the system to be modelled, availability of input data, applicability of the model, and accuracy of the output (Vaze *et al.*, 2012; Devia *et al.*, 2015).

Hydrologic Modelling System (HMS).

The Hydrologic Modelling System (HMS) is developed by the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers (USACE). It is designed to simulate various hydrological processes in a wide variety of watershed types. The program has extensive features including a graphical user interface with data entry utilities, database, computation engine, and results reporting tools. Tabular and graphical results from multiple elements and simulation runs can be viewed, printed, and stored in the output Data Storage System (DSS) file (USACE, 2016).

HEC-HMS has four main components; basin model, meteorological model, control specifications, and data input manager (USACE, 2016). The basin model consists of the elements of the basin and sub-basin that describe the catchment properties. The meteorological model helps to assign the data provided in the data input manager to the hydrologic elements of the basin. The control specifications are used to set the starting and ending dates and the simulation time steps of the rainfall-runoff processes (Sintayehu, 2015; Ramly and Tahir, 2016; Bhuiyan *et al.*, 2017).

The watershed model is developed by dividing the hydrologic cycle into various atmospheric and land surface components such as precipitation, evapotranspiration, snowmelt, solar radiation, canopy interception, surface depression storage, infiltration, surface runoff, and baseflow. Additional hydraulic components include inflows, channel routing, channel losses, diversion structures, and reservoirs (USACE, 2016). These components are represented by sub-basin elements; sources, river reaches, junctions, sinks, reservoirs and diversions (Bhuiyan *et al.*, 2017). They are used to compute the rainfall-runoff processes such as losses, runoff transform, and channel routing using basin characteristics, analysis of meteorological data, and parameter estimation

(Choudhari *et al.*, 2014; Rathod *et al.*, 2015; Mokhtari *et al.*, 2016; Thakur *et al.*, 2017).

HEC-HMS can be used to simulate the precipitation-runoff processes of dendritic catchment systems for a broad range of hydrologic problems and diverse water management applications (Thakur *et al.*, 2017). Several studies have used HEC-HMS for rainfall-runoff modelling in a wide range of geographic areas and climatic conditions (Abushandi and Merkel, 2013). Both single event and continuous hydrological modelling can be done to simulate rainfall-runoff processes (Bhuiyan *et al.*, 2017). The model has given reliable results in predicting spatial and temporal watershed responses as well as simulating various scenarios of river flows (Choudhari *et al.*, 2014; Mokhtari *et al.*, 2016; Sok and Oeurng, 2016).

HEC-HMS Model Setup. The estimation of streamflow along the Umba River was carried out by developing a rainfall-runoff model using the Hydrologic Modelling System (HMS). Watershed and meteorology information were combined to simulate the hydrologic responses. Like other physically-based hydrologic models, HEC-HMS simulates most of the key hydrologic processes at a watershed scale. The model is based on bulk parameter optimizations to the physical laws governing infiltration, soil-moisture accounting, and surface runoff. The processes involved in this study are setting the modelling objectives, model selection, data collection and analysis, model development, calibration process, model validation, and analysis and interpretation of the results.

Data collection and analysis. Topographic map of the study area (scale 1:50,000) was obtained from the Survey of Kenya, Nairobi. A 30m resolution DEM of the Umba River basin and its surrounding areas were obtained from USGS (United States Geological Survey) Earth Explorer website (<https://earthexplorer>.

usgs.gov). The catchment characteristics were estimated with the application of GIS, based on the digital elevation data. Land cover of the basin was obtained from (<http://www.esa.int/duie/ionia/globcover>), GLOBCOVER website prepared by the European Space Agency - Data User Element (ESA-DUE). Soil data of the basin was obtained from the Soil and Terrain (SOTER) database (<https://www.isric.org/explore/soter>) of the International Soil Reference and Information Centre (ISRIC).

Rainfall and daily river flow data were obtained from the Water Resources Authority (WRA), Nairobi. The rainfall data were collected from two meteorological stations at Vanga and Mwena. The streamflow data include the observations from the flow gauging station (3KG01) located near the town of Lunga-Lunga. However, the rainfall and daily flow data had missing records and poor areal representation in the basin. Daily measurements on precipitation, atmospheric pressure, relative humidity, air temperature, solar radiation, and wind speed were collected from the National Aeronautics and Space Administration (NASA) for Prediction of Worldwide Energy Resource (POWER) website (<https://power.larc.nasa.gov/>). Analysis of the streamflow and climate data involved checking data record consistency and selecting reliable data from the available record. The data analysis was performed using Microsoft Excel, HEC-DSSvue, and Hydrognomon.

Model development. To simulate the rainfall-runoff process of the Uмба River Basin, a semi-distributed and continuous hydrological model was developed using HEC-HMS version 4.2.1. The model was structured with the four main components: basin model, meteorological model, control specifications, and data input manager. In order to simulate the hydrologic processes, the model required various hydrologic parameters of the basin for input to the model components (Sintayehu, 2015; Ramly and Tahir, 2016; USACE, 2016).

HEC-GeoHMS integrated with ArcGIS software and Watershed Modelling System (WMS) were used to develop the basin model. The various atmospheric and land surface components of the hydrologic cycle were represented by sub-basin elements. The hydrologic elements contain the modelling components that describe canopy interception, surface storage, infiltration, surface runoff, and baseflow. The hydraulic components include source inflows, channel routing, channel losses, and outflows. These were represented by sources, reaches, junctions, and sink (outlet). Their principal purpose is to break the watershed into manageable pieces and convert the atmospheric conditions into streamflow at specific locations in the watershed. The basin model, hence provided the physical representation of the watershed by connecting the hydrologic elements and the hydraulic components in a dendritic network.

The basin model stored the physical datasets describing the catchment properties and was the primary component for visualizing the hydrologic elements and the topology of the stream network that represent the watershed (Bhuiyan *et al.*, 2017). In the process of the hydrologic model development, the spatial distribution information was derived from the 30m grid resolution DEM of the study area based on WGS 84 - UTM zone 37S. ArcGIS 10.1 was used for the spatial data preparation, to delineate the basin and generate the stream networks. In order to increase the performance of the model, the catchment was divided into 11 sub-basins (Figure 3) making a semi-distributed model.

The delineation of the watershed and sub-basins was carried out based on the automatic delineation procedure available in ArcHydro and HEC-GeoHMS extensions (USACE, 2013). The WMS was then used for extracting the basin characteristics of the river basin such as sub-basin features (area, slope, centroid, and elevation) and river characteristics (length, slope, and centroid). These physical characteristics of the

sub-basins and streams were used to estimate the hydrologic parameters of the basin model. By specifying a control point at the downstream outlet (location of the gauging station), the downstream boundary for the HEC-HMS project was defined. Finally, sub-basin and stream data derived from WMS were imported to the basin model of HEC-HMS. The resulting hydrologic elements (Figure 4) comprise 11 sub-basins, 11 junctions, 10 reaches and a sink (outlet).

Model Configuration. The evapotranspiration computations were carried out using INSTAT version 3.37 based on the Penman-Monteith method (Stern *et al.*, 2006). Daily precipitation and evapotranspiration of each sub-basin and observed river flow data of the basin outlet

were then added to the time series data manager component. The meteorological model was then used to define the time-variable boundary conditions of the sub-basins. The precipitation and evapotranspiration data were distributed spatially and temporally over the river basin using the user-specified hyetograph method (USACE, 2016). The observed flow data was assigned to the outlet of the basin to be used for calibration of the model. The control specifications manager was used to set the starting and ending dates and the simulation time step used in the rainfall-runoff processes. The control times were specified with one day step starting from July 01, 1983 up to December 31, 1985, for model calibration and from January 01, 1986 up to March 31, 2018 for model validation.

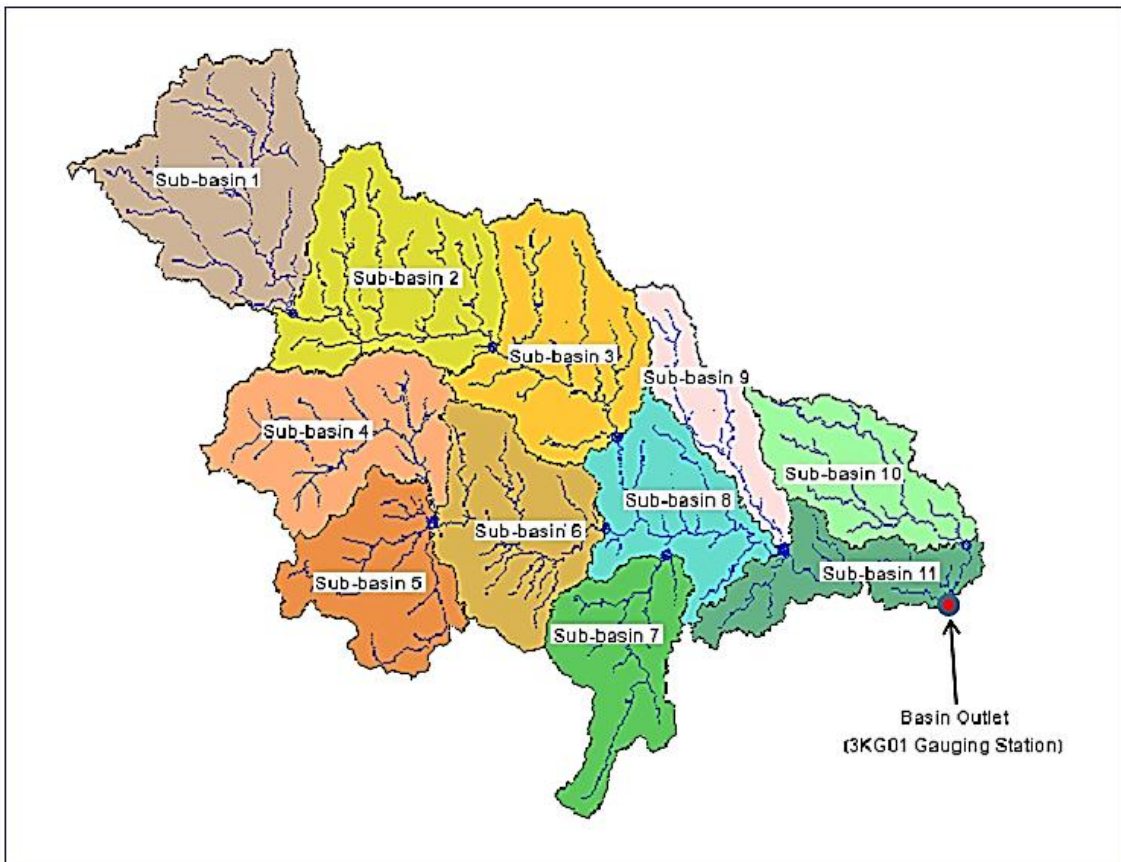


Figure 3. Umba River Sub-basins used in the Rainfall-Runoff Modelling

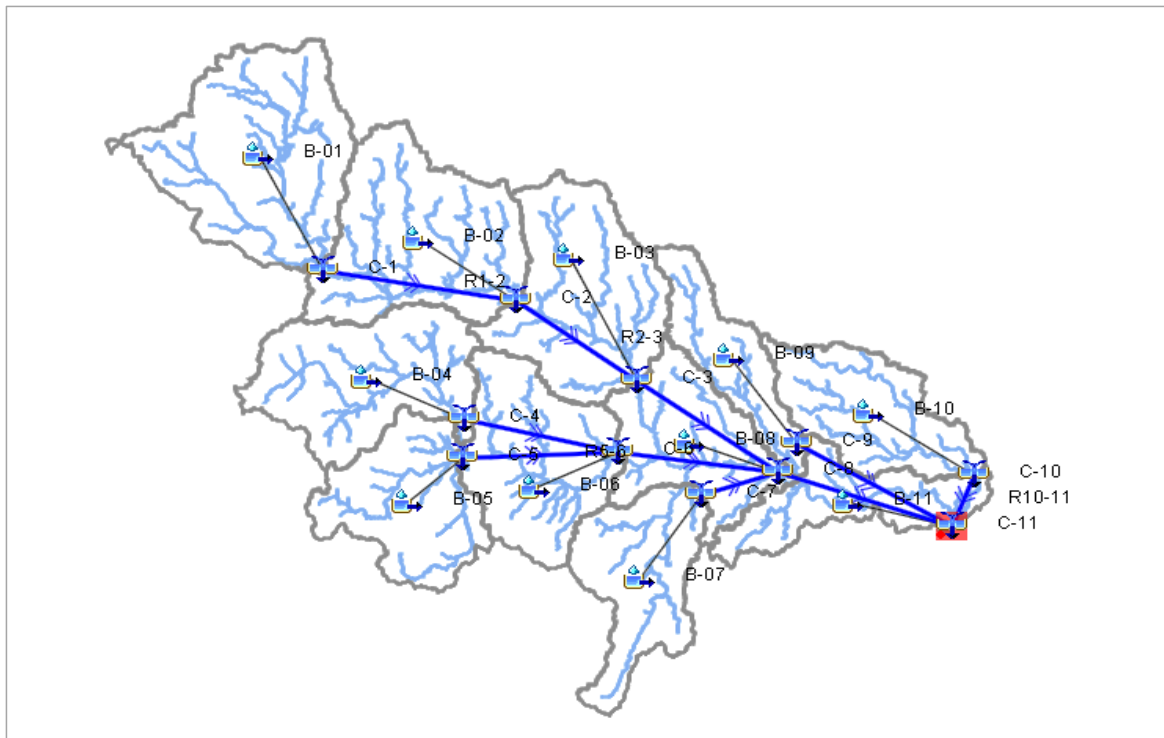


Figure 4. HEC-HMS Basin Model Setup for the Uмба River Basin (B = sub-basin element, C = junction element, and R = reach element)

Simple Canopy and Simple Surface methods were used to compute water interceptions on the vegetation and the ground surface. In these methods, all precipitations that arrive on plant canopy and the soil surface are captured until their storage capacities are filled. To transform the precipitation into the surface runoff, Soil Conservation Survey (SCS) Unit Hydrograph method was adopted. This method provides a generalized unit hydrograph that defines the shape of the runoff response using parameters of the flow. In order to evaluate the amount of water subtracted from surface runoff, soil moisture accounting method was used. This method uses three layers; soil storage, upper groundwater, and lower groundwater to represent the water movement dynamics in the soil. Parameters related to moisture conditions of the drainage basin were inserted to the model to calculate

the water loss in the three layers. This method is commonly applied with canopy and surface methods in continuous runoff modelling. The Lag routing method was used to describe how the water flows down the river channel. Recession method was adopted to represent the base flow pattern and identification of the base flows and recession rates were done by the analysis of the observed flow.

Model calibration and validation. Input parameters that define the geometry of streams and catchment were considered constant during the model simulation. Parameters that determine the state of the catchment and flow domain and that vary during the simulation were optimized (Beven, 2012). The estimation of the state parameters was carried out with reference to the range of values provided in HEC-HMS. Calibration of the model involved adjusting the

model parameter values to improve the match between the simulated results and the observed streamflow records. Automated optimization in conjunction with manual calibration was used to determine the optimum range of the parameter values. The optimization process began with initial parameter estimates and their values were adjusted until the simulated streamflow results matched the observed discharge as closely as possible.

Double mass curve analysis was used to measure the goodness-of-fit between the simulated streamflow and observed records. The slope of the trend line and the coefficient of determination (R^2) were used to assess the model performance. The calibration process was repeated, by adjusting the model parameters, until the values of the trend line and the coefficient of determination approached one. Then a simulation run was created by combining the basin model, meteorologic model, and control specification. The calibrated model, with the best fit parameter values, was used in

the validation process. The model calculated the rainfall-runoff response of the basin and provided daily time series of the river flow.

RESULTS AND DISCUSSION

Hydrological data analysis. In order to have an adequate understanding of the catchment's water balance, it was necessary to analyse the precipitation, temperature, and evapotranspiration of the basin. The annual average precipitation in the area was 877 mm with a maximum of 1297 mm received in 1997 and a minimum of 485 mm recorded in 2003 (Figure 5). From the spatial distribution of the rainfall, areas in the southwest of the basin received a higher annual rainfall of about 1030 mm while the areas on the north-western part of the basin received a lower annual rainfall of about 780 mm. The sharp rising of the Usambara Mountains probably gives rise to the increased rainfall in the southwest part of the basin.

Analysis of the historical rainfall distribution was conducted using Standardized Precipitation

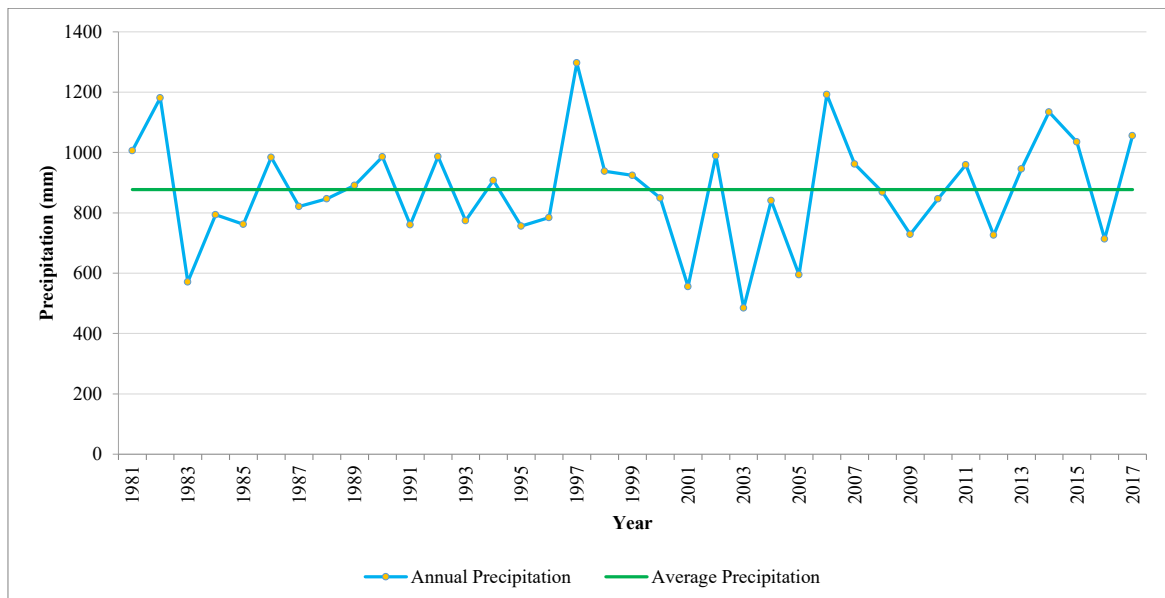


Figure 5. Annual precipitation in the Umba River Basin (1981-2017)

Index (SPI), a measure of deviation between a given rainfall value and the overall mean of the rainfall data (WMO-GWP, 2016). The SPI can be used to describe rainfall variability and to indicate the number of standard deviations that a rainfall event deviated from the average (Equation 1). The classification for the wetness and dryness of each year was done based on the classification scale given in Table 1, as suggested by Hayes *et al.* (1999). The SPI result, presented in Figure 6, indicated that the years 1997 and 2003 were extremely wet and extremely dry, respectively. The years 1982 and 2006 were

very wet while the years 1983, 2001, and 2005 were very dry. The annual rainfall in 2014 was moderately wet and the remaining years were found having normal rainfall distributions.

$$SPI = \frac{(P_a - P_m)}{\sigma} \quad (1)$$

Where: SPI = Standardized Precipitation Index, P_a = Annual Precipitation (mm), P_m = Mean Precipitation (mm), and σ = Standard Deviation (mm).

Table 1. Classification scale for SPI values

SPI Values	Category
More than 2.00	Extremely Wet
1.50 to 1.99	Very Wet
1.00 to 1.49	Moderately Wet
-0.99 to 0.99	Normal
-1.00 to -1.49	Moderately Dry
-1.50 to -1.99	Very Dry
Less than -2.00	Extremely Dry

Source: Hayes *et al.* (1999)

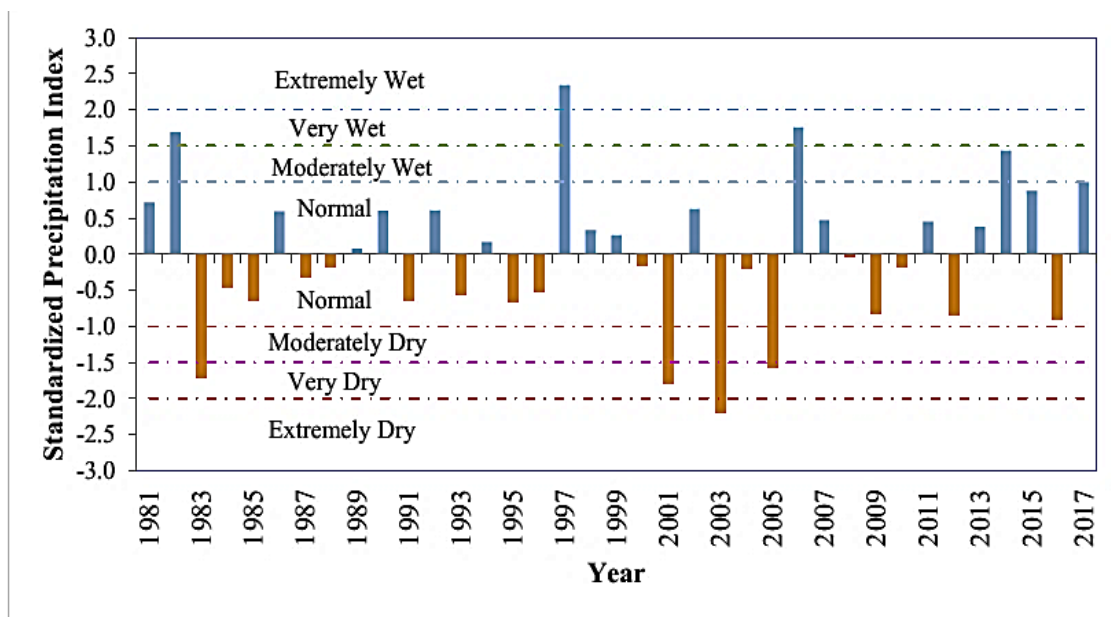


Figure 6. Annual standardized precipitation index for the Uмба River Basin (1981 to 2017)

The monthly precipitation (Figure 7) of the Umba River Basin indicates that the primary rainy season is from March to May and the short rains fall from October to December. The mean, minimum, and maximum temperatures of the basin were analysed to get an overview of their seasonal distributions. The average annual temperature in the study area was 24.21°C with the average maximum temperature of 35.36°C and the average minimum temperature of 14.27°C. Due to the high mean temperatures across the region, the rate of evapotranspiration was high with a mean value of 6.30 mm/day. The monthly temperature and evapotranspiration (Figure 7) results showed similar trends with their values incr up to July.

The Umba River has one flow gauging station (3kg01) on the Kenyan part of the river. It is located on the downstream side of a bridge near the town of Lunga-Lunga. Daily water levels in the river have been monitored at the gauging

station since 1966. The stage-flow rating curve (Figure 8) was developed by fitting the river flows measured from the gauging station to a rating curve equation using solver in Microsoft Excel. The goodness-of-fit between the rating curve equation (Equation 2) and the observed data was determined by the coefficient of determination (R^2), obtained as 0.984. The daily discharge of the river was computed from the measured stage using the rating curve equation.

$$Q = 1.64 (H - 0.054)^{2.8} \quad (2)$$

The flow data was further analysed, as shown in Figure 9, to check for the percentage of missing streamflow records. The result shows that the majority of the available records cover the period from 1966 to early 1987. In addition to some data gaps existing within the observation period, there is a large period (1988 to 2017) with a high percentage of missing flow records.

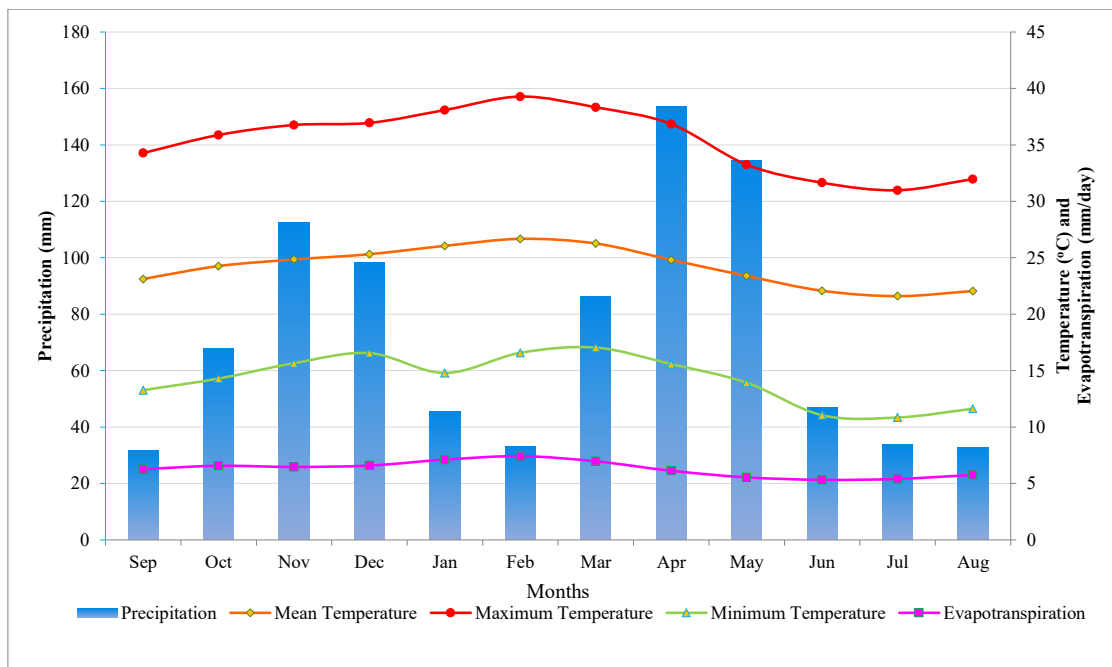


Figure 7. Monthly precipitation, temperature, and evapotranspiration in the Umba River Basin (1981-2017)

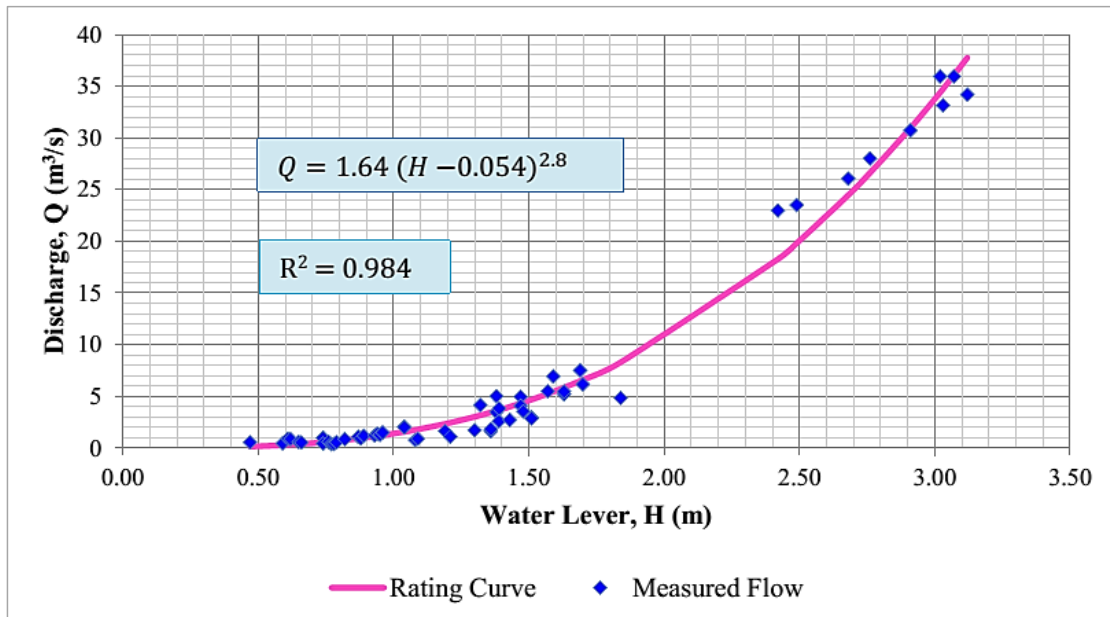


Figure 8. Stage-flow rating curve for 3kg01 gauging station located near Lunga-Lunga

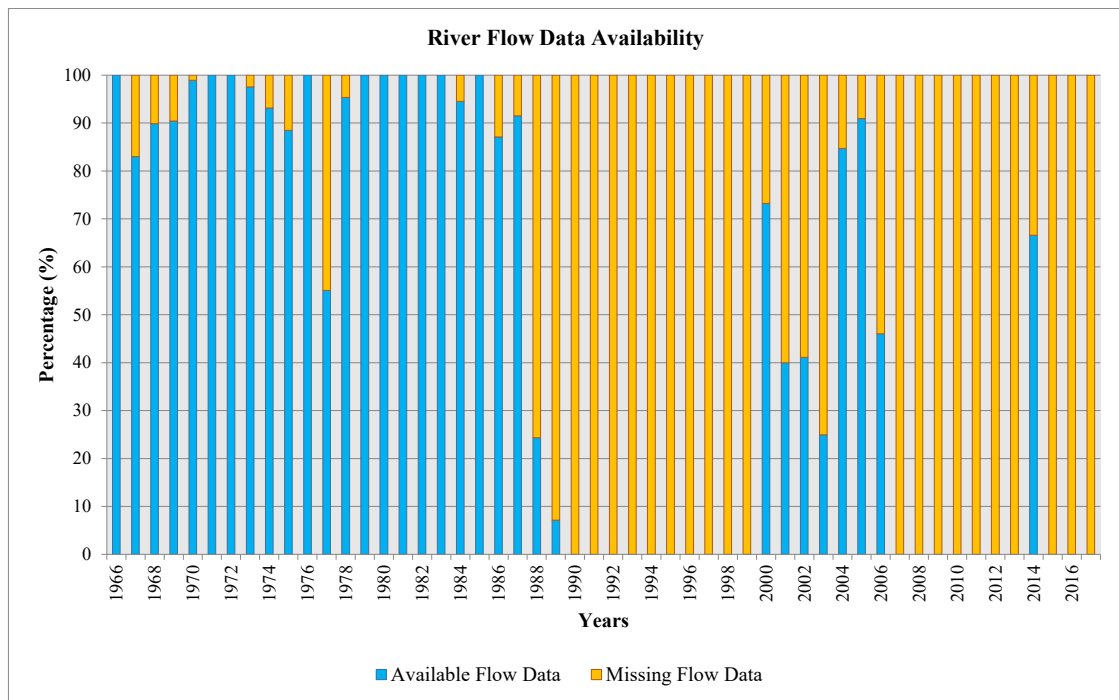


Figure 9. River Flow data availability for 3kg01 gauging station

Rainfall-runoff modelling results. The rainfall-runoff model developed using HEC-HMS was used to produce an estimate of the streamflow from the Umba River basin. Hydrological parameters such as precipitation, evapotranspiration, catchment characteristics, and soil properties were input to each sub-basin. The catchment and stream characteristics extracted from WMS are presented in Table 2. These physical parameters define the geometry of the sub-basins and streams in the basin model. Parameters that determine the state of the catchment and flow domain and that vary during the simulation were optimized during the model calibration process. Table 3 presents the state parameters of sub-basin 1 optimized during the model simulation. These parameters were used to estimate the losses (canopy interceptions, surface storages, infiltrations, and groundwater percolations), to transform the precipitation into the surface runoff, to describe the water flows in the river channels, and to represent the base flow patterns. Similar optimized parameter results were obtained for all the other sub-basins.

The outflow from the basin was computed from the rainfall data by subtracting the losses, transforming the excess precipitations into the

surface runoff, and adding the base flows. The combined hydrographs for the daily observed flow data (measured at 3kg01 gauging station) and the daily simulated results computed from HEC-HMS are presented in Figure 10. From the graphical comparison of the simulated and observed hydrographs, the model generated more peak flows.

The quantitative measure for the goodness-of-fit between the computed outflow and observed streamflow was done using the double mass-curve analysis (Figure 11). After the last optimization trial, the slope of the trend line and the coefficient of determination (R^2) were determined as 1.16 and 0.96, respectively. These values were used to evaluate the overall performance of the model for the calibration period (1983 to 1985) and it was found satisfactory. Points plotted on the 45-degree line (slope = 1) indicate the computed flow is exactly equal to the observed flow. However, from the analysis, the slope of the trend line is more than one, which suggests that the simulated flow was higher than the observed flow. The coefficient of determination provided a statistical measure of how close the computed outflow and observed streamflow were to the fitted regression line.

Table 2. Catchment and Stream Characteristics of the Umba River Basin

Sub-basin	Average Area (km ²)	Sub-basin Slope (%)	Mean Elevation (m)	Centroid Stream Distance (km)
1	968.58	9.40	730.06	33.65
2	855.07	8.74	613.04	35.48
3	786.66	10.26	503.87	24.24
4	729.85	13.46	618.47	32.63
5	556.45	26.85	1167.59	13.88
6	664.00	9.64	421.83	28.23
7	519.62	13.63	423.16	26.84
8	538.67	10.19	271.80	29.66
9	346.15	14.16	363.40	33.74
10	510.65	12.70	156.10	31.73
11	409.69	11.59	119.40	33.89

Table 3. State Parameters of Sub-basin 1 Optimized during the simulation of the HMS Model

S. N.	Parameters	Units	Minimum value	Maximum value	Optimized value
1	Simple Canopy - Initial Storage	%	0.001	100	0.12
2	Simple Canopy - Max Storage	mm	0.01	1500	3.48
3	Simple Surface - Initial Storage	%	0.001	100	0.30
4	Simple Surface - Max Storage	mm	0.01	1500	12.50
5	Soil Moisture Accounting - Initial Soil Content	%	0.001	100	5.86
6	Soil Moisture Accounting - Initial GW1 Content	%	0.001	100	18.06
7	Soil Moisture Accounting - Initial GW2 Content	%	0.001	100	55.06
8	Soil Moisture Accounting - Max Infiltration	mm/hr	0.01	500	8.68
9	Soil Moisture Accounting - Soil Storage	mm	0.01	1500	78.75
10	Soil Moisture Accounting - Tension Storage	mm	0.01	1500	56.64
11	Soil Moisture Accounting - Soil Percolation	mm/hr	0.01	500	8.06
12	Soil Moisture Accounting - GW1 Storage	mm	0.01	1500	98.66
13	Soil Moisture Accounting - GW1 Storage Coefficient	hr	0.01	10000	23.26
14	Soil Moisture Accounting - GW1 Percolation	mm/hr	0.01	500	11.26
15	Soil Moisture Accounting - GW2 Storage	mm	0.01	1500	264.06
16	Soil Moisture Accounting - GW2 Storage Coefficient	hr	0.01	10000	46.46
17	Soil Moisture Accounting - GW2 Percolation	mm/hr	0.01	500	26.46
18	SCS Unit Hydrograph - Lag Time	min	0.01	1440	164.16
19	Recession - Initial Discharge	m ³ /s	0.01	100	1.12
20	Recession - Threshold Discharge	m ³ /s	0.01	100	1.29
21	Recession - Recession Constant	-	0.01	1	0.82
22	Lag - Lag	min	0.01	1440	200.14
23	Constant - Flow Rate	m ³ /s	0.01	100	0.59
24	Constant - Fraction	-	0.001	1	0.19

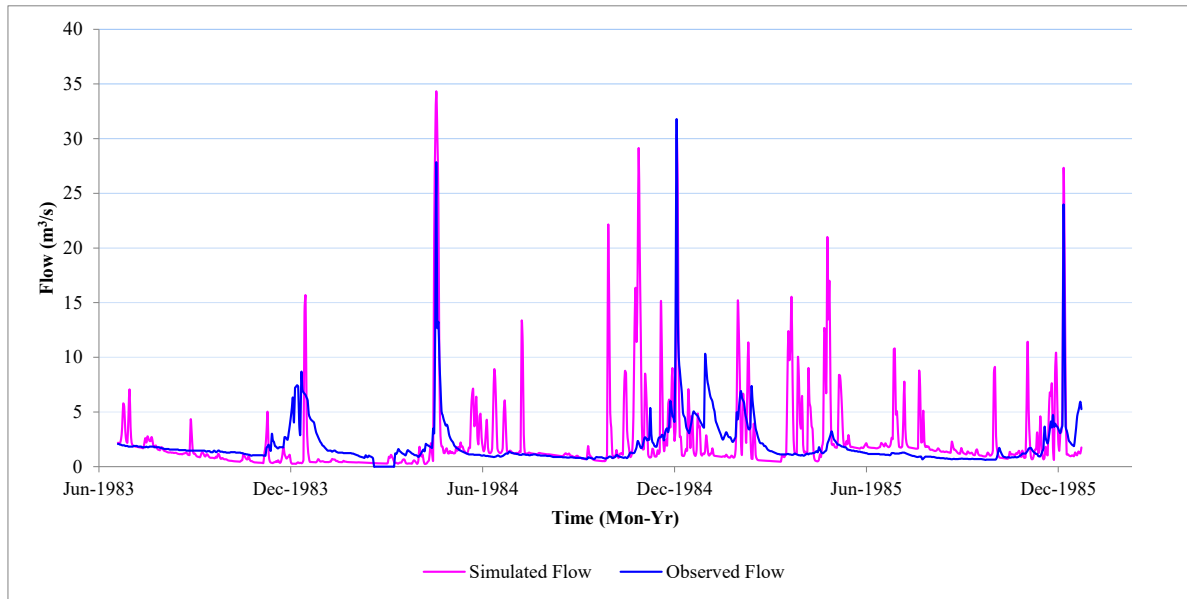


Figure 10. Daily observed and simulated time series for model calibration using HEC-HMS at 3kg01 gauging station

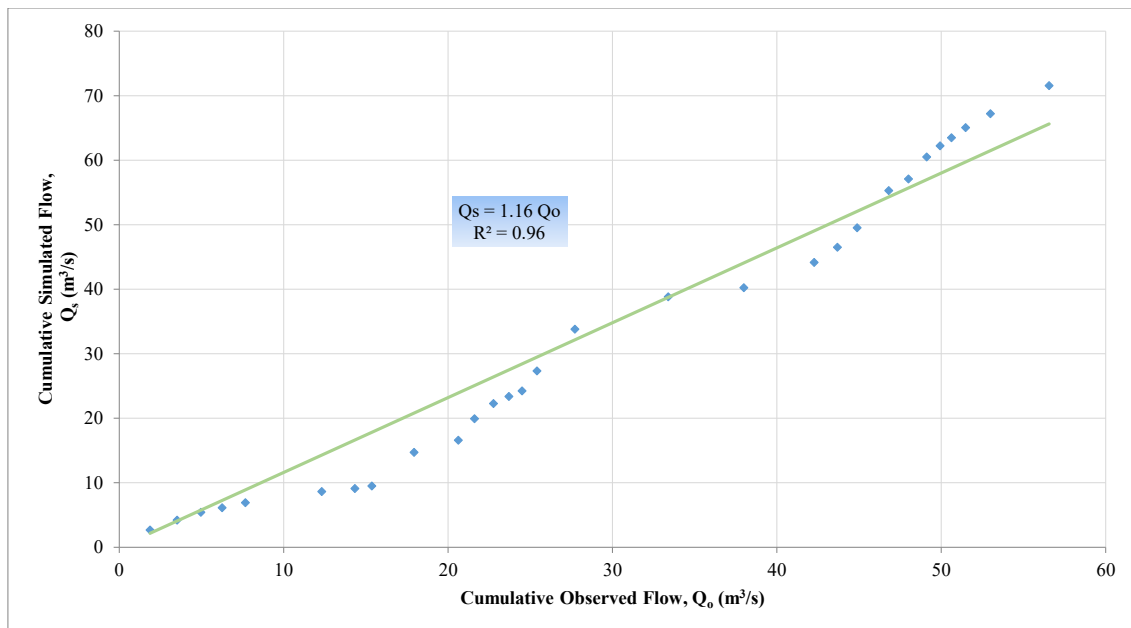


Figure 11. Double mass-curve for flow comparison of the simulated and observed flows during model calibration at 3kg01 gauging station

The optimized parameter values obtained during the model calibration process were used for simulation of the rainfall-runoff response of the basin in the validation period. The simulation was performed to estimate the discharge for infilling the missing records and to extend the flow data of the river. Daily time series of discharge of the Umba River basin was estimated for the entire duration of the validation time defined in the control specification. As shown in Figure 12, the daily simulated flow covered the period of 01/01/1986 to 31/03/2018 and the daily observed flow is distributed from 01/01/1986 to 30/11/1987.

The quantitative measure for the goodness-of-fit between the computed outflow and observed streamflow was done using the mass-curve (Figure 13). The slope of the trend line

and the coefficient of determination (R^2) were determined as 1.16 and 0.94, respectively. These values were used to evaluate the overall performance of the model for the validation period (1986 to 2017) and it was found satisfactory.

The HEC-HMS hydrologic modelling approach was adopted to generate the continuous time series of daily streamflow for the last 30 years. The hydrographs created by the program can be used for studies of water availability, flow regulation, and other water management plans. Moreover, the hydrological model is helpful to understand the hydrological processes with the help of spatial and temporal data of rainfall, catchment characteristics and other climate data (Gao *et al.*, 2018).

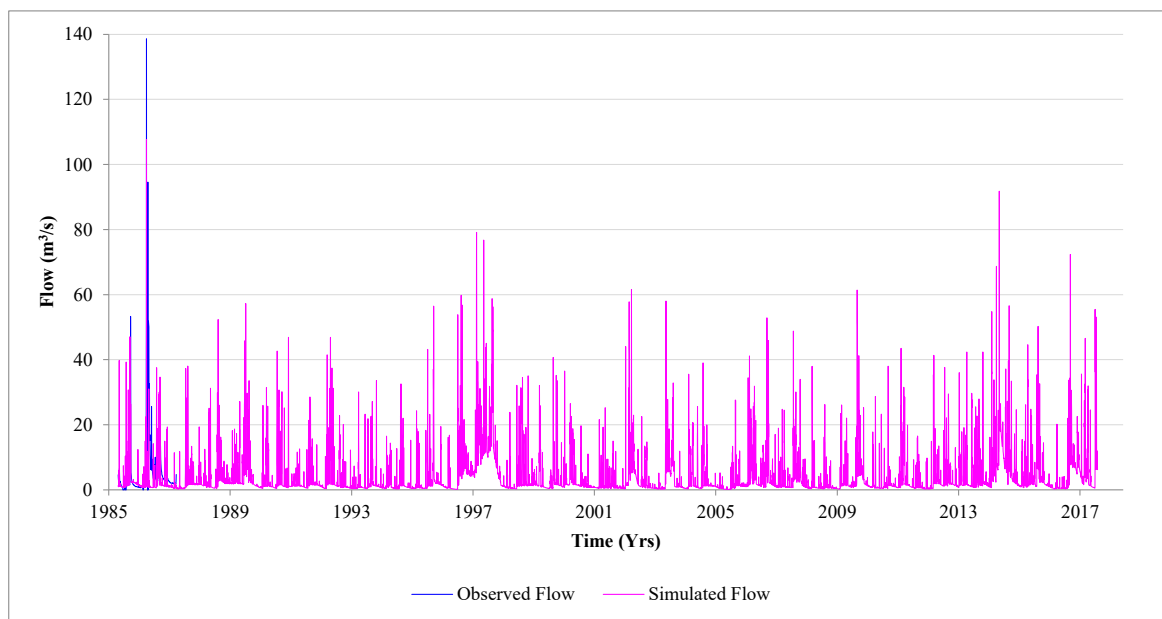
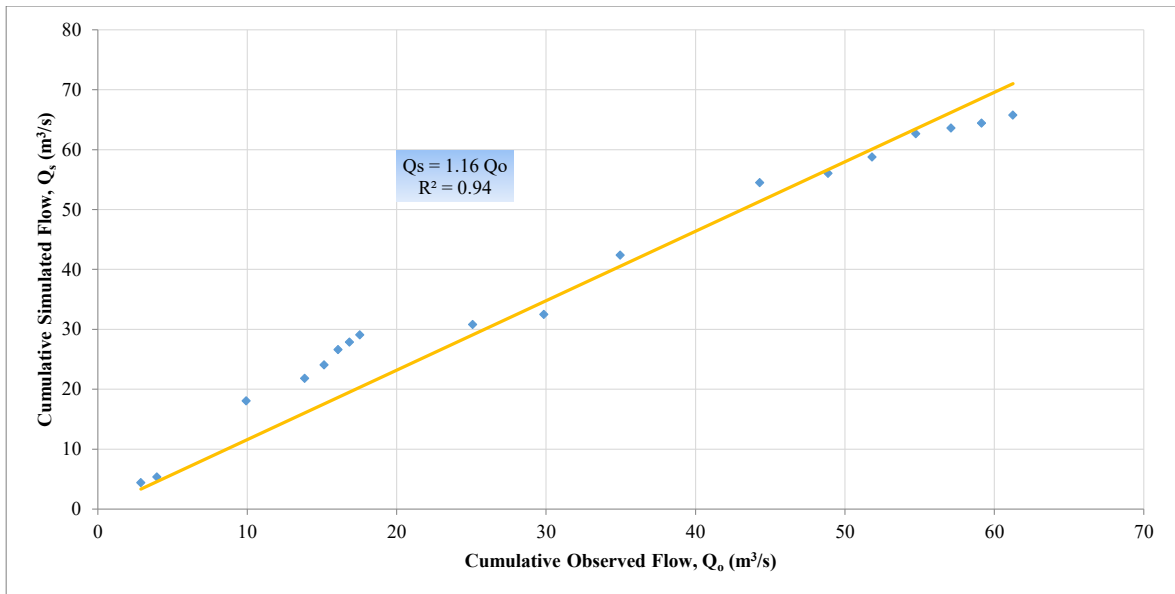


Figure 12. Daily observed flow and simulated streamflow for model validation using hec-hms at 3kg01 gauging station



CONCLUSIONS

In this study, HEC-HMS hydrological model was developed to execute the rainfall-runoff process of the Umba River basin. The calibration of the model was carried out by comparing the computed runoff with the observed flow records. The quantitative measure for the goodness-of-fit between the computed outflow and observed streamflow was done using double mass-curve analysis. The slope of the trend line and the coefficient of determination (R^2) were obtained as 1.16 and 0.96 for the Model Calibration and 1.16 and 0.94 for the Model Validation. The model performance was thus found satisfactory to simulate the basin runoff and generate continuous time series of daily streamflow in the last 30 years. The model provided reliable results to infill the missing records and to extend the streamflow data of the river. The results of the model and the measured flow records can be used for planning water development projects and managing water resources to meet developmental and environmental needs.

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STATEMENT OF NO-CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in this paper.

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