*International Journal of Environment and Climate Change*

***Volume 14, Issue 4, Page 719-738, 2024; Article no.IJECC.115515***
***ISSN: 2581-8627***
*(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)*

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# Rainfall-runoff Modelling Using MIKE11 NAM Model for Ravishankar Sagar Catchment, Chhattisgarh, India

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

***Article Information***

DOI: 10.9734/IJECC/2024/v14i44153

**Open Peer Review History:**
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/115515

***Original Research Article***

***Received: 24/02/2024***
***Accepted: 29/04/2024***
***Published: 03/05/2024***

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## ABSTRACT

Estimating rainfall-runoff within a catchment is inherently intricate and crucial for water resource planning via hydrological evaluations. The study focuses on utilizing the MIKE 11 NAM model to simulate rainfall-runoff dynamics within the Ravishankar Sagar Reservoir catchment in the Chhattisgarh state. In order to ensure accurate estimation, data on stream flows from 2004 to 2015 was used for calibration, and from 2016 to 2020 was used for validation. The MIKE 11 NAM model accurately predicted daily runoff and adequately reproduced the hydrological response of the Ravishankar Sagar watershed to rainfall. The calibrated model outputs were good to employ in the water resources management model, specifically for MIKE BASIN. During calibration, the optimal values of the nine NAM model parameters were determined and subsequently employed in the simulation. The reliability of the MIKE 11 NAM model was assessed for the study area using the

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Coefficient of Determination ($R^2$) and the Nash–Sutcliffe Efficiency Index (EI). The sensitivity analysis helped to determine the most important model parameters. $R^2$ values of 0.730 and 0.704 were obtained from the model's calibration and validation, respectively. With an Efficiency Index of 81%, the model demonstrated its efficiency and ability to forecast runoff for Ravishankar Sagar Reservoir over an extended period. This study helps to manage the water resource and to improve the reservoir operation policy for the reservoir.

*Keywords: MIKE 11 NAM; MIKE BASIN; simulation; Nash–Sutcliffe efficiency index.*

## ABBREVIATIONS

| | |
|---|---|
| *RSR* | *: Ravishankar Sagar Reservoir* |
| *CC* | *: Climate Change* |
| *$R^2$* | *: Correlation Determination* |
| *NSE* | *: Nash-Sutcliffe Efficiency* |
| *IMD* | *: India Meteorological Department* |
| *Avg* | *: Average* |
| *etc.* | *: Etcetera (so on)* |
| *et al.* | *: Et Alia (and others)* |
| *i.e.* | *: id est (that is)* |
| *mcm* | *: Million Cubic meter* |
| *Max* | *: Maximum* |
| *RF* | *: Rainfall* |
| *NSE* | *: Nash–Sutcliffe Efficiency* |
| *EI* | *: Efficiency Index* |

## 1. INTRODUCTION

Rainfall and runoff estimations are important for many reasons, including decision-making, policy-making, pollution management, flood forecasting, planning for water resources, and interbasin water transportation. Factors that affect rainfall-runoff modeling include soil types, watershed topography, evaporation, transpiration, abstraction, and distribution of precipitation [1]. A common hydrological challenge involves determining the runoff from a catchment in response to rainfall and guiding the runoff downstream through a river network. The relationship between rainfall and runoff is highly intricate and challenging due to numerous interconnected variables. Effective models typically perform optimally when provided with data on the physical attributes of the watershed at the grid scale of the model [2,3,4]. Due to its non-linear and multi-dimensional nature, rainfall-runoff modeling poses significant complexity [5]. The established models for predicting rainfall-runoff encompass the rational method [6], Soil Conservation Service-Curve Number Method [7] and Green - Ampt Method [8].

The watershed's characteristics, seasonal rainfall, and numerous other elements affect the runoff volume and flow rate at a river site throughout time. Many models, which can be categorized into "physical," "conceptual," and "black box" models, have been developed to simulate hydrological phenomena like the rainfall-runoff process. All these models have their own advantages and disadvantages as the requirements of data differ temporally as well as spatially. The duration also differs in these different methods as well. In 1972, the Danish Hydraulic Institute (DHI) developed the MIKE 11 NAM model, a conceptual and integrated model of rainfall-runoff that can simulate base, subsurface, and surface flow, in order to address these issues. The sensitivity analysis problem for the MIKE 11 NAM rainfall-runoff model is indicated in a broad multi-objective framework [9] using a unique sensitive analysis approach. Model calibration is necessary because the parameters of such models cannot be obtained directly from counts of quantifiable features of watersheds. Adjusting parameters by trial and error is a part of manual calibration. The actual and simulated hydrographs are visually compared as the basis for the calibration procedure in these cases. According to a predetermined search strategy and the resulting numerical measures of the goodness of fit, modelling parameters are automatically calibrated in auto-calibration [10]. The MIKE 11 NAM model has been widely utilized for rainfall-runoff modeling in diverse global regions, demonstrating its effectiveness, particularly in areas with limited data availability [11,12,13,14,15]. The MIKE 11 NAM model apply to an ungauged catchment in the Nzhelele River sub-quaternary catchment, successfully transferring parameters to achieve optimal results in rainfall-runoff modeling [16]. Another study conducted on a modeling of rainfall and runoff processes, incorporating the MIKE 11 NAM model alongside two other models, and achieved commendable results [17].

The NAM model applied to forecast runoff rates in the Liang River, situated in the northern region of Malaysia, achieving satisfactory results with the model's predicted values closely aligning with historical data [18]. SCS-CN and the MIKE 11 NAM model used compared two models for rainfall-runoff simulation in the Shipra River basin of Madhya Pradesh, India using four performance evaluation techniques, they found that the MIKE 11 NAM model performed better than the SCS-CN [19]. In a similar vein, study revealed how well the MIKE NAM rainfall-runoff model performed when simulating daily flows in the Gonbad catchment in Hamedan Promising results from their study revealed the effectiveness of the model at three different catchment stations [20].

The study area of the research is the catchment of Ravishankar Sagar Reservoir which is constructed on Mahanadi River in Dhamtari district of Chhattisgarh. The reservoir is one of the biggest reservoirs of Chhattisgarh state. The rainfall-runoff modelling for this reservoir is done with the help of Mike 11 NAM model which is a lumped, conceptual and deterministic model. This water of the reservoir is supplied to fulfil the irrigation, domestic and industrial demands of the Mahanadi basin. As the requirement of this basin increases rapidly, there is a need to calculate the availability of water and plan it accordingly.

## 2. STUDY AREA

The Mahanadi River is one of India's most significant river systems, comprising twelve main river basins. Situated in the upper reaches of the Mahanadi River is the Mahanadi Reservoir Project (MRP). The MRP complex consists of four reservoirs: Ravishankar Sagar, Dudhawa, Murumsilli, and Sondhur Reservoir. The first three reservoirs are situated in the Mahanadi Basin, while the last one is located in the Pairi basin on the Sondhur River. The reservoir is constructed on river Mahanadi in Dhamtari district of Chhattisgarh. The Ravishankar Sagar Project (RSP) is the name given to the three-reservoir system that is part of the Mahanadi basin. In the RSP system, Murumsilli and

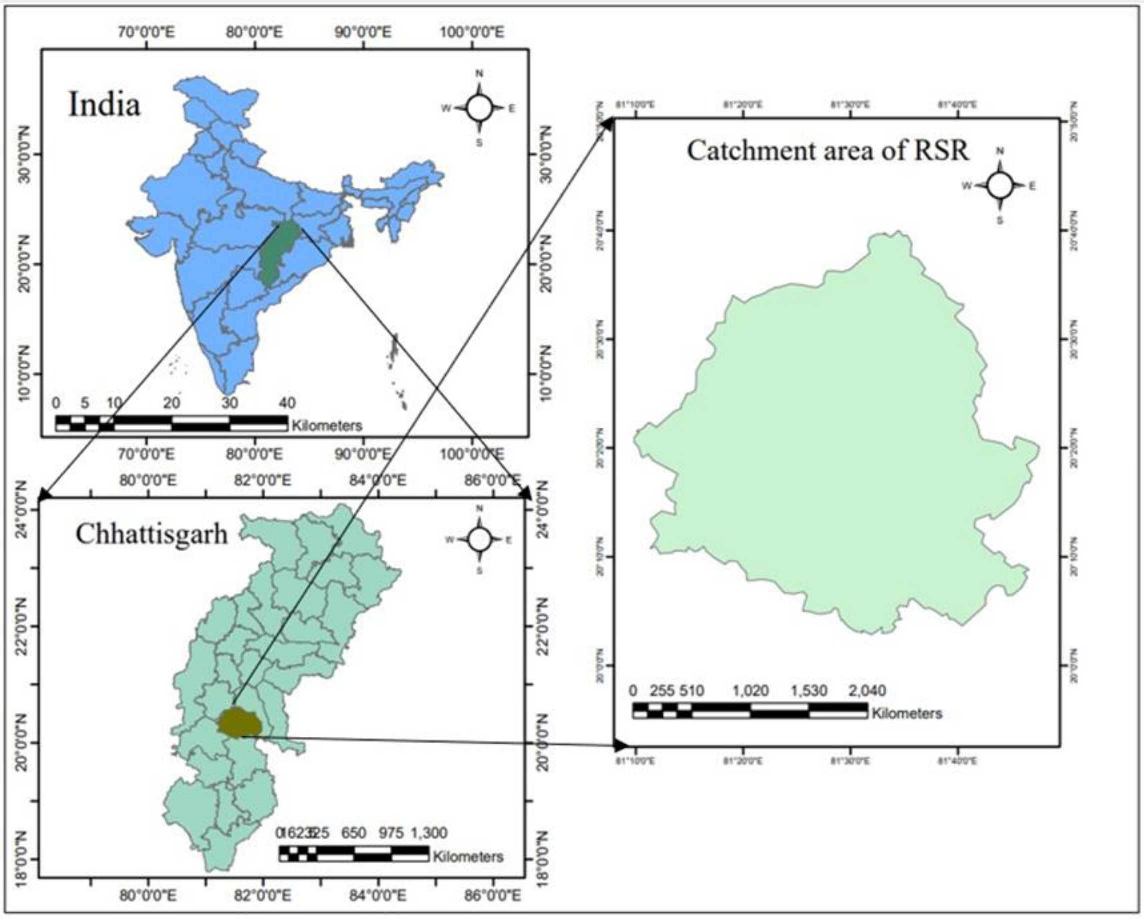

Fig. 1. Index map of Ravishankar sagar reservoir

Dudhawa reservoirs act as feeders to the Ravishankar Sagar reservoir. The one of the upstream reservoirs namely Murumsilli, do not have any irrigation demands and only storage regulation structure while the other reservoir, Dudhawa have separate irrigation demands. The reservoir was built primarily for irrigation and also for hydroelectricity, but it is now also used for drinking water and to supply the adjacent Bhilai Steel Plant in the district of Durg. The system is therefore a multiple-reservoir system with several uses. The Ravishankar Sagar Reservoir has been chosen to develop the rainfall runoff model. It is situated at latitude 20⁰37'00" N and longitude 81⁰34'00" E. With a catchment area of 2509 km$^2$, Ravishankar Sagar receives 1274.65 mm of rain on average annually. The index map of the Ravishankar Sagar Reservoir is displayed in Fig. 1. The topography of the basin is usually seen to be undulating and rolling. Soil that looks like black cotton covers most of the terrain. Nonetheless, the southern and northern sections of the study area have clay loam soil and sandy clay loam soil. The major rocks that may be found nearby are basalt, quartzite sandstone, lime stone, and sandstone. The principal land cover and land use, including bare ground, human settlements, forests, and agriculture. The principal crops grown during the Kharif and Rabi seasons, are Paddy and moong, chana respectively. The region's average lowest and maximum temperatures in May and June are 11.50°C and 40.70°C, respectively.

## 3. METHODOLOGY

### 3.1 Mike 11 Nam Model

The MIKE 11 module, developed by the Danish Hydraulic Institute (DHI) in Denmark, integrates the rainfall-runoff model called MIKE11 NAM. This program is designed to simulate water quality, sediment transport, and flow in various water bodies such as rivers, irrigation systems, and channels. As a component of the MIKE HYDRO program, the MIKE 11 NAM model functions as a deterministic, lumped, conceptual rainfall-runoff model. It maintains continuous monitoring of moisture content across three distinct storage compartments, representing overland flow, interflow, and base flow. [21]. Fig. 2 illustrates the physical procedures necessary for simulating runoff in the MIKE11 NAM model. This involves parameters and variables that depict average values for the entire sub-catchment, treating each sub-catchment as a unified unit. As a result, the model produces a continuous time series of the catchment's runoff throughout the modeling period. MIKE11 NAM accounts for peak and base flow conditions, considering soil moisture conditions throughout the modeled time period. The NAM model has been utilized in numerous catchments globally, assesing a range of hydrological regimes and climatic conditions. Researchers [22,23,24,25,18] and numerous others have conducted rainfall-runoff modeling using the MIKE 11 NAM model.

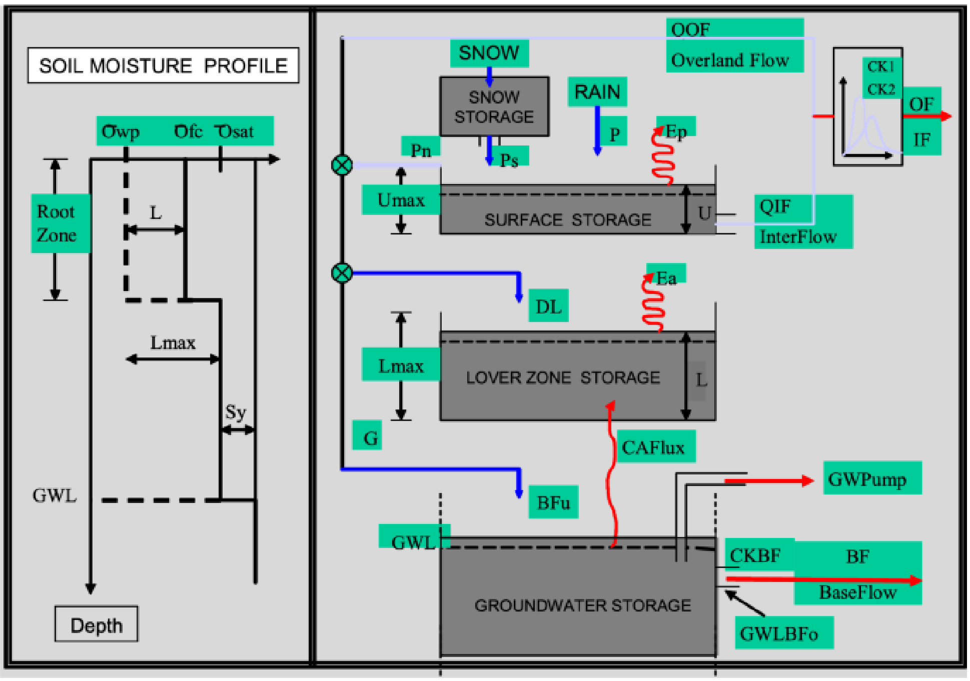

**Fig. 2. Structure and Processes of NAM Model**

**Table 1. Model parameter description and effects**

| Parameters | Unit | Specification | Effect |
|---|---|---|---|
| *Umax* | mm | Maximum water content in surface storage | Overland flow, infiltration, evapotranspiration, interflow |
| *Lmax* | mm | Maximum water content in lower zone/root storage | Overland flow, infiltration, evapotranspiration, base flow |
| *CQOF* | | Overland flow coefficient | Volume of overland flow and infiltration |
| *CKIF* | hrs | Interflow drainage constant | Drainage of surface storage as interflow |
| *TOF* | | Threshold for overland flow | Soil moisture required to be satisfied for overland flow to occur |
| *TIF* | | Threshold for interflow | Soil moisture required to be satisfied for interflow to occur |
| *TG* | | Threshold for groundwater recharge | Soil moisture required to be satisfied for groundwater recharge to occur |
| *CK1* | hrs | Timing constant for overland flow | Routing overland flow along catchment slopes and channels |
| *CK2* | hrs | Timing constant for interflow | Routing interflow along catchment slopes |
| *CKBF* | hrs | Timing constant for base flow | Routing recharge through linear groundwater recharge |

The NAM model incorporates a total of 9 parameters and features four storage layers, namely (i) snow, (ii) surface, (iii) lower zone, and (iv) underground, encompassing overland flow (QOF), interflow (QIF), and underground flow (QBF). The parameter Umax denotes the maximum capacity of water that can be stored on the surface.

Within the soil, the lower zone storage, denoted as L, represents moisture in the root zone - a layer of soil beneath the surface that vegetation can tap into for transpiration. Lmax signifies the maximum quantity of water this storage layer can hold. Initially, evapotranspiration demands are met at the potential rate from the surface storage. However, once surface storage exceeds its maximum capacity (U > Umax), surplus water from precipitation leads to both overland flow and infiltration. QOF denotes the proportion of precipitation that contributes to overland flow, while QIF is assumed to be directly proportional to U and fluctuates linearly with the relative moisture content of the lower zone storage. The interflow travels along a route through two parallel linear reservoirs sharing the same time constant, Ck1k2. Overland flow routing similarly utilizes the linear reservoir principle but with a variable time constant. The volume of infiltrating water, which replenishes groundwater storage G, depends on the moisture level of the soil in the root zone. The discharge from a linear reservoir with time constant CKBF is used to compute base flow (BF) originating from the groundwater storage. Table 1 shows a comprehensive overview of the parameters and their corresponding impacts.

## 3.2 Input Data

The MIKE11 NAM model relies on essential input data, primarily meteorological and discharge data, to facilitate model calibration, define catchment parameters, and establish initial conditions. The essential meteorological time series needed comprise precipitation and potential evapotranspiration. Based on this data, the model generates a time series of catchment runoff, demonstrating the evolution of subsurface flow contributions to the channel across time. Moreover, the model gives information about diverse elements of the land phase in the hydrological cycle, including soil moisture content and groundwater recharge. These outputs enrich the comprehension of hydrological dynamics within the catchment, augmenting the model's capability to simulate and scrutinize runoff behavior.

### 3.2.1 Rainfall

During the modeling process, daily rainfall data are collected from five rain-gauge stations (Mahod, Khajurawan, Birgudi, Murumsilli, and Gangrel) were employed for a sixteen-year period spanning from 2004 to 2020. To derive areal precipitation for the entire area, the Thiessen Polygon Method (1911) was applied to the point precipitation data from these rain-gauge stations. The ArcMap 10 software facilitated the calculation of areal precipitation, enabling a spatial representation that considers the influence of each rain gauge's coverage area. This method enhances the accuracy of estimating precipitation over the entire region by accounting for spatial variations based on the proximity of each rain gauge station. For the modeling phase, daily rainfall data from five rain-gauge stations—Mahod, Khajurawan, Birgudi, Murumsilli, and Gangrel—were utilized over a sixteen-year period spanning from 2004 to 2020. Using ArcMap 10 software, the areal precipitation for the area was computed from the point precipitation data employing the Thiessen Polygon Method (1911).

#### 3.2.2 Runoff

In the context of modeling rainfall runoff for the Ravishankar Sagar, gauge-discharge data spanning a sixteen-year period (2004 to 2020) was collected from Water Resource Department, Raipur Chhattisgarh. To ensure the reliability and consistency of the rainfall and runoff records, an assessment was conducted. This process included determining the correlation coefficient between the two time series and calculating the runoff coefficients for annual runoff. These measures of correlation and runoff coefficients were examined to gauge the degree of association between rainfall and runoff patterns. The evaluation of these statistical parameters served as a crucial step in validating the data before proceeding with the construction of the rainfall-runoff model, providing confidence in the data's suitability for modeling purposes.

#### 3.2.3 Potential evapotranspiration

In the development of the MIKE 11 NAM model, potential evapotranspiration (ETo) plays a crucial role as it significantly influences runoff through surface evaporation. ETo was estimated using the CROPWAT 8.0 software, which employs the Penman Monteith Method (1965). This method considers meteorological parameters such as temperature, wind speed, humidity, and sunshine hours to calculate potential evapotranspiration. The climatological data from the meteorological department of Indira Gandhi Krishi Vishwavidyalaya in Raipur, Chhattisgarh, was utilized to gather the necessary meteorological information for ETo estimation. By incorporating these climatic variables into the Penman Monteith Method through the CROPWAT 8.0 software, an estimation of potential evapotranspiration was derived. This information contributes as a key input to the MIKE 11 NAM model, providing insights into the water loss through evapotranspiration in the modelled area.

### 3.3 MIKE 11 NAM Model Setup

The MIKE 11 NAM model was set for the Ravishankar Sagar reservoir, situated within the Mahanadi River basin, featuring a catchment area of 2509 km² and an average annual rainfall of 1229 mm. Rainfall-runoff modeling was conducted using the MIKE ZERO software, which facilitated the conversion of daily input data for rainfall, runoff, and potential evapotranspiration spanning sixteen years (2004 to 2015) into dfso format. This dfso format was then applied to the model development process. The input data for the model encompassed daily records of rainfall, runoff, and potential evapotranspiration at the Ravishankar Sagar for the entire sixteen-year period, extending from 2004 to 2020. During the calibration phase of the NAM model, parameters were fine-tuned to achieve a close match between the simulated and observed stream flow data. This calibration process ensures that the model accurately captures the hydrological behavior of the Ravishankar Sagar catchment, thereby enhancing its reliability and predictive capabilities.

### 3.4 Model Calibration

The process of standardizing predicted values is referred to as calibration. During calibration, deviations between predicted and observed values for a specific area are scrutinized to calculate correction factors. These correction factors are subsequently applied to adjust predicted values, thereby aligning them more closely with observed values. In the case of the MIKE 11 NAM model, the calibration process extended over eleven years, from 2004 to 2015, subsequent to the input of pertinent data.following the input of relevant data. Utilizing the NAM model's automatic calibration option, model parameters underwent adjustments to enhance the model's accuracy during this calibration period. The auto calibration option streamlined the parameter tuning process. The optimal parameters obtained through automatic calibration were further verified using trial and error methods. These refined parameters were then employed in calculating runoff from the Ravishankar Sagar.

The calibration phase involved testing the model for the selected time period (2004 to 2015), and model statistics from calibration and validation outputs were analyzed. This examination served to confirm the model's effectiveness in predicting runoff. The MIKE11 NAM model was successfully set up for the Ravishankar Sagar reservoir, incorporating input data and undergoing calibration for eleven years (2004 to 2015). The calibrated model parameters, as detailed in Table 6, fell within their specified ranges. This set of refined parameters aimed to achieve the best fit, enabling the model to simulate runoff with a high level of agreement with observed runoff.

### 3.5 Model Validation

Model validation involves evaluating the performance of the calibrated model using a portion of historical records that were not utilized during the calibration process. Following the calibration phase, the MIKE 11 NAM model underwent validation for the final four years, encompassing the period from 2016 to 2020. During validation, the model was run without the auto-calibration mode, employing the set of refined model parameters acquired during the calibration period. The primary goal during validation was to simulate runoff using the calibrated model and assess its performance against observed data. By comparing the simulated results with actual runoff data, statistical analyses of the simulated output were conducted. This process aimed to confirm that the calibrated model could effectively replicate the observed runoff patterns, providing confidence in its predictive capabilities. In summary, model validation is a crucial step to ensure that the calibrated model performs well on data not used in the calibration process, thus enhancing its reliability for predicting runoff beyond the calibration period.

### 3.6 Accuracy Criteria

The efficiency index (EI), and coefficient of determination ($R^2$) can all be used to evaluate the model's accuracy. The coefficient of determination is used to evaluate a model's goodness of fit and determine how well it accounts for and forecasts future events. It is represented as a number between 0 and 1. The following equation was used to determine the MIKE 11 NAM model's coefficient of determination ($R^2$):

$$\mathrm{R}^2 = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}}(\mathrm{q_0} - \bar{\mathrm{q}}_0)(\mathrm{q_0} - \bar{\mathrm{q}}_s)}{\sum_{\mathrm{i=1}}^{\mathrm{n}}\ (\mathrm{q_0} - \bar{\mathrm{q}}_0)^2(\mathrm{q_0} - \bar{\mathrm{q}}_s)^2} \qquad (1)$$

Where, $q_o$= observed flow, $\overline{q}_o$= mean value of observed flow, $q_s$= simulated flow and $n$ = number of data points. The value of efficiency index lies between 0 to 1. The efficiency index equal to 1 indicates the best performance of the model.

The reliability of the model was evaluated on the basis of Efficiency Index (EI) as described by the Nash and Sutcliffe. EI is directly proportional to errors in the model's input data and is dependent on errors in the model, such as missing data or inconsistent data. The formula below was used to obtain the efficiency index:

$$\mathrm{EI} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}}(\mathrm{q_0} - \bar{\mathrm{q}}_0\ )^2 - \sum_{\mathrm{i=1}}^{\mathrm{n}}(\mathrm{q_0} - \mathrm{q}_s)^2}{\sum_{\mathrm{i=1}}^{\mathrm{n}}(\mathrm{q_0} - \bar{\mathrm{q}}_0\ )^2} \qquad (2)$$

Where, $q_o$= observed flow, $\overline{q}_o$= mean value of observed flow, $q_s$= simulated flow and $n$ = number of data points. The value of efficiency index lies between 0 to 1. The efficiency index equal to 1 indicates the best performance of the model.

### 3.7 Sensitivity Analysis

The MIKE11 NAM model is systematically evaluated to determine the sensitivity of its output to variations in individual parameters. In this case, the model was run multiple times, each time with one parameter set as a variable while keeping the other parameters constant. The chosen parameter's values from the calibrated model were then adjusted by both increasing and decreasing them by 20%.

By systematically varying each parameter and observing the resulting changes in model output, sensitivity analysis helps identify which parameters have the most significant impact on the model's behavior. This analysis is valuable for understanding the relative importance of different parameters and their influence on the model's predictions. Sensitivity analysis contributes to refining the model and improving its accuracy by highlighting the parameters that have the most substantial impact on the modeled system.

### 3.8 SPI (Standardized Precipitation Index)

Seasonal and annual Standardized Precipitation Index (SPI) values for the period between 2004

**Table 2. Parameter description of Standardized Precipitation Index (SPI)**

| Categories | Wet Year | Normal Year | Dry Year |
|---|---|---|---|
| Standardized Precipitation Index (SPI) | >0.5 | -0.5 to 0.5 | <-0.5 |

and 2020 were calculated for 5 stations situated in Ravishankar Sagar Catchment, based on various threshold values outlined in Table 2 Shiau and Wu [26,27]. The results are illustrated in Fig. 4. Over the 18-year study period, the area has encountered prolonged spells of either dry or wet conditions annually, spanning at least 18 years. On an individual basis, these areas have undergone 8 years of drought and 7 years of heightened precipitation, with some instances being particularly severe. Significantly, nearly all stations have witnessed both extreme wet and dry conditions.

The calculation of the Standardized Precipitation Index (SPI) involves normalizing the deviation of seasonal-monthly rainfall from the long-term mean by its standard deviation. Mathematically, it is represented as:

$$\text{SPI} = \frac{X_{ij} - X_{im}}{\sigma} \tag{3}$$

Here, $X_{ij}$ represents the seasonal-monthly rainfall at the i-th station and j-th observation, $X_{im}$ signifies the long-term rainfall mean, and $\sigma$ is the standard deviation. To effectively capture climatic variability signals, the determination of SPI requires a minimum of 30 years of long-term rainfall data. This duration is considered necessary as shorter periods may not provide a robust representation of the climatic patterns [27,28].

## 4. RESULTS

The MIKE 11 NAM model was developed utilizing the daily rainfall data from the five rain gauge stations Mahod, Khajurawan, Birgudi, Murumsilli and Gangrel to perform rainfall-runoff modeling at Ravishankar Sagar with a catchment area of 2509 Km$^2$. Fig. 3 displays the study area's Thiessen polygon map. Khajurawan and Birgudi are the two raingauge stations that have the greatest influence and cover the largest ground out of the five. Table 2 presents the weights of rain gauge stations relative to their corresponding representative areas. Additionally, Fig. 4 illustrates the distribution of monthly rainfall, and Table 3 presents a statistical analysis of yearly and seasonal rainfall.

From the analysis of the monthly rainfall distribution illustrated in Fig. 4 indicates that the southwest monsoon significantly influences the region's total annual precipitation, contributing approximately 97% of the annual rainfall. This underscores the significant impact of the monsoon season on the overall precipitation in the research area.

According to the statistical analysis provided in Table 3, the average annual rainfall in the research area is reported to be 1229 mm. Additionally, the average seasonal rainfall is recorded at 1154 mm. These figures contribute to a comprehensive understanding of the region's precipitation patterns, emphasizing the dominance of the southwest monsoon in shaping the annual and seasonal rainfall characteristics. The seasonal rainfall in the research region varied from 14.27 to 27.93, indicating a moderate fluctuation in rainfall. The coefficient of variance for the annual rainfall varied from 13.34 to 25.41 in Khajurawan to Murumsilli, with an almost similar pattern as seasonal Rainfall. The standard deviation range of the annual rainfall between 151 and 305 mm was found to be the for all five stations.

### 4.1 Relation Between Rainfall and Runoff

The correlation between rainfall and runoff represents a widely adopted approach in hydrology. Different researchers have developed various methods for simulating the rainfall-runoff process. Researchers established a runoff-rainfall relationship, subsequently validating it using a statistical mode [28]. While this phenomenon bears similarities to those observed in rural settings, its manifestation in urban areas typically occurs on a smaller temporal and spatial scale compared to rural environments. [29].

In another study titled "On the Influence of the Spatial Distribution of Rainfall on Storm Runoff," the aim is to assess the importance of precipitation accuracy in the rainfall-runoff modeling of a small catchment. [30]. The extent of interflow depends on the geological characteristics of a given catchment, as interpreted by Subramanya [32], providing fundamental insight into runoff generation with regard to climate conditions, particularly rainfall and infiltration [31].

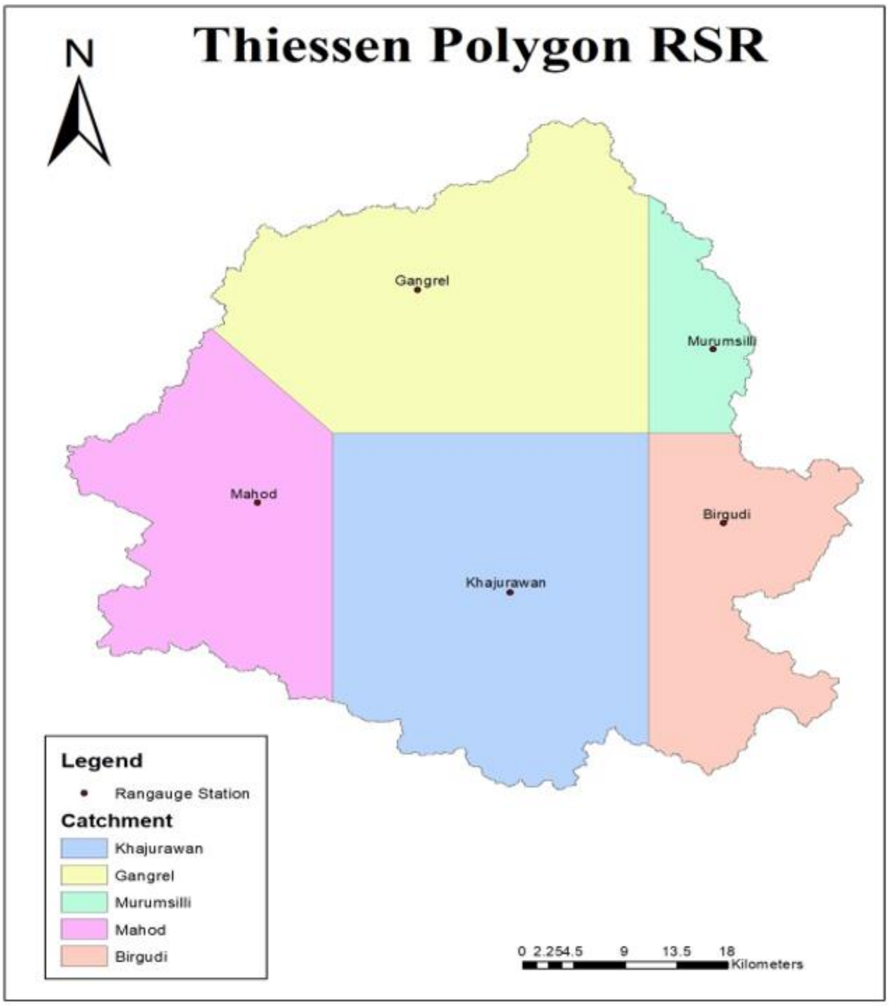

Fig. 3. Thiessen weights for raingauge stations

**Table 3. Thiessen weights for raingauge stations**

| Station | Raingauge Station | Weights |
|---|---|---|
| 1 | Mahod | 0.134 |
| 2 | Khajurawan | 0.229 |
| 3 | Birgudi | 0.288 |
| 4 | Murumsilli | 0.213 |
| 5 | Gangrel | 0.136 |

**Table 4. Statistical analysis of annual and seasonal rainfall**

| Station | Annual rainfall | | | Seasonal rainfall | | |
|---|---|---|---|---|---|---|
| | Mean (mm) | Standard deviation (mm) | Coefficient of variance | Mean (mm) | Standard deviation (mm) | Coefficient of variance |
| Mahod | 1309 | 282 | 21.58 | 1221 | 234 | 19.13 |
| Khajurawan | 1257 | 215 | 17.14 | 1162 | 205 | 17.66 |
| Birgudi | 1240 | 214 | 17.31 | 1159 | 182 | 15.73 |
| Murumsilli | 1136 | 151 | 13.34 | 1072 | 153 | 14.27 |
| Gangrel | 1201 | 305 | 25.41 | 1156 | 323 | 27.93 |
| Average | 1229 | 234 | 18.96 | 1154 | 219 | 18.94 |

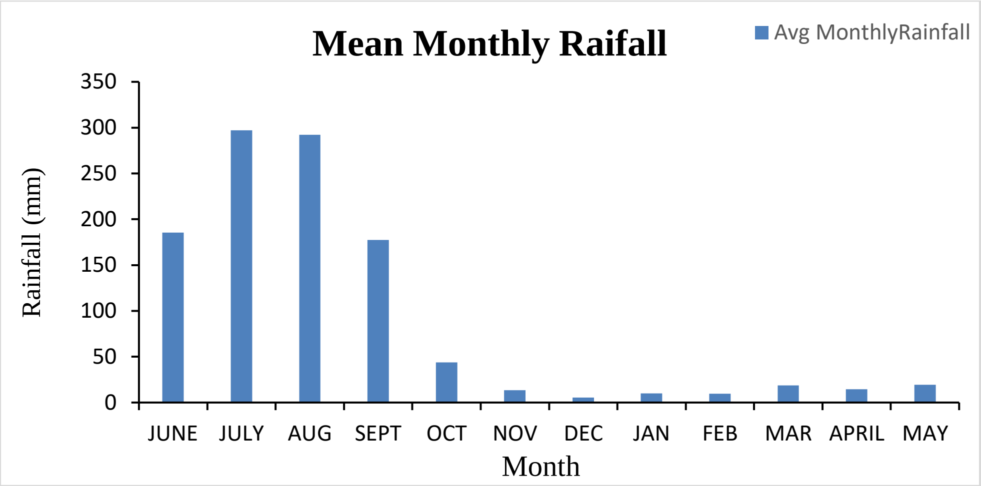

Fig. 4. Mean monthly rainfall of study area

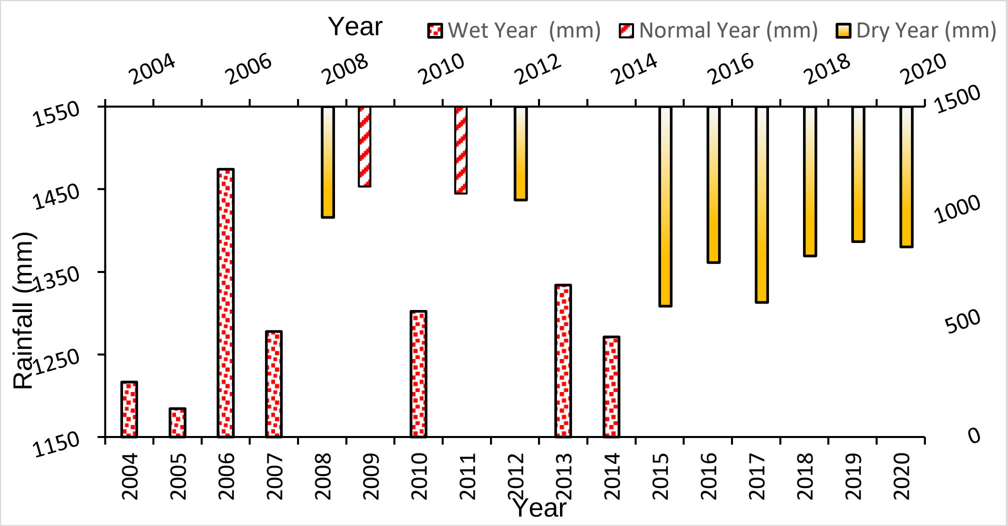

Fig. 5. Annual Rainfall of the study area in different years

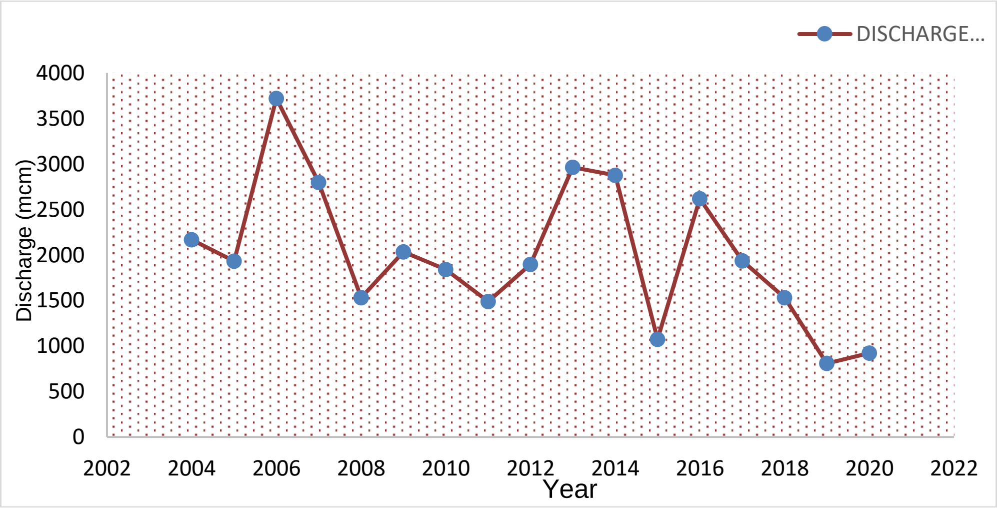

Fig. 6. Annual Runoff of Study Area in different years

The findings of this research lead to the inference that SPI serves as a crucial indicator for assessing the changes over time and the spatial distribution of dry and wet conditions across a region. Using annual rainfall data from 5 stations spanning the years 2004 to 2020, this investigation examined the annual variations in dry and wet conditions in the central region of Chhattisgarh. Fig. 5 shows the variation in annual rainfall from 2004 to 2020. During the study period from 2004 to 2007 and 2013, 2014 years are comes under wet years, while 2015 to 2020 were dry years and 2009 and 2011 were Normal years based on the SPI index Shiau and Wu [26,27].

Fig. 6 shows the variation of Runoff from years 2004 to 2020 it was found that maximum Runoff occurred in the year 2006 i.e. 3720.09 MCM while minimum Runoff was 808.07 MCM in year 2019.

From this Fig. 7 the values of Rainfall and runoff for the Wet year is clearly shown. In year 2006, the runoff is equal to rainfall which shows that as the runoff increases with increase in rainfall.

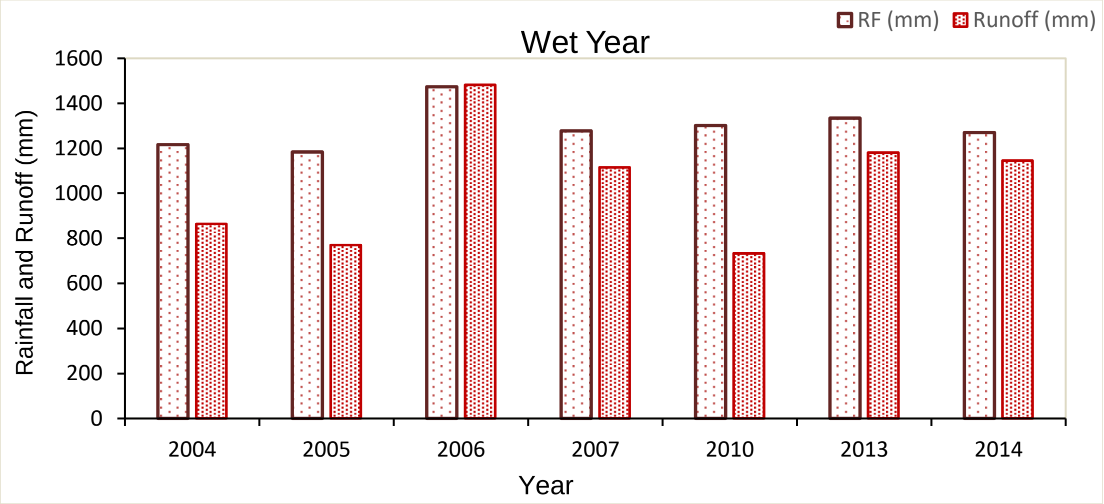

**Fig. 7. Annual Runoff of Study Area in during wet year**

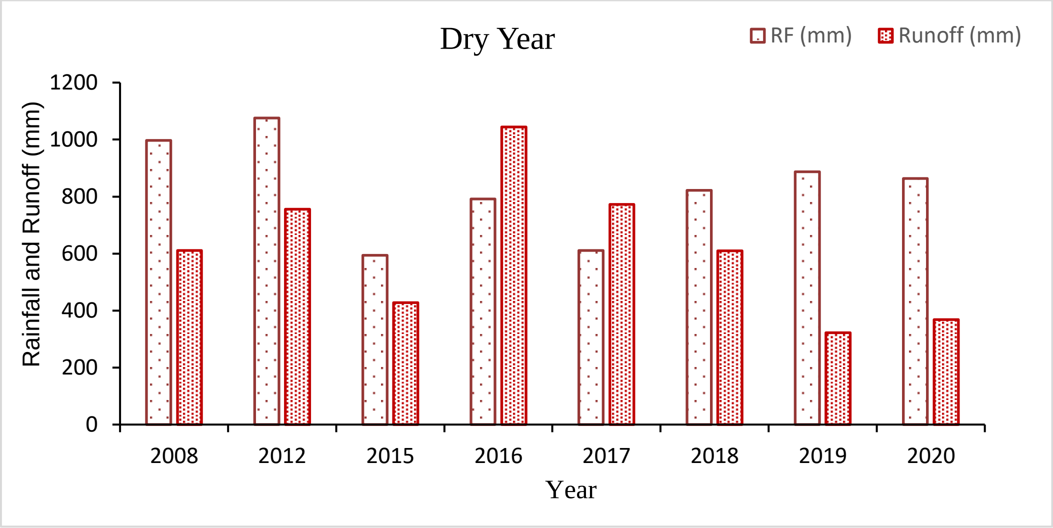

**Fig. 8. Annual runoff of study area in during dry year**

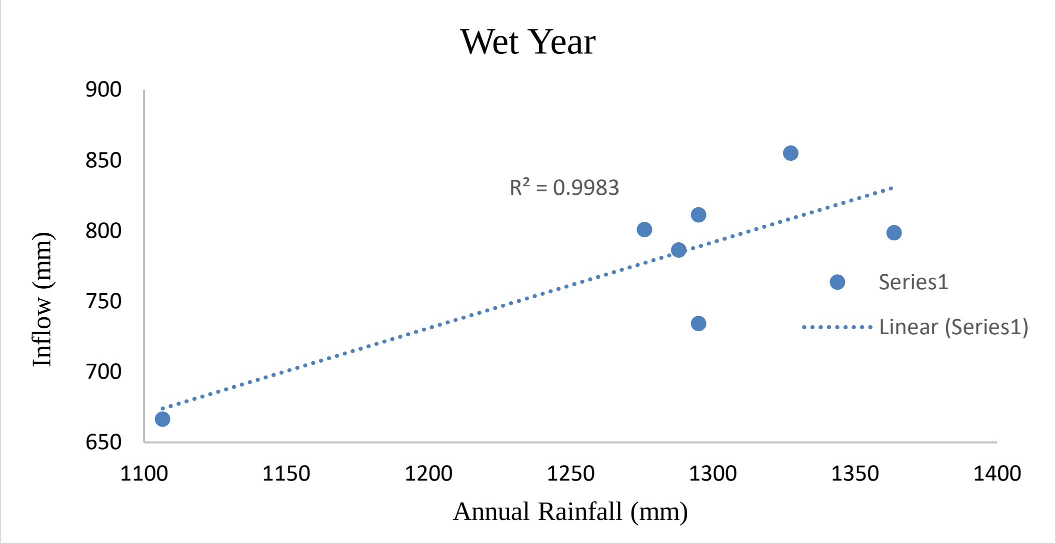

**Fig. 9. Linear relation between rainfall and runoff in wet years**

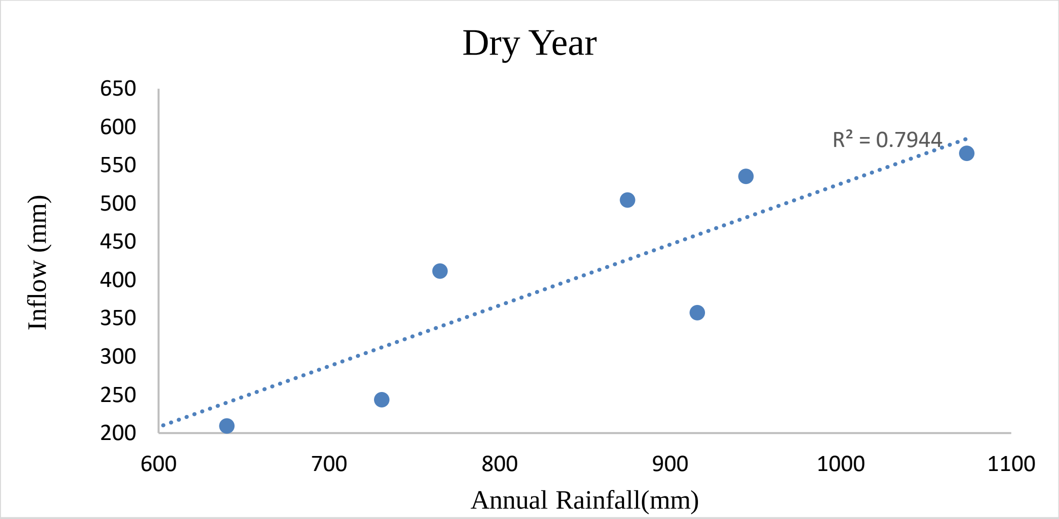

**Fig. 10. Linear relation between rainfall and runoff in dry years**

The relationship between precipitation and runoff offers a comprehensive understanding of how annual runoff varies with changes in rainfall across the Ravishankar Sagar Catchment in Chhattisgarh. Furthermore, the study establishes an association between annual Rainfall and runoff. These relationships were visually represented through graphs and tables. The graph analysis reveals a robust correlation in the annual rainfall-runoff value for wet year with a correlation coefficient ($R^2$) equal to 0.99, It implies that both variables move in the same direction because of the positive correlation. This signifies a perfect positive relationship, indicating a strong association between the two. The study also reveals a significant correlation between rainfall and runoff. But in dry year, rainfall and runoff are linearly correlated with low values 0.79 due to variation in rainfall and effect of another climatological parameter.

## 4.2 Model Calibration

Before initiating the model development, the accuracy of the rainfall data was assessed by comparing annual rainfall against annual runoff, as depicted in Figs. 7 and 8. The correlation coefficient of both wet and dry year indicates a strong and positive relationship between rainfall and actual runoff. The resulting linear relationship, demonstrated by the straightline graph, suggests that rainfall data can be considered reliable for further rainfall-runoff modeling. To further evaluate the relationship, runoff coefficients were determined by comparing measured annual runoff to annual rainfall, as presented in Table 5. Runoff coefficients, representing the ratio of runoff to rainfall, ranged from 0.28 to 0.68. These coefficients provide insights into how much of the rainfall contributes to runoff in different years.

The predicted yearly total of potential evapotranspiration (ETo) was reported as 2210.1 mm, with peak ETo values occurring in May (357.686 mm) and April (275.387 mm), and troughs in December (86.893 mm). This information adds valuable context to the water balance in the research area and contributes to the understanding of potential evapotranspiration patterns throughout the year.

The MIKE11 NAM model was configured for the Ravishankar Sagar reservoir, incorporating all the necessary input data, and underwent calibration for a sixteen-year period from 2004 to 2015. The goal of this calibration process was to determine the best-fit model parameters that could simulate runoff with a high degree of agreement with the observed runoff data. As indicated in Table 6, the calibrated model parameters were found to fall within their predetermined range, demonstrating that the model was successfully fine-tuned to represent the hydrological behaviour of the Ravishankar Sagar catchment during the specified period. This alignment with the predetermined range adds confidence to the model's reliability and its ability to accurately simulate runoff conditions.

**Table 5. Representing runoff coefficient**

| Year | RF | Q-obs | R Coeff |
|---|---|---|---|
| 2004 | 1217 | 629.9 | 0.518 |
| 2005 | 1185 | 566.4 | 0.478 |
| 2006 | 1474 | 858.6 | 0.582 |
| 2007 | 1278 | 734.1 | 0.575 |
| 2008 | 997 | 509.3 | 0.511 |
| 2009 | 1137 | 717.7 | 0.631 |
| 2010 | 1302 | 786.4 | 0.604 |
| 2011 | 1106 | 679.8 | 0.615 |
| 2012 | 1076 | 585.5 | 0.544 |
| 2013 | 1334 | 916.3 | 0.687 |
| 2014 | 1271 | 833.4 | 0.656 |
| 2015 | 594 | 196.1 | 0.33 |
| 2016 | 792 | 254.6 | 0.321 |
| 2017 | 611 | 171.1 | 0.28 |
| 2018 | 822 | 342.4 | 0.417 |
| 2019 | 887 | 290.8 | 0.328 |
| 2020 | 863 | 286.3 | 0.332 |

**Table 6. Model parameter values of model calibration and their range**

| S. No. | Parameters | Unit | Selected Values for Model Parameter | Range for Parameter |
|---|---|---|---|---|
| 1 | *Umax* | *mm* | 11.000 | 5.76 – 20 |
| 2 | *Lmax* | *mm* | 135.000 | 100 – 300 |
| 3 | *CQOF* | | 0.515 | 0.1- 1 |
| 4 | *CKIF* | *hrs* | 287.300 | 200 – 1000 |
| 5 | *CK1K2* | *hrs* | 23.200 | 10 – 50 |
| 6 | *TOF* | | 0.0701 | 0 - 0.99 |
| 7 | *TIF* | | 0.419 | 0 - 0.99 |
| 8 | $T_G$ | | 0.0266 | 0 - 0.99 |
| 9 | *CKBF* | *hrs* | 1154.000 | 500 – 1000 |

**Table 7. Model calibration result (all values are in mm)**

| **S. No.** | **Year** | **Q-obs** | **Q-Sim** | **% Diff** | **RF** | **PET** | **AET** | **GWR** | **OF** | **IF** | **BF** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2004 | 629.9 | 528.3 | 16.1 | 1217 | 2210.1 | 670.1 | 285.7 | 227 | 28.5 | 272.8 |
| 2 | 2005 | 566.4 | 535.2 | 5.5 | 1185 | 2164.6 | 645.5 | 289 | 221.4 | 26.6 | 287.1 |
| 3 | 2006 | 858.6 | 795.4 | 7.4 | 1474 | 2133.1 | 672.4 | 410.3 | 356.7 | 34.1 | 404.6 |
| 4 | 2007 | 734.1 | 676.5 | 7.8 | 1278 | 2154.8 | 603.8 | 342.1 | 289 | 41.5 | 346 |
| 5 | 2008 | 509.3 | 455.3 | 10.6 | 997 | 1912.6 | 538.2 | 234.3 | 190.5 | 29.3 | 235.5 |
| 6 | 2009 | 717.7 | 592.3 | 17.5 | 1137 | 1987.1 | 507.8 | 319.4 | 255.9 | 27.3 | 309.1 |
| 7 | 2010 | 786.4 | 714.8 | 9.1 | 1302 | 1882.8 | 579.1 | 356.9 | 314.2 | 46.8 | 353.8 |
| 8 | 2011 | 679.8 | 621.6 | 8.6 | 1106 | 1627.6 | 521.6 | 309.6 | 276.8 | 29.3 | 315.4 |
| 9 | 2012 | 585.5 | 505.1 | 13.7 | 1076 | 1688.3 | 570.8 | 244.7 | 206 | 43.4 | 255.8 |
| 10 | 2013 | 916.3 | 730.7 | 20.2 | 1334 | 1600.3 | 596.4 | 371 | 317.7 | 48.9 | 364.1 |
| 11 | 2014 | 833.4 | 821.6 | 1.4 | 1271 | 1691.7 | 449.1 | 417.5 | 374.8 | 34.4 | 412.4 |
| 12 | 2015 | 196.1 | 165.3 | 15.7 | 594 | 1632.8 | 458.2 | 87.7 | 54.9 | 4.5 | 105.9 |
|  | Total | 8013.5 | 7142.1 | 133.6 | 13970.15 | 22685.8 | 6813 | 3668.2 | 3084.9 | 394.6 | 3662.5 |
| **Coefficient of Determination = 0.730** |  |  |  |  |  |  |  |  |  |  |  |

*(Q=Runoff, RF=Rainfall, PET=Potential Evapotranspiration, AET=Actual Evapotranspiration, GWR=Ground Water Recharge, OF=Overland Flow, IF=Inter Flow and BF=Base Flow)*

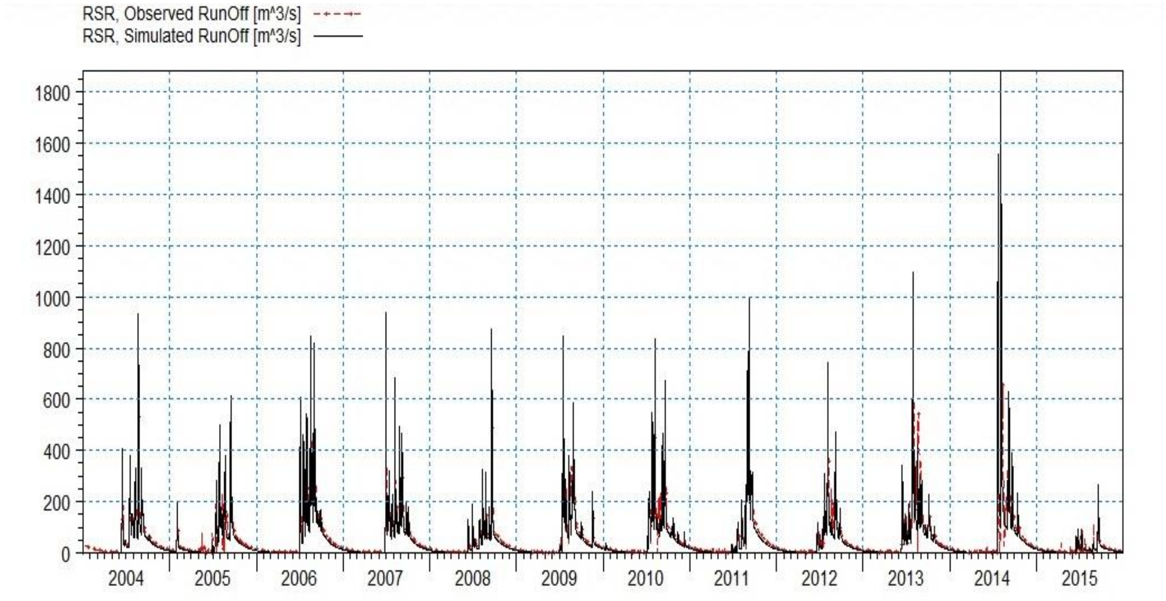

**Fig. 11. Observed and simulated runoff hydrograph during model calibration**

Table 7 displays the statistical information pertaining to different facets of the hydrological cycle, encompassing metrics such as runoff, actual evapotranspiration, groundwater recharge, overland flow, interflow, and base flow. The data presented corresponds to simulations conducted during the model calibration, and these values are structured to represent a water balance.

The observed coefficient of determination ($R^2$) for the model calibration was found to be 0.730. This value indicates good agreement in terms of time, rate, and volume between the observed and simulated runoff. The modest 10% differences between the total observed and simulated flows suggest an acceptable match between the simulated and observed runoff, enhancing the reliability of the model. Based on the analysis of the simulation results over the sixteen-year calibration period, out of the total rainfall of 13,970 mm, the simulated discharge was 10,810 mm. During this period, 3,085 mm of overland flow was formed, 395 mm of water was contributed as interflow, and 3,663 mm as base flow. The remaining 3,668 mm of water was contributed to groundwater recharge. These details provide a comprehensive overview of the water balance components and their interactions within the Ravishankar Sagar catchment during the specified calibration period.

Fig. 11 presents a comparison between observed and simulated yearly runoff volumes. The visual representation in the Fig. 12 indicates a close match between the simulated and observed runoff volumes, suggesting that the model accurately captures the variations in runoff over different months. In Fig. 11, which illustrates runoff hydrographs of various events over the calibration period, it is observed that there is generally good agreement between the shapes of the hydrographs for both observed and simulated runoff. This indicates that the model is capable of reproducing the temporal patterns of runoff events throughout the calibration period. The comparison shows that the simulated and observed runoff closely match each other, suggesting the model's capability to accurately simulate hydrograph shapes and runoff volumes. While there may be some differences in the amplification of peak values of runoff events, the times of the beginning and ending of observed and simulated runoff events are reported to match well. Overall, these visual analyses provide confidence in the model's ability to replicate the observed runoff dynamics during the calibration period.

## 4.3 Model Validation

The MIKE 11 NAM model was then validated using the same set of model parameters that had been found during the model calibration process for the four years, from 2016 to 2020.the model. Table 8 furnishes data on the simulated hydrological components during the model validation for the four years from 2016 to 2020, using the same set of model parameters identified during the calibration process.

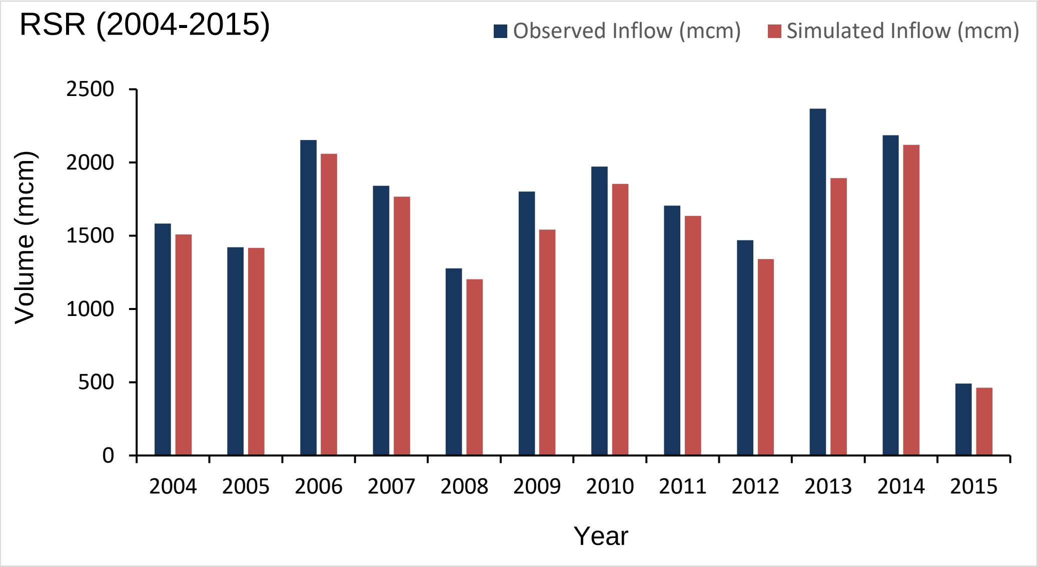

**Fig. 12. Observed and simulated monthly runoff volume during model calibration**

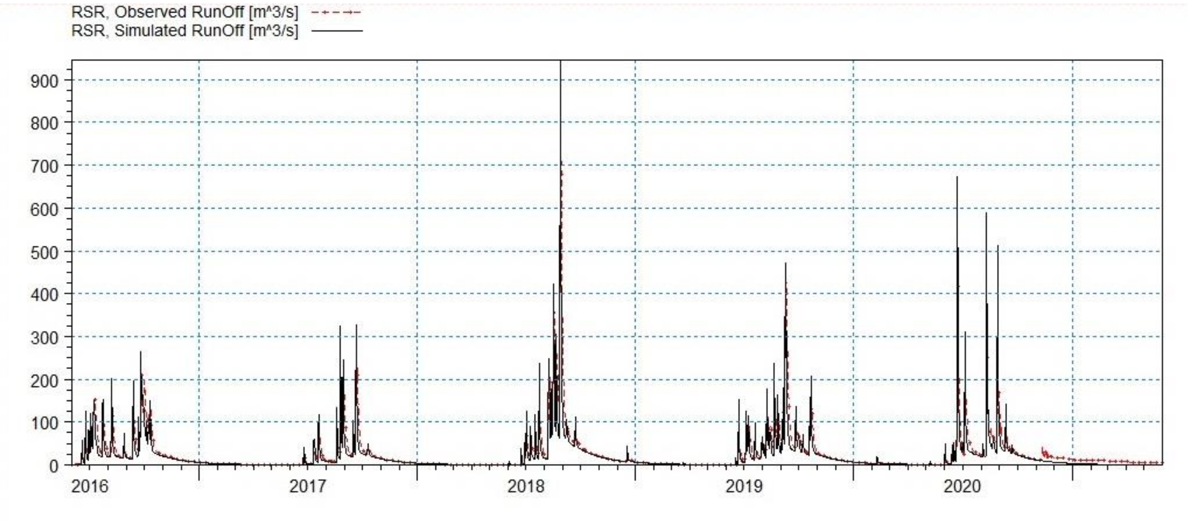

**Fig. 13. Observed and simulated runoff hydrograph during model Validation**

**Table 8. Model validation result (all values are in mm)**

| S. No. | Year | Q-obs | Q-Sim | % Diff | RF | PET | AET | GWR | OF | IF | BF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2016 | 295.9 | 212.5 | 28.2 | 792 | 1801.6 | 543.9 | 188.3 | 9.6 | 29.8 | 173.1 |
| 2 | 2017 | 186.3 | 148.3 | 20.4 | 611 | 1802.3 | 474.1 | 126.3 | 6.4 | 10.2 | 131.7 |
| 3 | 2018 | 338 | 309.2 | 8.5 | 822 | 1645.3 | 489.3 | 280.1 | 14.6 | 22.8 | 271.8 |
| 4 | 2019 | 319.7 | 260.8 | 18.4 | 887 | 1698.5 | 629.6 | 221.8 | 11.4 | 28.1 | 221.3 |
| 5 | 2020 | 292.1 | 259 | 11.3 | 863 | 1504.8 | 627.7 | 219.5 | 11.2 | 18.7 | 229.1 |
|  | Total | 1432 | 1189.8 | 36.8 | 3975 | 8452.5 | 2764.6 | 1036 | 53.2 | 109.6 | 1027 |
| **Coefficient of Determination = 0.704** |  |  |  |  |  |  |  |  |  |  |  |

*(Q=Runoff, RF=Rainfall, PET=Potential Evapotranspiration, AET=actual evapotranspiration, GWR=Ground Water Recharge, OF=Overland Flow, IF=Inter Flow and BF=Base Flow)*

Throughout the validation period, the model's coefficient of determination was 0.704. This value suggests that the MIKE 11 NAM model performed well in simulating runoff, exhibiting good agreement with observations in terms of timing, rate, and volume. The modest 11.3% difference between the total observed and simulated runoff further indicates an acceptable match between the model's predictions and the actual observed runoff during the validation period. These results affirm the model's robustness and reliability in reproducing the hydrological dynamics of the Ravishankar Sagar catchment not only during the calibration period but also during the subsequent validation period from 2016 to 2020. The consistency between observed and simulated values further supports the credibility of the MIKE 11 NAM model for runoff prediction in this specific context.

Based on the analysis of Fig. 14, which shows a strong correlation between the monthly runoff volume observed and the simulated data during the validation phase, it can be inferred that the model that was created in this way continued to perform effectively throughout the longer time period. Fig. 13 illustrates a close match between the hydrographs of various events in both simulated and observed runoff during the validation period. This suggests that the model parameters established during calibration were successful in accurately predicting runoff. The results from the model validation investigation indicate that the developed NAM model performed well, demonstrating its ability to generate or forecast runoff time series for an extended period in Ravishankar Sagar with a commendable level of precision. The calibration process resulted in an Efficiency Index (EI) indicating the effectiveness of the NAM model in accurately predicting runoff. Additionally, it can be inferred that the NAM model, developed specifically for Ravishankar Sagar in the Mahanadi basin, holds promise for simulating runoff in other sub-basins with similar characteristics.

## 4.4 Sensitivity Analysis

To identify the most sensitive model parameters, the MIKE11 NAM model underwent individual runs, with each parameter treated as a variable while maintaining the constancy of other parameter values. Equations 2 were employed to calculate the Efficiency Index (EI) for each simulated runoff time series. By plotting EI against the respective model parameters, a comprehensive analysis of the output results was conducted. Fig. 16 reveals that the parameters CQOF, Lmax, and CK1K2 emerged as the most sensitive and influential, while the remaining parameters were observed to be non-sensitive, as illustrated in Fig. 15.

## 4.5 Effect of Model Parameters on Runoff

Through sequential runs of the model with adjustments to individual parameter values, the impact of these parameters on simulated peak and low flows was assessed. The analysis highlighted that the parameters CQOF, Lmax, and CK1K2 significantly influenced both peak and low flows. In contrast, parameters such as Umax, CKIF, TIF, and CKBF exhibited no discernible effect on either peak or low flows.

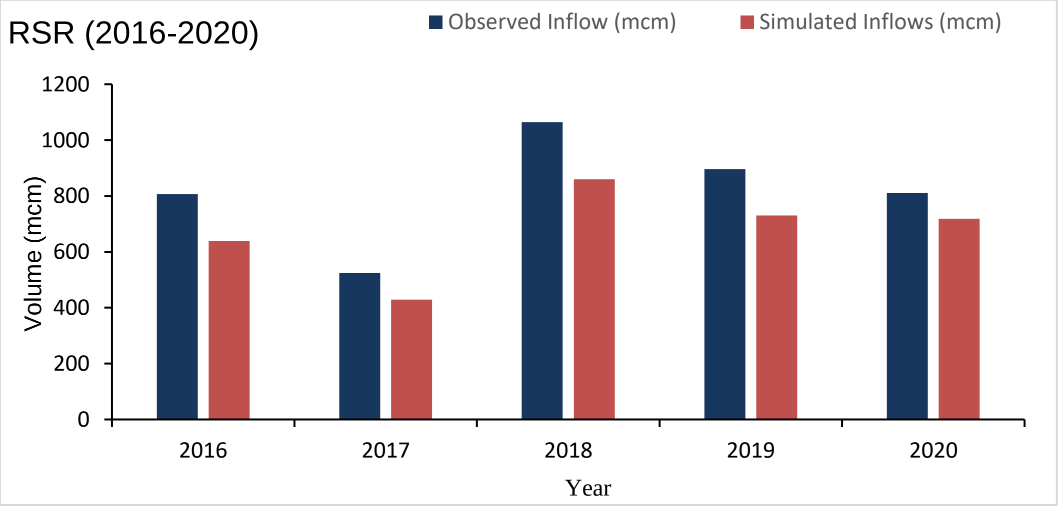

**Fig. 14. Observed and simulated runoff hydrograph during model Validation**

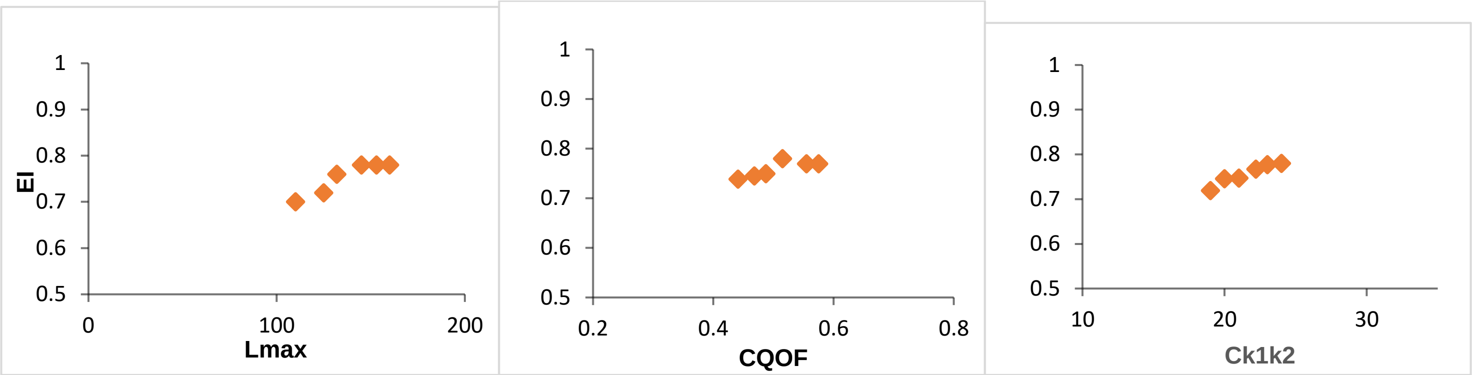

**Fig. 15. Graph between EI against the non-sensitive model parameters**

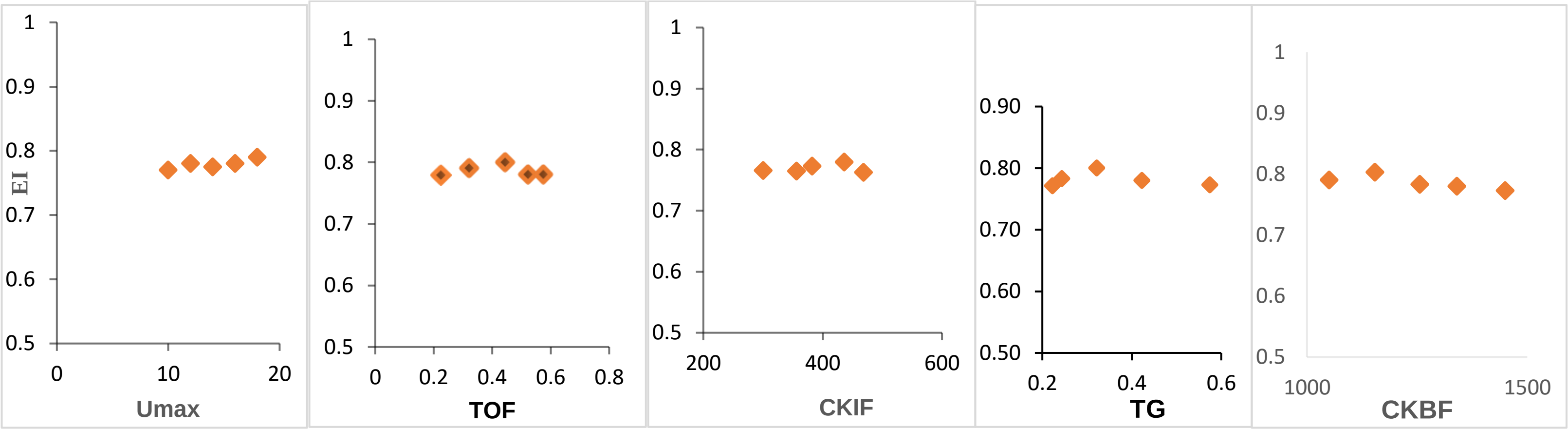

**Fig. 16. Graph between EI against the sensitive model parameter**

## 5. DISCUSSION AND CONCLUSION

The study revealed that the Ravishankar Sagar within the Mahanadi basin could proficiently replicate the hydrological response to rainfall and accurately forecast daily runoff. This success was achieved through the application of the MIKE11 NAM rainfall runoff model. Understanding the interconnection between precipitation and runoff is crucial for gaining insights into how annual runoff experiences fluctuations in response to varying rainfall patterns within the Ravishankar Sagar Catchment in Chhattisgarh. Additionally, the study establishes significant relationship between annual rainfall and runoff. Observations indicated that the model successfully predicted and simulated runoff in terms of time, rate, volume, and hydrograph shape, demonstrating its effectiveness in replicating the observed runoff. The model's calibration and validation produced $R^2$ values of 0.730 and 0.704, respectively. The model proved its effectiveness and capacity to predict runoff for Ravishankar Sagar Reservoir over a long period of time, with an Efficiency Index of 81%. The model was substantiated as effective in generating runoff using rainfall data, suggesting its potential as a crucial tool for water resources management and the development of the Ravishankar Sagar. It was determined that the MIKE 11 NAM model made sense for characteristics like CQOF, Lmax, and CK1K2. It was found that these parameters were shown to have significant effects on both low and high flows, was an important modeling component.

## ACKNOWLEDGEMENT

The authors express their gratitude to the National Institute of Hydrology, Regional Centre, Bhopal, for their assistance and provision of facilities during the study. Additionally, the authors also thankful to the State Water Data Centre, Water Resources Department, Government of Chhattisgarh, Raipur, for supplying rainfall and discharge data for the Ravishankar Sagar reservoir.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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