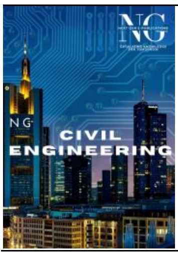

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Hydrologic Modelling of Mahanadi River Using Rainfall-Runoff Method

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HIGHLIGHTS

- Thirty years of rainfall data were used to develop hydrological models for the Mahanadi River basin.
- Linear regression successfully forecasted rainfall trends for the next seven years.
- Runoff and flood behavior were effectively simulated using the SCS–Mockus method.

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ABSTRACT

Hydrological modeling is a real-world system which implies the simplification that leads for better understanding, managing and prediction of water resource system. These hydrological models are used to estimate the rainfall–runoff behaviors. This study shows the results of rainfall forecasts obtained with mathematical analysis techniques, using past rainfall data for thirty years. This study describes the hydrological model of the largest river of Odisha i.e. the Mahanadi. Hydrological models are formulated using thirty years of rainfall data. Analytical models are developed to analyzing and forecasting the behavior of the river during rain periods throughout every season of the year. For rainfall prediction linear regression analysis is done which gives the forecasting data of next seven years. The discharge or the estimated runoff is calculated using Mockus model which is the empirical formula of SCS method by taking some river stations of the Mahanadi. In this thesis, flood forecasting models based on linear regression have been evaluated along with other performances using analytical model using MS Excel has been analyzed for a channel reach of the Mahanadi River in Odisha.

1. INTRODUCTION

Hydrological modeling is a fundamental tool in water resources engineering for understanding and predicting watershed responses to rainfall. The rainfall–runoff relationship forms the backbone of flood forecasting, reservoir operation, irrigation scheduling, and basin-scale water management (Singh, 1995; Beven, 2012). Reliable runoff estimation is therefore essential for sustainable development and disaster risk reduction. The present study focuses on the hydrological modeling of the Mahanadi River, the largest river of Odisha, using rainfall–runoff methods. Hydrological models are developed using thirty years of rainfall data (1986–2015). Seasonal analyses are carried out for winter, pre-monsoon, southwest monsoon, post-monsoon, and total rainfall periods. Rainfall prediction is performed using linear regression analysis, while runoff is estimated using the Mockus model, an empirical formulation of the

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SCS (Soil Conservation Service) method. The performance of these models is evaluated for selected channel reaches of the Mahanadi River in Odisha

The Mahanadi basin drains an area of about 141,589 km² and the river flows approximately 851 km before joining the Bay of Bengal, making it one of the most important river systems in eastern India.

Rainfall–runoff modeling has been widely applied to simulate watershed behavior under different climatic and land-use conditions. Singh (1995) and **Beven (2012)** emphasized that hydrological models play a crucial role in understanding catchment processes and supporting water resources planning. Among various modeling approaches, empirical and conceptual models remain popular due to their simplicity and data efficiency.

The Soil Conservation Service Curve Number (SCS-CN) method, originally proposed by Mockus (1949) and later standardized by the USDA-SCS (1972), is one of the most widely used empirical techniques for runoff estimation. It relates rainfall, soil type, land use, and antecedent moisture conditions to direct runoff and has been successfully applied in both gauged and ungauged basins (Mishra & Singh, 2003; Ponce & Hawkins, 1996). The method's simplicity and reasonable accuracy have led to its extensive use in watershed hydrology and flood studies worldwide.

Statistical techniques such as linear regression analysis are frequently employed for rainfall forecasting and hydrological prediction. Kisi (2004) and Subramanya (2013) reported that regression-based models provide reliable short-term rainfall predictions when long-term historical data are available. Several studies have combined SCS-CN runoff estimation with regression-based rainfall forecasting to enhance flood prediction and water management efficiency (Chow, Maidment & Mays, 1988; Jain & Singh, 2003).

In Indian river basins, hydrological modeling studies have demonstrated the effectiveness of combining empirical runoff models with statistical rainfall analysis for basin management and flood forecasting (Jain et al., 2012; Ghorbani et al., 2020). These findings support the methodological framework adopted in the present study for the Mahanadi River basin.

The primary objective of this research is to develop a comprehensive understanding of the hydrological behavior of the Mahanadi River basin through rainfall–runoff modeling. This includes analyzing long-term rainfall and runoff data to identify seasonal and interannual variations in the hydrological response of the basin. By examining these variations, the study aims to improve knowledge of how the river system reacts to changing rainfall patterns under different climatic conditions.

Another important objective is to develop reliable seasonal rainfall–runoff models for the Mahanadi River using appropriate hydrological and statistical techniques. The study seeks to represent the rainfall–runoff process during winter, pre-monsoon, southwest monsoon, post-monsoon, and annual periods so that the influence of each season on river discharge can be clearly understood and quantified.

A further objective of this research is to estimate surface runoff using the Mockus model based on the Soil Conservation Service (SCS) methodology. Through this approach, the study aims to evaluate the applicability and effectiveness of the SCS–Mockus model for runoff estimation in the Mahanadi River basin and assess its potential use for flood forecasting and water resources planning in the region.

In addition, the study aims to predict future rainfall trends using linear regression analysis applied to long-term observed rainfall data. This forecasting component is intended to provide insight into future hydrological conditions of the basin and to support proactive planning for water resources management, irrigation development, and flood risk mitigation.

Finally, the research seeks to evaluate the overall performance of the developed hydrological models by comparing estimated and observed hydrological data for selected channel reaches of the Mahanadi River. This evaluation is expected to establish the reliability of the proposed modeling framework and its usefulness for practical applications in river basin management and decision-making.

2. STUDY AREA AND DATA COLLECTION

The Mahanadi river basin enlarges over five states of India. They are Chhattisgarh and Odisha and relatively smaller quantities in the states of Jharkhand, Maharashtra and Madhya Pradesh. The Mahanadi originates from the northern hills of Dandakaranya which is present in the Chhattisgarh state. The drainage area of Mahanadi is 141470 Sq.km which is a bigger part of the total geographical area of the country. The Mahanadi is a perennial river means a permanent river because it never becomes in dry seasons. The geographical volume of the basin lies between 80°28′ and 86°43′ longitudes in the east and 19°8′ and 23°32′ latitudes in the north. The basin has maximum length 558 km. The elevation of the Mahanadi is 890 m or 2920ft. The average discharge of this river is 2119 cubic meter per second and the maximum discharge of Mahanadi is 56,700 cubic meter per second. The Mahanadi is an important river of the country and it is the largest river of Odisha state (Figure 1). By taking account water potential and flood generating capacity, it has second rank to the Godavari. The left tributaries of Mahanadi are Seonath, Mand, Ib and Hasdeo . The right tributaries of Mahanadi are Ong, Parry, Jonk, Telen. The false point of the Mahanadi is Jagatsinghpur, odisha. The most important part of basin is blanketed with agricultural land accounting to 57% of the total area and 4.45% of the basin area is included by means water bodies. There is a dam constructed over Mahanadi is called Hirakud Dam. This dam has the length of 55 kilometers and it is one of the multipurpose reservoirs of India. Other than this reservoir this river has six dams.

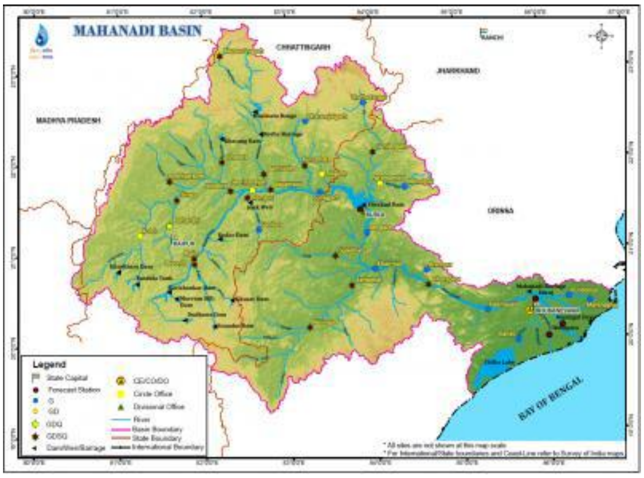

Figure.1 Study area

3. METHODOLOGY

Mockus in 1949 proposed plotting direct runoff versus storm runoff. Mockus built this idea and suggested that surface runoff could be estimated from collection of factors such as soil type, areal extent, and location, land use, areal extent, and location, antecedent rainfall, duration and depth of a storm, average annual temperature and date of storm (Sankalp et al., 2023).

b value was used as the second independent variable (P being the primary independent variable) in a graph of P versus Q in which

$$Q = P\{1-(10)^{-bP}\} \quad (1)$$

Where Q = direct runoff in inches and P is the storm rainfall in inches.

Mockus (1949) combined parameters to solve value b from the equation:

$$b = 0.0374(10)^{0.229M}C^{1.061}/T^{1.990}D^{1.333}(10)^{2.271(S/D)} \quad (2)$$

where M = 5-day antecedent rainfall in inches.

C = cover practice index.

T = seasonal index (a function of date and temperature (° F)).

D = duration of storm in hours.

S is a soil index in inches per hour.

It follows that the "b" in condition 1 is identified with tempest and watershed qualities. Subsequently it was conceivable to assessed Q for any tempest on any watershed when these attributes and the tempest profundity are known (Mockus 1949). Apparently, the runoff condition was grown first and Mockus accomplished extra work to regionalize the worth b. A few impediments on condition 1 and 2 were perceived. Mockus (1949) summed up the aftereffects of testing conditions 1 and 2 as follows: "Better outcomes were gotten for huge tempests than for little tempests, for short tempests than long tempests, and for blended spread instead of single-spread watersheds. Breaking long tempests into parts containing the more extreme time frames and including the processed Q esteems improved the evaluations for long tempests. There was trouble in characterizing sums and terms of tempests for enormous watersheds." The enduring documentation doesn't give any sign of the watersheds utilized, decency of-fit for condition 1 or estimations of the lists required. Condition 1 is legitimate just up to the point of $0<=dQ/dP<=1$. As far as possible happens when $P=1/[b\ln(10)]$

For the formulation of percentage of departure, the departure value is calculated by the subtraction of normal rainfall from actual rainfall and the percentage is calculated by taking the departure value with respect to the normal rainfall.

Regression analysis is a statistical approach for modeling of relationship between a scalar response and one or more explanatory variables. The case of single explanatory variable is called linear regression. The equation for the regression analysis is

$$Y = mx + c$$

Where m = slope

C= intercept

X= observed variable

Y= required data

This regression analysis is a very successful method for identifying about the variables with topic of interest and this process helps to determine the factors which matters the most and the factors which are to be ignored and the influence of these factors among each other.

4. RESULTS AND DISCUSSIONS

The hydrographs for the four monitoring stations show notable differences in discharge patterns. Figure 1 (reproduced from Figure 2) plots the flow rate at the Baronda station against time. The hydrograph reveals alternating periods of high and low discharge, with the peak discharge of approximately 1035 m^3/s in 2004, which is the highest recorded among all stations.

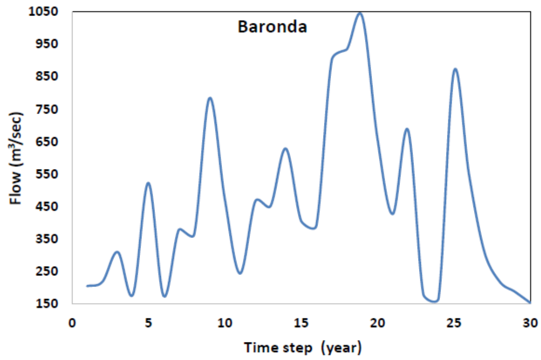

Figure 2. Hydrograph showing the variation of flow rate over time at the Baronda station

A secondary peak of around 900 m^3/s occurs in the late 1990s. Overall, the flow at Baronda exhibits high inter-annual variability, reflecting the influence of monsoon rainfall and catchment characteristics.

Figure 3 presents the hydrograph for the Rajim station. Although the general pattern is similar to that of Baronda, the magnitude of discharge is slightly lower. The peak discharge reaches approximately 1005 m^3/s in 2004, and the hydrograph displays longer periods of moderate discharge. These differences likely arise from variations in catchment area, land use, and local rainfall distribution. Baronda, being located further upstream, collects larger runoff volumes than Rajim.

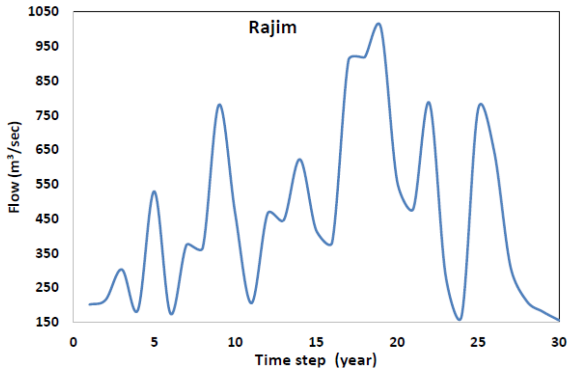

Figure 3. Hydrograph illustrating flow rate versus time step at the Rajim station.

Table 1 summarises key statistics of the flow data, including maximum and minimum discharge values and the year of peak discharge for each station.

Location (station)	Maximum discharge (m^3/s)	Year of max discharge	Minimum discharge (m^3/s)	Remarks
Baronda	1035	2004	150	Highest flows recorded
Rajim	1005	2004	155	Slightly lower peak than Baronda
Seorinarayan	1015	2004	151	Intermediate discharge pattern
Basantpur	992	2004	165	Lowest peak among stations

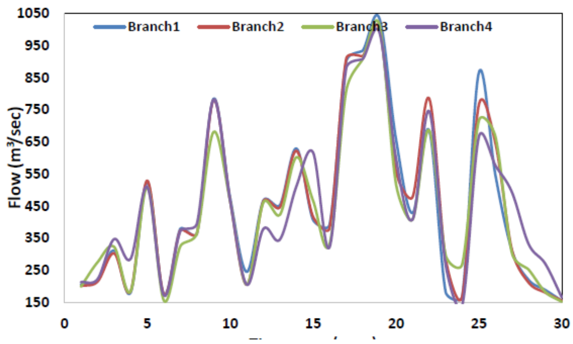

Figure 4. Merged hydrograph of all four stations showing comparative flow rates

Figure 4 presents the merged hydrograph, combining all four monitoring stations. Baronda consistently records the highest discharges, while Seorinarayan and Basantpur exhibit similar but slightly lower peaks. The merged graph shows that years with high discharge at one station generally coincide with high discharge at the others, confirming that major rainfall events affect the entire basin. However, in certain years, discharge patterns diverge, suggesting localized rainfall variability and differences in catchment response.

4.2 Seasonal Rainfall Analysis

Winter Season

Figure 5 illustrates the relationship between actual rainfall, normal rainfall, and departure percentage. In many years, actual winter rainfall is lower than normal, resulting in negative departures. Notable exceptions include 1994–1995, when rainfall exceeded normal and the departure reached +132 %, and 2006–2007, when rainfall was exceptionally high, yielding a departure of +513 %. Such anomalies indicate episodic winter storms producing unusually high rainfall.

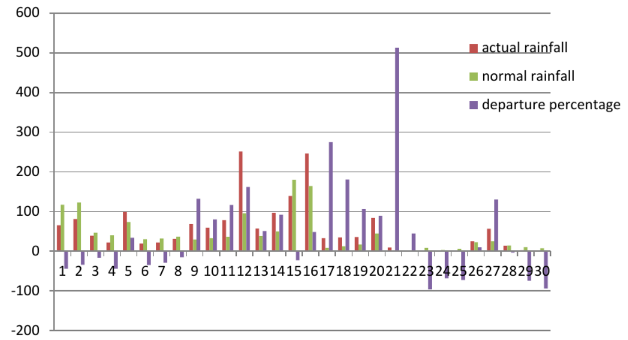

Figure 5 Winter season rainfall analysis showing actual rainfall, normal rainfall and departure percentage

Figure 5 Overall, the basin receives relatively low winter rainfall with frequent deficits. Years with positive departures may contribute to groundwater recharge and irrigation but can also cause localized flooding when rainfall intensity is high.

Pre-Monsoon Period

The pre-monsoon analysis indicates that actual rainfall from March to May is generally lower than normal. Departures range from –15 % to –99 %, demonstrating persistent rainfall deficits. However, certain years (e.g., 2005 and 2012) show positive departures due to early convective storms. Pre-monsoon rainfall is crucial for land preparation and reducing soil moisture deficit before the onset of the main monsoon.

Southwest Monsoon Period

The southwest monsoon accounts for the majority of annual rainfall. Table 5.4 shows that while most years remain close to the long-term normal, notable departures include –21 % in 1986 and +32 % in 1996. This variability can either alleviate or intensify water scarcity. Years with high positive departures often correspond to flood conditions and increased soil erosion, whereas negative departures contribute to drought stress and reduced reservoir storage.

Post-Monsoon Period

The post-monsoon analysis (Table 5.5 and Figure 5.i) demonstrates that actual rainfall is commonly below normal, with departures reaching as low as –95 %. Only a few years exhibit positive departures, such as 1989–1990, when rainfall exceeded normal by 150 %. Low post-monsoon rainfall can extend dry conditions into the rabi cropping season, whereas excessive rainfall may cause waterlogging and delay winter sowing.

Total Rainfall and Volume Analysis

Table 5.6 combines all seasons to evaluate total annual rainfall. The departure varies from –23 % to +29 %, with the highest recorded rainfall volume of 286.38 billion m³ in 1988 and the lowest of 20.29 billion m³ in 1986. Negative departures correspond to drought years, while positive departures are associated with flood conditions. Understanding this long-term variability is essential for reservoir operation and basin-scale water resource planning.

4.3 Rainfall Prediction and Regression Analysis

Linear regression analysis of observed rainfall data from 1986–2015 produced a best-fit model with $R^2 = 0.863$, indicating that 86.3 % of the variability in rainfall is explained by the linear trend. The regression line shows a slight downward slope, suggesting a gradual decrease in rainfall over the 30-year period. However, substantial scatter around the trendline highlights strong inter-annual variability, and extreme events such as 2008, when observed rainfall reached 2,828 mm, were underestimated by the model.

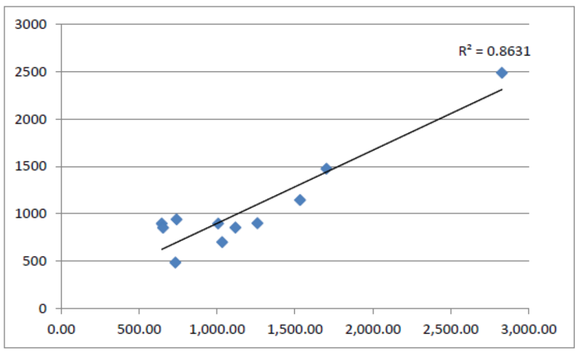

Figure 6. Scatter plot comparing observed and forecasted rainfall

Forecasted rainfall for 2016–2022 indicates a decline from 914 mm in 2016 to 573 mm in 2020, followed by a slight rise to 809 mm in 2022. If this downward trend persists, the basin may face increased drought risk, emphasizing the need for improved water conservation and adaptive management strategies.

5. CONCLUSIONS

The flow analysis reveals substantial spatial variability in discharge behavior across the monitored locations of the Mahanadi River system. The Baronda station exhibits the highest peak discharge of 1035 m^3/s in 2004, followed by Seorinarayan with 1015 m^3/s, Rajim with 1005 m^3/s, and Basantpur with 992 m^3/s. This pattern indicates that upstream reaches of the basin contribute larger runoff volumes, likely due to higher catchment area contribution, greater rainfall intensity, and steeper terrain characteristics. The consistent occurrence of peak flows in 2004 across all monitoring stations highlights the influence of a basin-wide extreme rainfall event, confirming the strong coupling between precipitation and river discharge dynamics.

Seasonal rainfall analysis provides important insight into the hydro-climatic variability of the basin. During the pre-monsoon period, the highest positive rainfall departure occurred in 1997–1998, with an increase of 58% above normal, reflecting the occurrence of intense convective rainfall prior to the main monsoon. Conversely, the extremely low departure of –99% in 2006–2007 demonstrates the vulnerability of this season to severe rainfall deficits, which can significantly affect soil moisture availability and agricultural preparedness.

The winter season exhibits the most extreme variability, with a remarkable positive departure of +513% in 2006–2007, indicating the occurrence of exceptional rainfall events. In contrast, the year 2008–2009 experienced a dramatic decline of –96%, highlighting the highly irregular nature of winter precipitation in the basin. Such large fluctuations can strongly influence groundwater recharge, reservoir storage, and winter crop irrigation.

The southwest monsoon, which supplies the majority of the basin's annual rainfall, shows relatively moderate variability compared to other seasons. The highest positive departure of +32% in 1996–1997 corresponds to enhanced flood potential, whereas the lowest departure of –22% in 1991–1992 reflects monsoon weakening that may contribute to drought conditions and reduced reservoir inflows. This variability underscores the need for robust monsoon monitoring and adaptive water management strategies.

During the post-monsoon period, the largest positive departure of +180% in 1993–1994 indicates significant rainfall after the main monsoon, which can be beneficial for soil moisture replenishment but may also cause waterlogging and delayed agricultural operations. Conversely, the extreme negative departure of –95% in 2003–2004 demonstrates the susceptibility of this season to prolonged dry spells that extend drought conditions into the rabi cropping season.

Analysis of total annual rainfall shows that the basin experienced its highest positive departure of +29% in 2012–2013, whereas the lowest departure of –23% occurred in 2009–2010. The corresponding volume analysis reveals the maximum annual rainfall volume of 286.38 billion cubic meters in 1988 and the minimum of 20.19 billion cubic meters in 1986, illustrating the enormous inter-annual variability of water availability in the basin. These extremes have critical implications for flood risk, drought management, reservoir operation, and long-term water security.

The rainfall prediction model developed using linear regression yields a coefficient of determination $R^2 = 0.863$, indicating that approximately 86.3% of the variability in rainfall is explained by the model. This strong statistical performance demonstrates the suitability of the regression approach for medium-term rainfall forecasting in the Mahanadi basin. The predicted rainfall values for 2016–2022 provide valuable information for strategic planning, although the presence of extreme events in the historical record suggests that additional modeling approaches may further improve prediction accuracy.

Overall, the integrated analysis of discharge behavior, seasonal rainfall variability, and predictive modeling highlights the complex hydrological dynamics of the Mahanadi River basin and emphasizes the importance of combining statistical forecasting with hydrological modeling for effective water resource management and climate resilience.

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Author Contributions: The author solely conceived and designed the study; collected, processed, and analyzed the data; interpreted the results; and wrote, reviewed, and approved the final manuscript.

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