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HYDROLOGICAL CHARACTERISTICS, PATTERN AND PROCESSES OF SEDIMENT FLUX IN NARMADA RIVER BASIN

Doctoral Dissertation Abstract

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During the past few decades, major river basins across the world have encountered a significant alteration in their streamflow and capacity of sediment transportation owing to climatic and human induced interventions. Human interventions coupled with climate change have not only interrupted the amount of atmospheric water vapour but have also disrupted the surface characteristics of the river basins. A little change in the amount, intensity and frequency of rainfall has the potential to alter the streamflow and erosion processes of a river that further determine the capacity of sediment conveyance to the oceans. Since the major source of water flow in Peninsular Rivers in India is summer monsoons, the unpredictable behaviour of monsoon under changing climate and increasing anthropogenic activities have caused a significant transformation in their natural flow. The variability in streamflow and sediment discharge causes serious problems in the functioning of hydropower plants, hydrologic structures, channel stabilization, water and soil resources management. Narmada River Basin (NRB), the lifeline of central India, is facing several challenges pertaining to sustainable management of water and soil resources, and sectoral competition of freshwater under changing climatic regime. Recent studies have reported an upsurge in the frequency and

intensity of extreme rainstorms over the central India, which can intensify the soil loss from the NRB. Also, the river has undergone extensive hydrological transformation, primarily due to the construction of large-scale water related projects and hydraulic structures (4000 hydropower projects and 277 dams). A realistic evaluation of amount and distribution of rainfall, its seasonality, erosivity, streamflow and sediment flux over the NRB is essential for effective planning and management of water and soil resources, designing, installation and operation of hydropower projects and hydrologic structures, and preparations against the hydrological extremes. The inherent hydrological characteristics of NRB have not been studied extensively. Previous studies have provided limited insights into the dynamics of sediment flux from its sub-basins, but as a whole, the basin has almost remained unexplored. The present study, therefore, has been attempted to investigate the hydrological characteristics, spatio-temporal pattern and processes of sediment flux in the NRB.

Objectives of the Study

Major objectives of the study are:

- to determine the best alternative to gauge-based rainfall measurements over the NRB;
- to investigate the long-term trends and

variability in rainfall, its seasonality and concentration using best fitted dataset;

- to explore the geographic distribution of rainfall erosivity (RE) and erosivity density (ED) over the basin;
- to scrutinize the impacts of climate change and human activities on streamflow variability, and
- to reveal the spatial and temporal changes in sediment flux on account of climatic and human induced factors over the basin.

Study Area

The present study pertains to the NRB, which originates from the Amarkantak Hills at an elevation of about 1,057 m amsl and spreads over the state of Madhya Pradesh (86.21 per cent), Gujarat (11.55 per cent), Maharashtra (1.52 per cent) and Chhattisgarh (0.72 per cent). It flows for about 1312 km in length before out falling into the Arabian Sea. With a drainage area of 96,060 km², the basin stretches between 21° 27' to 23° 37' N latitudes and 72° 38' to 81° 43' E longitudes. It is surrounded by the Vindhyas in the north, Satpuras in the south, Maikala Range in the east, and by the Gulf of Khambhat in the west. The basin experiences a tropical and humid climate, where southwest monsoon supplies more than 90 per cent of total annual rainfall. The mean annual rainfall varies from less than 800 mm in the western region to more than 1400 mm in the eastern parts. The mean temperature ranges from 27°C to 34.4°C in summer and from 19°C to 22°C in winter. Mostly clayey, and stony soils are found across the basin (shallow red and yellow), but in its upper parts, loam and clay loam (deep black) soils are more dominant.

Database and Methodology

For the accomplishment of present study, time series data pertaining to rainfall, temperature, streamflow, suspended sediment concentration (SSC) and associated factors (geology, geomorphology, soil group, groundwater, water withdrawal, number of reservoirs and dams, land use, population, urbanization etc.) have been collected from different secondary sources. Daily streamflow (1973-2020) for 14 monitoring stations and SSC (1987-2020) data for 10 monitoring stations have been collected from the India-WRIS (Water Resource Information System) website (<https://indiawriss.gov.in>) and Central Water Commission, Bhopal. Rainfall data have been downloaded from the India Meteorological Department (IMD) gridded dataset at daily scale during 1981-2020.

Prior to conducting any statistical or time-series analysis, collected data have been analysed through pre-processing techniques for the quality check (missing values, outliers, auto-correlation). No missing records have been detected in IMD rainfall series, but satellite rainfall products exhibit missing values, which have been replaced with nil amount of rainfall. Streamflow and SSC series also contain missing values, which have been addressed using mean imputation and linear regression techniques. The missing SSC records for non-monsoon months (December-May) during 1987-2005, have been addressed by using the linear regression developed from the daily streamflow and SSC of two non-monsoon (October-November) months. Likewise, the presence of outliers has been checked by using Z- score test. No outlier has been detected in dataset as the values of Z-score have been found to be ranging within the threshold values, i.e., -3.0 to +3.0. Further,

monthly, seasonal and annual rainfall series have been developed from the daily records of rainfall, streamflow and sediment load (SL). The classification of seasons i.e., monsoon (June-September), post-monsoon (October-November), winter (December-February) and pre-monsoon (March-May) has largely been used in the present study. The performance of different rainfall products has been evaluated using continuous and categorical methods. Trends in time-series have been analysed using both parametric and non-parametric tests and the year of abrupt change has been recognized with the help of homogeneity tests. Further, double mass curve along with linear regression model has been used to quantify the relative contribution of climate change and human activities on the streamflow and sediment transport. The possible linkages of streamflow and sediment flux with their controlling factors have been assessed through Pearson's correlation, auto-regressive distributed lag model, random forest and partial least squares regression (PLSR).

Major Findings of the Study

IMD gridded product outperforms in estimating rainfall, followed by POWER (Prediction of Worldwide Energy Resources) and PERSIANN-CDR (Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Network-Climate Data Record) with respect to gauge-based records, but the performance of CHIRPS (Climate Hazards Group Infrared Precipitation with Station) has been found less satisfactory as it detects more false rainfall events. Majority of the products have overestimated the low rainfall and underestimated the high rainfall. Remarkably, rainfall estimates tend to improve with increasing time scale (season to annual)

because a strong correlation and low PBIAS (Per cent Bias) have been detected between rainfall estimates and gauge-based records at annual scale as compared to the seasonal. This study divulged that IMD gridded product is the best alternative to gauge-based measurements.

A high variability has been detected in rainfall distribution over the NRB, ranging between 667 and 1584, with a mean value of 1064 mm (coefficient of variation = 19.78 per cent and standard deviation = 203.42 mm). Spatially, a decrease from the east (>1200 mm) to west (<800 mm) has been witnessed in mean annual rainfall, except in the westernmost part (>1000 mm). The highest rainfall has been received in monsoon season (973 mm), followed by post-monsoon (41 mm), winter (26 mm) and pre-monsoon (22 mm) seasons, indicating that rainfall distribution over the NRB is primarily controlled by southwest monsoon. Further, a non-significant increase has been observed in annual (1.97 mm/year), monsoon (2.54 mm/year), and pre-monsoon (0.17 mm/year) rainfall, whereas the post-monsoon (-0.27 mm/year) and winter (-0.16 mm/year) rainfall have exhibited non-significant decreasing trends. Likewise, August (-0.87 mm/year) and October (-0.22 mm/year) months have witnessed a decrease in rainfall. Rainfall has been found positively correlated with physiography, sea surface temperature and Dipole Mode Index (DMI), but air temperature and Oceanic Niño Index have affected it negatively.

The seasonality and concentration indices have divulged that most of the rain occurs in three or less months over the NRB. Spatially, an increase in rainfall has been observed in rainfall seasonality while moving from the eastern to western parts. The eastern part receives most of the rain in 3 or less

months, while the western part has exhibited extreme irregularities, in receiving all rainfall in just 1-2 months. The stations situated at high elevation and receiving high annual rainfall exhibit less heterogeneity as compared to the stations situated in the plains with low rainfall. Likewise, PCP (Precipitation Concentration Period) index infers that the rainy season arrives earlier in the eastern and western parts than in the middle one. The heterogeneity in rainfall distribution has increased during 1981-2020 as concentration indices have exhibited increasing tendency. Remarkably, rainfall seasonality and concentration have been found to be negatively correlated with climatic and geographical factors, being significant with rainfall amount.

Likewise, RE and ED exhibit a very high variability, ranging from $1500 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ ($1.20 \text{ MJ ha}^{-1} \text{ h}^{-1}$) in the middle and western-most parts to $750 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$ ($0.75 \text{ MJ ha}^{-1} \text{ h}^{-1}$) in the south and western parts of NRB. Remarkably, June-September months account for nearly 99 per cent of annual RE, indicating that soil erosion over the NRB intensifies during the monsoon season. Among months, the highest RE has been detected in August, while the maximum ED has been observed in July owing to the occurrence of high intensity and shorter duration rainstorms. Further, a statistically non-significant upward trend has been found in annual, monsoon and pre-monsoon RE, whereas the post-monsoon and winter seasons have exhibited downward trends in rainfall. The gravity centre analysis reveals a higher risk of erosion in the middle parts of NRB, which has shifted a little towards the eastern side during the study period. RE has demonstrated a strong positive association with rainfall, but physiography has exhibited a little influence on the spatial distribution of RE and

ED. Among climatic oscillations, DMI followed by ENSO (El-Niño Southern Oscillation) have been found to exert the maximum influence on changing pattern of RE.

Despite witnessing of positive trends in annual rainfall, a significant reduction in annual, monsoon and post-monsoon streamflow has occurred in the main channel, primarily due to rise in temperature, water withdrawal, and water retention structures that have impounded incoming upstream water and create hindrances in natural flow. However, these structures have played a significant role in sustaining minimum flow during the dry season; therefore, the basin has witnessed increasing trends in winter and pre-monsoon streamflow. Tributaries have also demonstrated an upward trend in streamflow owing to increased rainfall and less human interference. The human activities have contributed about 107.97 per cent in reducing streamflow after 1994, while changing climate has enforced a counteracting effect (-7.97 per cent).

Annual, seasonal and monthly SL exhibits a high variability. Nearly 95 per cent of the annual SL is transported during the monsoon season, while the other seasons together transport a minimal amount (5 per cent). The higher sediment yield and erosion rates observed in Manot, Mohgaon and Gadarwara sub-basins indicate towards erosional hotspots and potentially critical areas requiring management interventions. A significant decrease in sediment transport after 1994 has overwhelmingly resulted from the human activities (accounting nearly 102 per cent) as large reservoirs trap the sediments before reaching at the outlet. Conversely, climate change has exerted counteracting influence (-2 per cent). The SSC-discharge relationship has exhibited lagged sediment

delivery at upstream and downstream stations relative to the water discharge owing to distant sources of sediments and supply limitations, while intermediate stations dominated by fine suspended sediments have exhibited rapid sediment flux coinciding with discharge peaks. The correlation analysis and PLSR have revealed river discharge as the most critical driver of sediment yield, followed by rainfall amount and erosivity, especially in the upper basins, whereas cumulative and antecedent rainfall influence the sediment mobilizations in the downstream reaches.

These findings of the present study can be helpful for the planners, water resource administrators, and risk-reduction managers in formulating effective policies related to the

sustainable use and management of regional water resources, designing hydraulic structures, prevention of soil erosion, and resolving the issues associated with floods and droughts. This study has divulged a drastic impact of human activities on streamflow and sediment flux over the NRB, highlighting the need for an integrated management strategy for soil and water conservation, and maintenance of channel health in future. Also, the findings decipher that approximately 2.13 per cent of basin area, primarily lying in the western-most, middle and northern parts, is highly prone to soil erosion, which requires to be given top priority in implementing the conservation practices towards the management of soil and water resources over the NRB.

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