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Impact of rainfall variability and land use/land cover dynamics on runoff in the Madamsilli dam catchment, India

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Abstract

This study investigates how land cover and use have changed over a 30-year time period and its impact on runoff. The researchers used GIS and the SCS CN method to estimate runoff and analyze trends in rainfall. The study divided the time period into ten-year intervals and focused on the catchment Madamsilli dam watershed. ArcGIS was used to process USGS Landsat images from 1991, 2001, 2011, and 2021 in order to classify land cover and land use.

The results revealed a notable decline in the amount of water cover by 15.27 sq. km, suggesting possible modifications to the hydrological regime in the region. This reduction accounted for 68.99% of the original water cover. Forest cover experienced a minimal decrease of only 0.87 sq. km, suggesting some deforestation but not at a significant level. Barren land cover increased by 48.53 sq. km, implying changes in land use practices such as vegetation clearing, mining, or overgrazing. The increase in barren land cover amounted to 31.55%. Building cover moderately increased by 4.87 sq. km, indicating changes in urbanization patterns or population growth leading to new construction or urban expansion. The building cover increased by 4.09%.

The researchers computed runoff using maps of land use/cover and soil in the Madamsilli watershed. The hydrologic soil group was created based on the FAO soil map, and the Curve Number (CN) was calculated considering the land cover and soil group. Runoff was then determined using the assigned CN values. The rainfall and runoff analysis revealed the least amount of precipitation and runoff in 2002 (611 mm and 66.24 mm, respectively). The highest rainfall occurred in 2003, while the highest runoff was observed in 1991 (1991.3 mm and 381.95 mm, respectively).

Keywords: Runoff estimation, GIS, SCS curve number method, rainfall trend analysis

1. Introduction

Land use and land cover (LULC) changes caused by anthropogenic activities have become one of the most significant drivers of hydrological alteration in watershed systems. Rapid urbanization, agricultural expansion, deforestation, and mining activities modify the natural landscape, thereby influencing infiltration, evapotranspiration, groundwater recharge, and surface runoff processes. These alterations ultimately affect water availability, sediment transport, and water quality within river basins. Several studies have demonstrated that land use transitions significantly influence watershed hydrology and runoff generation (Ololade *et al.*, 2008; Duncan *et al.*, 2009; Sewnet, 2016; Pande *et al.*, 2021) [6, 4, 12, 8].

Rainfall variability is another critical factor affecting hydrological processes. In India, the South-West monsoon contributes nearly 75–80% of the annual rainfall and plays a crucial role in sustaining agriculture and water resources. However, climate change has altered rainfall patterns, leading to increased frequency of extreme events such as droughts and floods. Rising temperatures, erratic precipitation distribution, and shifts in seasonal rainfall trends have significantly impacted rainfed agricultural systems (Prakasam, 2010) [10]. Therefore, understanding long-term rainfall variability and its relationship with land use changes is essential for sustainable watershed management.

Remote sensing and Geographic Information System (GIS) techniques have emerged as powerful tools for monitoring spatio-temporal changes in land use and hydrological parameters.

Multi-temporal satellite imagery enables accurate mapping of land cover dynamics and supports hydrological modelling applications (Zubair, 2006; Bedini *et al.*, 2008; Agaton *et al.*, 2016) [17, 3, 1]. These tools facilitate the assessment of watershed characteristics, including slope, drainage, vegetation cover, and impervious surfaces, which are critical inputs for runoff estimation models.

Among various hydrological models, the Soil Conservation Service Curve Number (SCS-CN) method is widely used for estimating direct surface runoff from rainfall events. The method integrates land use, soil type, and antecedent moisture conditions to compute runoff depth. Due to its simplicity and reliability, the SCS-CN approach has been successfully applied in several Indian watersheds (Patel *et al.*, 2017; Sutradhar, 2018; Satheeshkumar *et al.*, 2017) [9, 13, 11]. Integration of GIS with the SCS-CN method enhances spatial runoff estimation accuracy and enables watershed-scale analysis (Malekani *et al.*, 2014) [5]. Trend analysis of rainfall and runoff is equally important for evaluating climate variability impacts. Non-parametric statistical tests such as the Mann–Kendall (MK) test are widely applied to detect monotonic trends in hydrological time series without assuming normal data distribution (Vivekanandan, 2007; Malik & Kumar, 2020; Tiwari & Pandey, 2019) [16, 6, 15]. These methods are particularly useful in identifying significant increasing or decreasing rainfall trends, which can inform water resource planning and reservoir management strategies.

Dams and reservoirs play a vital role in regional economic development by supporting irrigation, hydropower generation, and drinking water supply. However, land use transformation in dam catchments can significantly alter runoff patterns and sediment yield. Studies have shown that deforestation and urban expansion increase impervious surfaces, thereby enhancing runoff and reducing groundwater recharge (Bagwan & Gavali, 2021; Tewabe & Fentahun, 2020) [2, 14]. Conversely, vegetation cover promotes infiltration and reduces peak discharge.

The Madamsilli Dam catchment, located in Dhamtari district of Chhattisgarh, is an important watershed that supports irrigation, hydroelectric power generation, and domestic water supply. Over the past three decades, the region has experienced noticeable land use changes due to agricultural intensification, population growth, and infrastructural development. Additionally, rainfall variability in central India has shown fluctuations influenced by monsoonal dynamics and climate variability. These combined factors necessitate a comprehensive assessment of LULC changes and rainfall trends in the catchment.

Despite several studies on LULC change detection and rainfall trend analysis in different regions of India, limited research has specifically examined the combined effect of rainfall variability and land use change on runoff generation in the Madamsilli Dam watershed. Therefore, this study aims to:

- Assess spatio-temporal changes in land use and land cover using multi-temporal satellite imagery.
- Estimate surface runoff using the SCS-CN method integrated with GIS techniques.
- Analyze rainfall trends using the non-parametric Mann–Kendall test.
- Examine the relationship between rainfall variability, land use dynamics, and runoff response in the catchment.

The findings of this study will contribute to improved watershed management, reservoir sustainability planning, and climate-resilient water resource strategies in central India.

2. Study Area

The Madamsilli Dam, is an earth-fill embankment dam located on the Silari River, a tributary of the Mahanadi in central eastern India also known as the Babu Chhotelal Shrivastav Dam. It was constructed between 1914 and 1923 under the supervision of the British Raj governor, Madamsilli, after whom it was named. Situated in Chhattisgarh's Dhamtari District, the dam is approximately 95 kilometers from Raipur and is considered a notable architectural marvel in the region. Its primary function is to provide irrigation water to agricultural areas.

The Madamsilli Dam serves various purposes, including irrigation for the agricultural regions of Dhamtari district, hydroelectric power generation, and fulfilling the drinking water needs of the area. It has played a crucial role in the economic development of the region by boosting agricultural production, providing employment opportunities, and generating hydroelectricity. However, the dam has faced challenges such as silting and environmental damage, which pose risks to sustainable development. To tackle these issues, the government has implemented measures such as reservoir desilting.

The Madamsilli Dam is an important and versatile structure with a surface area of 110 square kilometers and 1,170 million cubic meters of reservoir capacity. During its construction, the government relocated and rehabilitated people residing in the reservoir area, providing compensation and rehabilitation packages to ensure a smooth transition for the affected individuals.

Despite the challenges faced, the Madamsilli Dam has made substantial contributions to the region's economic growth by increasing agricultural productivity, generating hydroelectric power, and supplying potable water to the local population. The government has taken proactive steps, including desilting the reservoir, to address issues like silting and environmental damage and ensure the dam's sustainable development.

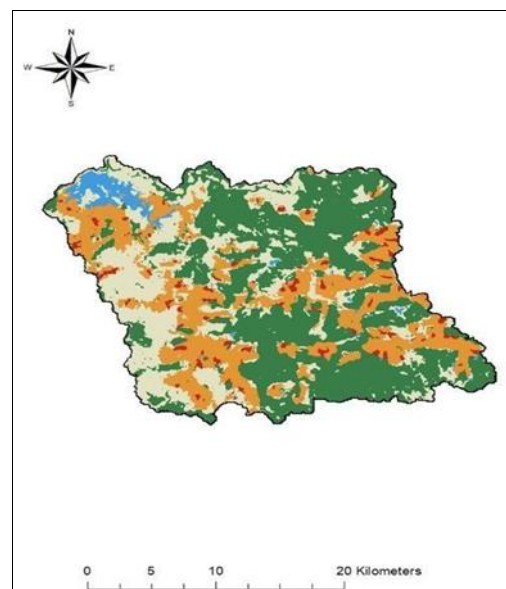


Fig 1: Study Area

3. Methodology

Data Collection and Preparation

The present study integrates remote sensing, GIS, hydrological modelling, and statistical trend analysis to assess the impact of rainfall variability and land use/land cover (LULC) changes on runoff generation in the catchment of Madamsilli Dam. The following datasets were used:

- Satellite Data
- Rainfall Data (1990–2021)
- Soil Data
- Topographical Data

All spatial datasets were projected to a common coordinate system and processed using ArcGIS software.

Land Use/Land Cover Classification

Supervised classification using the Maximum Likelihood Algorithm was performed to classify the satellite images into four major classes:

- Water
- Forest
- Barren land (including agricultural land and open spaces)
- Built-up area

Post-classification comparison was used to detect LULC changes between:

- 1991–2001
- 2011–2021

Change detection was computed using:

$$\text{Change} = AT_2 - AT_1$$

where:

A_{t1} = Area at initial year

A_{t2} = Area at final year

Percentage change was calculated as:

$$\% \text{Change} = \frac{(A_{t2} - A_{t1})}{A_{t1}} \times 100$$

Hydrological Soil Group (HSG)

The Hydrological Soil Group classification is based on infiltration capacity and runoff potential, as defined by the Natural Resources Conservation Service (NRCS). Soils were categorized into four groups:

- Group A – High infiltration, low runoff potential
- Group B – Moderate infiltration
- Group C – Low infiltration
- Group D – Very low infiltration, high runoff potential

The soil map was overlaid with the LULC map in GIS to assign Curve Number (CN) values.

Runoff Estimation Using SCS-CN Method

Surface runoff was estimated using the Soil Conservation Service Curve Number (SCS-CN) method, which integrates rainfall, land use, soil type, and antecedent moisture condition.

Step 1: Calculation of Potential Maximum Retention (S)

$$S = \frac{25400}{CN} - 254$$

S = Potential maximum retention (mm)

CN = Weighted Curve Number

Step 2: Calculation of Direct Runoff (Q)

If:

$P > 0.2S$

Then runoff is calculated as:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Where:

Q = Direct runoff (mm)

P = Rainfall depth (mm)

If $P \leq 0.2S$, then $Q = 0$.

Weighted Curve Number Calculation

The weighted Curve Number for the watershed was calculated using:

$$CN_w = \frac{\sum(CN_i \times A_i)}{\sum A_i}$$

Where:

CN_i = Curve number for land use–soil combination

A_i = Area of each land use–soil class

Antecedent Moisture Condition (AMC)

Antecedent Moisture Condition (AMC) represents soil moisture prior to rainfall events and influences runoff generation.

AMC was classified into:

- AMC I – Dry condition
- AMC II – Average condition
- AMC III – Wet condition

Equivalent Curve Numbers were computed using:

For AMC I:

$$CN_I = \frac{CN_{II}}{2.281 - 0.01281 \times CN_{II}}$$

For AMC III:

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573 \times CN_{II}}$$

AMC II was considered as the standard condition for annual runoff estimation.

Trend Analysis Using Mann–Kendall Test

Rainfall trend analysis was conducted using the non-parametric Mann–Kendall (MK) test, which does not require normally distributed data.

The test statistic S is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(x_j - x_i)$$

Where:

$$\text{sign}(x_j - x_i) = \begin{cases} +1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

The standardized test statistic Z is calculated as:

$$Z = \frac{S}{\sqrt{\text{Var}(S)}}$$

At 95% confidence level:

- If $|Z| > 1.96 \rightarrow$ Significant trend
- If $|Z| \leq 1.96 \rightarrow$ No significant trend

The test was applied to:

1. Pre-monsoon rainfall
2. Monsoon rainfall
3. Post-monsoon rainfall
4. Annual rainfall

4. Hydrological Soil Group (HSG)

Below fig. represents Natural Resource Conservation Service (NRCS) Soil classification which is based on runoff potential of soil

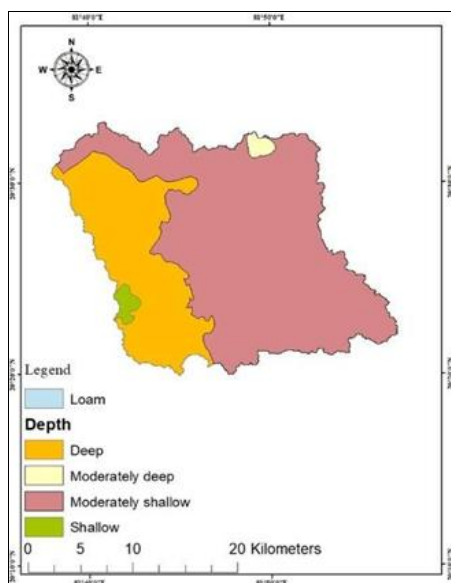


Fig 2: Resource Conservation Service (NRCS) Soil classification

5. Trend Analysis of Rainfall Using the Non-Parametric Mann–Kendall Test

Trend analysis of rainfall was conducted using the non-parametric Mann–Kendall (MK) test. The MK test is widely used in hydrological and climatological studies because it does not require the data to follow a normal distribution. Furthermore, it is relatively insensitive to outliers and missing values, making it suitable for long-term rainfall time series analysis.

The MK test evaluates the null hypothesis (H_0) that the data are independent and randomly ordered against the alternative hypothesis (H_1) that a monotonic increasing or decreasing trend exists over time. A key assumption of the test is that the observations are serially independent.

Mann–Kendall Test Statistic

The Mann–Kendall test statistic (S) is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(x_j - x_i)$$

Where:

$$\text{sign}(x_j - x_i) = \begin{cases} +1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases}$$

Here:

- x_i and x_j are sequential data values at time i and j ,
- n is the total number of observations.

A positive value of S indicates an increasing trend, while a negative value indicates a decreasing trend.

Mean and Variance of S

Under the assumption that the data are independent and identically distributed, the mean of S is:

$$E(S) = 0$$

The variance of S is calculated as:

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^m t_k(t_k-1)(2t_k+5)}{18}$$

Where:

- n = number of observations
- m = number of tied groups
- t_k = number of data points in the k -th tied group

Standardized Test Statistic (Z)

The standardized test statistic Z is computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 \end{cases}$$

The corresponding p -value is then obtained from the standard normal distribution.

Interpretation of Results

At a 95% confidence level ($\alpha = 0.05$):

- If $|Z| > 1.96 \rightarrow$ The trend is statistically significant.
- If $|Z| \leq 1.96 \rightarrow$ The trend is not statistically significant.

A positive Z value greater than 1.96 indicates a significant increasing trend, whereas a negative Z value less than -1.96 indicates a significant decreasing trend.

Since Z approximately follows a standard normal distribution for large sample sizes ($n > 10$), the MK test is suitable for long-term rainfall datasets such as the one used in this study.

Antecedent Moisture Condition (AMC)

Antecedent Moisture Condition (AMC) represents the wetness condition of the watershed prior to a rainfall event. It reflects the soil moisture status at the beginning of rainfall and plays a critical role in determining the magnitude of surface runoff. Higher antecedent soil moisture generally results in greater runoff generation due to reduced infiltration capacity. AMC is classified into three categories based on the total rainfall received during the previous five days:

- AMC I – Dry soil condition, characterized by low soil moisture and high infiltration capacity.

- AMC II – Average soil moisture condition, representing normal field conditions.
- AMC III – Wet or saturated soil condition, resulting from significant rainfall during the preceding five days.

In the SCS-CN method, Curve Number (CN) values are typically provided for AMC II conditions. However, equivalent CN values for AMC I and AMC III can be computed using the following empirical relationships:

Calculation of Curve Number for AMC I

$$CN_I = \frac{CN_{II}}{2.281 - 0.01281 \times CN_{II}}$$

Calculation of Curve Number for AMC III

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573 \times CN_{II}}$$

Where:

- CN_{II} = Curve Number under average moisture condition
- CN_I = Curve Number under dry condition
- CN_{III} = Curve Number under wet condition

AMC II is generally considered the standard condition for annual runoff estimation unless specific rainfall event data are available.

Table 1: Classification of Antecedent Moisture Conditions (AMC)

AMC Class	Total 5-Day Antecedent Rainfall (mm) – Dormant Season	Total 5-Day Antecedent Rainfall (mm) – Growing Season
AMC I < 13 < 36	AMC I < 13 < 36	AMC I < 13 < 36
AMC II 13 – 28 36 – 53	AMC II 13 – 28 36 – 53	AMC II 13 – 28 36 – 53
AMC III > 28 > 53	AMC III > 28 > 53	AMC III > 28 > 53

This classification ensures that runoff estimation accounts for soil moisture variability under different seasonal conditions, thereby improving the accuracy of the SCS-CN runoff model.

6. Results

Significant transformations in land use and land cover were observed in the catchment between 1991 and 2001, indicating progressive modification of the watershed environment. The areal extent of water bodies declined from 22.19 sq. km to 6.918 sq. km, corresponding to a reduction of 15.27 sq. km (68.99%). Such a substantial contraction in surface water area suggests alterations in reservoir storage dynamics, possibly influenced by rainfall variability, sediment deposition, evapotranspiration losses, and upstream water abstraction. A reduction in water spread area can directly affect irrigation reliability and seasonal water availability.

Forest cover showed a marginal decline of 0.87 sq. km during this period. Although the reduction appears limited, even minor losses in vegetative cover can influence interception capacity,

soil aggregation, and infiltration rates. Forested areas typically enhance groundwater recharge and regulate peak runoff; therefore, their gradual decline may contribute to altered runoff response during high-intensity rainfall events.

A pronounced increase in barren land was recorded, expanding by 48.53 sq. km (31.55%). In this study, barren land includes agricultural fields and exposed open areas. Expansion of such surfaces increases runoff potential due to reduced canopy interception and decreased soil protection. Exposed soils are more susceptible to erosion, which may enhance sediment transport toward the reservoir and accelerate siltation processes. The built-up area increased by 4.87 sq. km (4.09%), indicating moderate infrastructural growth during 1991–2001. Even modest increases in impervious surfaces can significantly elevate runoff coefficients, reduce infiltration capacity, and modify natural drainage patterns. Collectively, the LULC transitions during this decade suggest a gradual shift toward increased surface runoff potential within the watershed.

Analysis of annual rainfall and runoff data from 1990 to 2021 revealed marked inter-annual variability in hydrological conditions. Annual rainfall ranged from 611.00 mm (2002) to 1999.30 mm (2003), while annual runoff varied from 14.52 MCM (1998) to 594.32 MCM (1994). The year 2003 recorded the highest rainfall (1999.30 mm), reflecting an extreme monsoonal event. However, the highest runoff was observed in 1994 (594.32 MCM), indicating that runoff response is not solely governed by rainfall magnitude but also influenced by antecedent moisture conditions, land cover characteristics, and soil infiltration capacity.

The lowest rainfall occurred in 2002 (611.00 mm), which corresponded to relatively low runoff generation. Notably, the lowest runoff (14.52 MCM) was recorded in 1998, despite rainfall exceeding 800 mm, suggesting possible high infiltration losses or favorable antecedent moisture conditions. This highlights the non-linear relationship between rainfall and runoff within the catchment.

Several years, including 1992, 1993, 1995, 1996, 1997, 1998, and 2000, experienced comparatively lower rainfall, indicating potential drought conditions. Such fluctuations demonstrate the high climatic variability characteristic of monsoon-dominated regions in central India. The pronounced variability in runoff further reflects the combined influence of rainfall intensity, soil characteristics, and evolving land use patterns.

Between 2011 and 2021, further substantial land cover transformations were observed. The water spread area increased by 3.39 sq. km, possibly due to improved rainfall distribution, reservoir management interventions, or desiltation efforts. However, forest area declined significantly by 31.67 sq. km, representing a notable loss of vegetative cover. This reduction is hydrologically significant, as deforestation can reduce interception storage, decrease soil permeability, and increase surface runoff and erosion rates.

Barren land decreased by 12.26 sq. km during this period, potentially reflecting land conversion into built-up areas or partial vegetation recovery. The most prominent change was the sharp expansion of built-up area by 40.52 sq. km (46.04%), indicating rapid urbanization and infrastructural development within the catchment. Increased impervious surfaces enhance direct runoff, reduce groundwater recharge, and may intensify peak discharge during extreme rainfall events.

The cumulative effect of declining forest cover and expanding built-up area suggests an increasing trend toward anthropogenic

alteration of the watershed hydrology. Such modifications may influence runoff coefficients, sediment yield, and long-term reservoir sustainability.

The Mann–Kendall trend analysis revealed no statistically significant long-term trends in rainfall during the study period. The computed Z values for pre-monsoon (0.54), monsoon (−0.66), post-monsoon (0.24), and annual rainfall (−0.93) were all within the critical limits of ±1.96 at the 95% confidence level. Although slight decreasing tendencies were observed during the monsoon and annual periods, the associated p-values ($p > 0.05$) indicate that these trends are statistically insignificant.

Table 2: Change Detection of 1991 to 2001

Class	1991 Data (sq.km)	2001 Data (sq.km)	Change Detection (sq.km)
Water	22.19	6.918	-15.27
Forest	213.95	213.07	-0.87
Barren	154.08	202.67	48.53
Building	118.58	123.45	4.87

The definition of Barren area as used here denotes agricultural land and open spaces.

The absence of a significant monotonic trend suggests that rainfall variability in the region is characterized by short-term fluctuations rather than systematic long-term increase or decrease. However, when combined with land use transformation, even statistically insignificant rainfall variability may produce noticeable changes in runoff response.

Overall, the results indicate that while rainfall trends remain statistically stable, land use changes—particularly urban expansion and forest reduction—are likely playing a progressively important role in modifying runoff generation and hydrological behavior within the catchment of Madamsilli Dam.

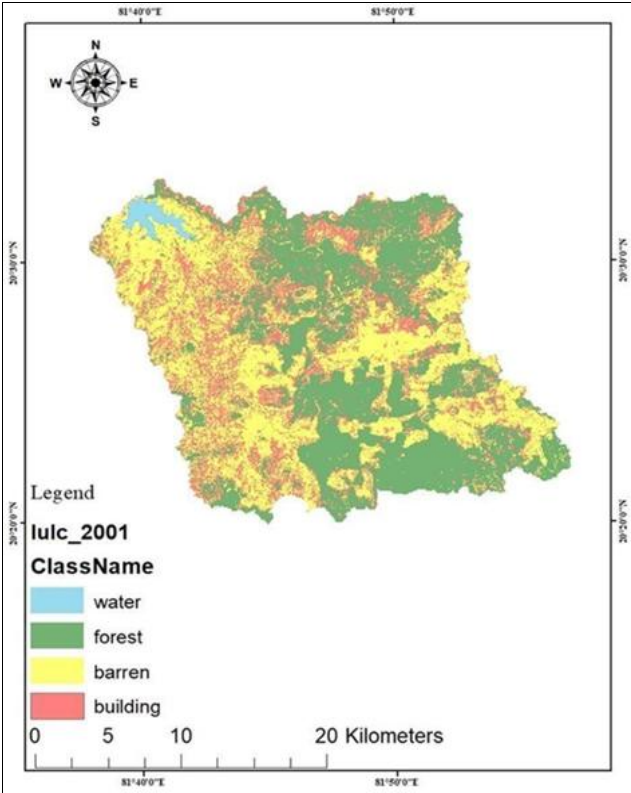


Fig 4: LULC 2001

Table 3: Change Detection of 2011 to 2021

Class	2011 Data (sq.km)	2021 Data (sq.km)	Change Detection (sq.km)
Water	20.56	23.95	3.39
Forest	260.98	229.31	-31.67
Barren	176.51	164.25	-12.26
Building	88.05	128.59	40.52

The definition of Barren area as used here denotes agricultural land and open spaces.

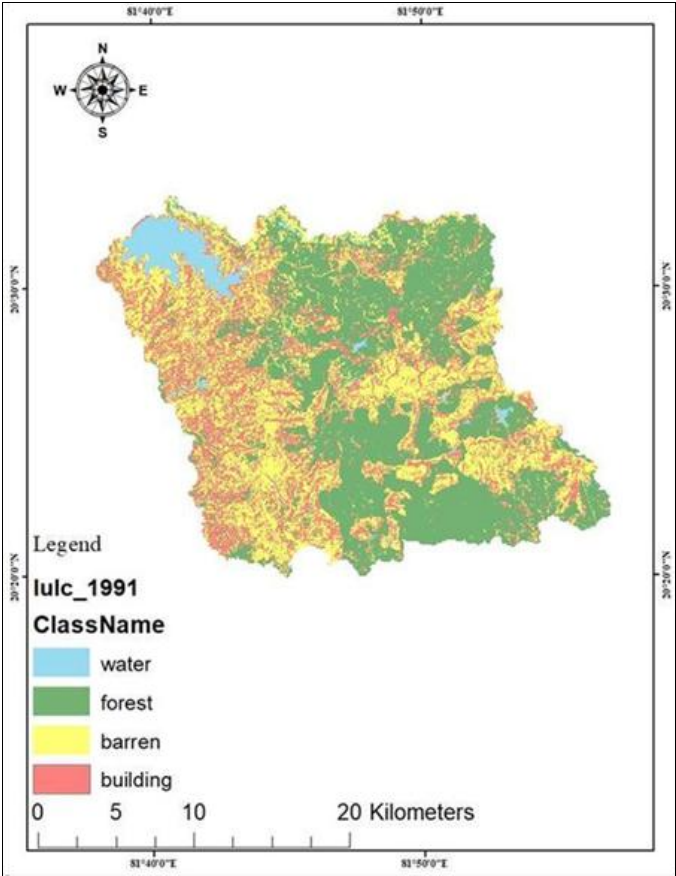


Fig 3: LULC 1991

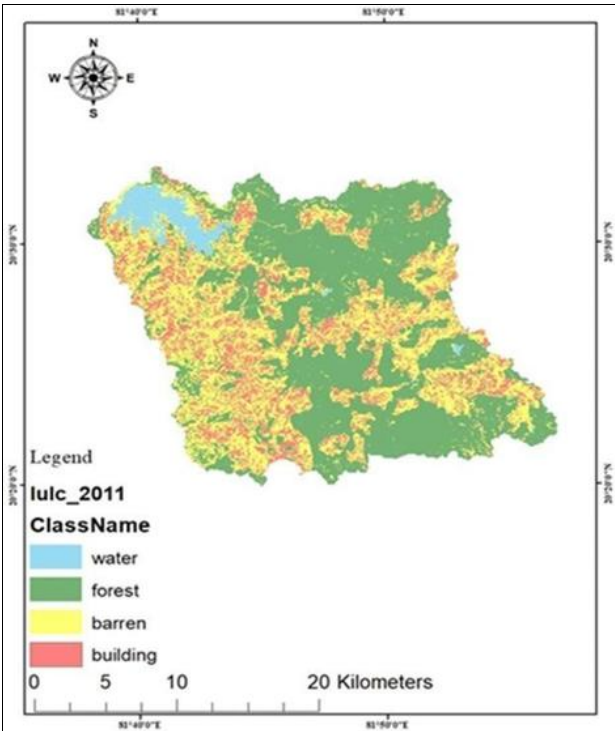


Fig 5: LULC 2011

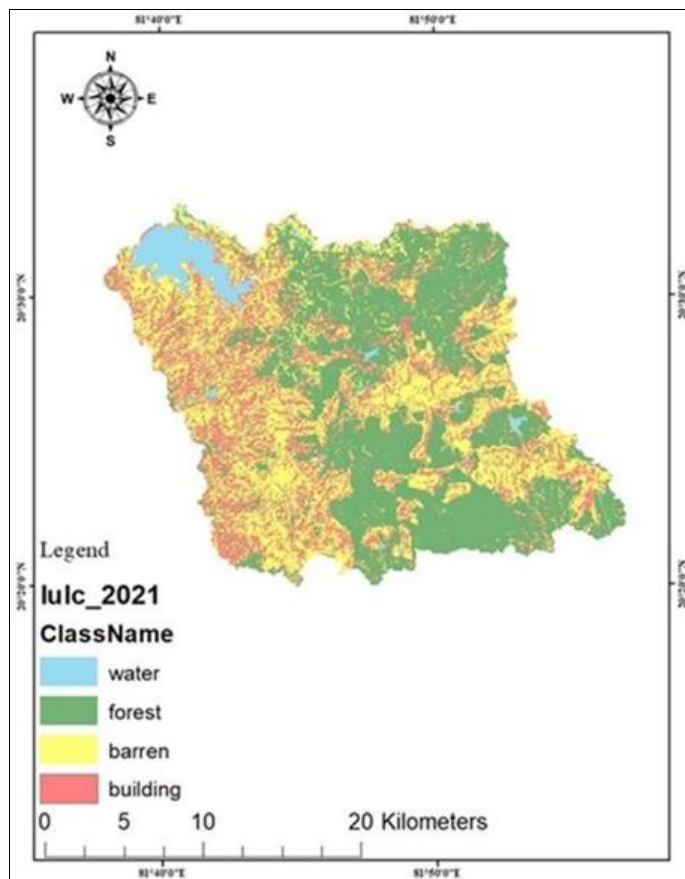


Fig 6: LULC 2021

Table 5: Annual Rainfall-Runoff for study area

Year	Annual Rainfall	Annual Runoff	Year	Annual Rainfall	Annual Runoff
1990	1764.85	343.46	2006	1437.00	312.92
1991	1382.25	381.95	2007	1506.00	310.87
1992	1077.70	326.03	2008	1192.00	156.53
1993	1164.00	156.62	2009	1252.80	204.76
1994	1682.65	594.32	2010	1519.70	250.75
1995	1252.75	315.02	2011	1073.00	188.18
1996	1047.50	195.22	2012	1160.00	157.20
1997	1107.35	152.16	2013	1479.00	205.05
1998	801.15	14.52	2014	1365.00	294.64
1999	1341.65	213.35	2015	981.00	87.745
2000	723.40	40.27	2016	1338.00	37.43
2001	1462.60	272.95	2017	987.00	124.17
2002	611.00	66.24	2018	1248.00	214.34
2003	1999.30	376.99	2019	1504.90	250.83
2004	1404.50	294.88	2020	1358.60	180.36
2005	1326.00	164.38	2021	1046.00	223.68

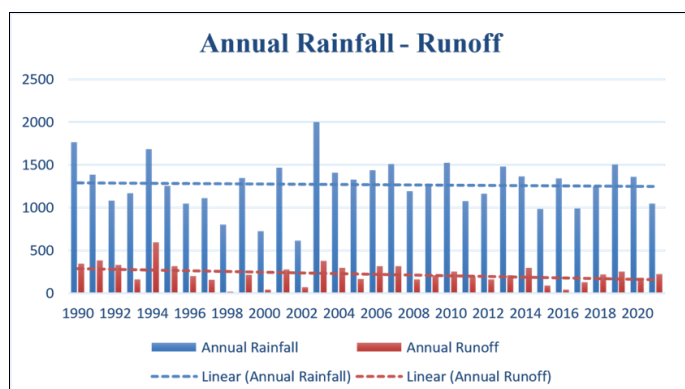


Fig 7: Trend analysis of Rainfall - Runoff

Table 6: Mann-Kendall test result

	Pre-monsoon	Monsoon	Post-monsoon	Annual
z	0.54	-0.66	0.24	-0.93
n	32	32	32	32
p	0.59	0.51	0.81	0.36
S	2	-42	1.4	-58

7. Conclusion

This study demonstrates that advancements in Geographic Information System (GIS) and remote sensing techniques provide effective and reliable tools for mapping, monitoring, and quantifying land use and land cover (LULC) changes in watershed systems. The integrated analysis conducted for the catchment area of Madamsilli Dam in Dhamtari district, Chhattisgarh, revealed significant spatial and temporal transformations in land cover over the study period. The combined use of satellite data, field observations, and hydrological analysis enabled a comprehensive understanding of landscape modification and its hydrological implications.

The analysis of annual rainfall and runoff data indicates substantial inter-annual variability in water availability within the catchment. Annual rainfall ranged from 611.00 mm to 1504.90 mm, with an average of approximately 1307.00 mm. Correspondingly, annual runoff varied between 37.40 million cubic meters (MCM) and 376.90 MCM, with an average of approximately 211.00 MCM. The highest rainfall was recorded in 2019, whereas the maximum runoff occurred in 2003. In contrast, the lowest rainfall was observed in 2002 and the lowest runoff in 2016. The wide fluctuations in runoff suggest that runoff generation is influenced not only by rainfall variability but also by land surface characteristics, antecedent moisture conditions, and land use dynamics. However, due to the absence of long-term regional climatological benchmarks, it is difficult to conclusively establish the occurrence of meteorological drought conditions during the study period.

Significant land cover changes were observed between 1991 and 2001. Water bodies declined markedly by 15.27 sq. km, indicating possible hydrological alterations due to sedimentation, reduced inflows, or climatic variability. Forest cover showed only a marginal decline of 0.88 sq. km, suggesting relatively stable forest conditions during this period. In contrast, barren land expanded by 48.53 sq. km, reflecting vegetation degradation, land clearing, or shifts in agricultural practices. Built-up area increased moderately by 4.87 sq. km, indicating gradual infrastructural development within the watershed.

Further analysis for the period 2011–2021 revealed intensified land transformation. Water cover increased by 3.39 sq. km, potentially due to improved reservoir management or favorable rainfall conditions. However, forest area declined significantly by 31.67 sq. km, indicating accelerated deforestation or land conversion. Barren land decreased by 12.26 sq. km, possibly reflecting conversion into built-up or agricultural land. Notably, built-up area increased substantially by 40.52 sq. km, highlighting rapid urbanization and expansion of settlements within the catchment.

Overall, the study confirms that rainfall variability combined with significant land use and land cover changes has influenced the hydrological response of the watershed. The increase in built-up areas and reduction in forest cover may enhance surface runoff, reduce infiltration, and alter watershed hydrodynamics. These findings emphasize the need for sustainable land management, watershed planning, and integrated water resource management strategies to ensure long-term hydrological stability and ecological balance in the catchment.

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