***Final Report***

# PRIORITIZATION OF SUB-CATCHMENTS OF THE SONG AND NAYAR RIVER CATCHMENTS FOR DEVELOPMENT OF RIVER REJUVENATION PLAN

**Submitted to**

**Watershed Management Directorate,**
**Dehradun, Uttarakhand**

**Submitted by**

**National Institute of Hydrology,**
**Jal Vigyan Bhawan, Roorkee (Uttarakhand) – 247667**

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# STUDY TEAM

| | |
|---|---|
| Dr. Y. R. S. Rao | Director, NIH |
| Dr. Y. R. S. Rao | Scientist ‘G’ & Head, EHD, NIH |
| Dr. Pradeep Kumar | Scientist ‘E’ & P.I., EHD, NIH |
| Dr. S. S. Rawat | Scientist ‘F’, C4S, NIH |
| Dr. Shakti Suryavanshi | Scientist ‘C’, EHD, NIH |
| Dr. Shailendra K. Kumre | Scientist ‘B’, EHD, NIH |
| Dr. S. M. Pingale | Scientist ‘D’, HID, NIH |

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# PRIORITIZATION OF SUB-CATCHMENTS OF THE SONG AND NAYAR RIVER CATCHMENTS FOR DEVELOPMENT OF RIVER REJUVENATION PLAN

## 1. INTRODUCTION

### 1.1 Background

The Song and Nayar River catchments, located in Uttarakhand, India, are critical hydrological systems that play a vital role in sustaining ecological balance, supporting biodiversity, and meeting the water demands of local communities. These river systems are increasingly experiencing hydrological stress due to a combination of natural and anthropogenic factors, including climate change, land use modifications, and urban expansion. The degradation of riverine ecosystems, declining water availability, and increasing sediment loads necessitate urgent intervention to ensure sustainable water resource management and ecological restoration.

Recognizing the criticality of these issues, the Spring and River Rejuvenation Authority (SARRA) initiated a state-level program aimed at the rejuvenation of key river systems in Uttarakhand, including the Song and Nayar Rivers. As part of this initiative, the National Institute of Hydrology (NIH), Roorkee, was assigned the task of assessing and prioritizing sub-catchments within these river basins for targeted conservation and restoration efforts. The overarching objective is to enhance water security, improve ecological resilience, and ensure the long-term sustainability of riverine habitats.

Hydrological systems are highly dynamic and governed by multiple interrelated parameters such as precipitation variability, terrain characteristics, soil permeability, and land use patterns. In recent decades, the Song and Nayar catchments have witnessed significant land use and land cover (LULC) changes, including deforestation, expansion of built-up areas, and shifts in agricultural practices. These changes have directly influenced hydrological regimes, affecting surface runoff, infiltration rates, and groundwater recharge potential. Additionally, the encroachment of urban areas and increased extraction of water resources have placed further stress on these river systems, altering their natural flow regimes and impacting water quality.

To ensure effective river rejuvenation, it is essential to identify and address the key drivers of hydrological degradation. Sub-catchments that exhibit significant ecological and hydrological stress need to be prioritized for intervention through measures such as afforestation, watershed management, and sustainable land use planning. Given the growing challenges posed by climate change, there is also an urgent need to enhance the resilience of these river systems by integrating nature-based solutions and adaptive management strategies.

This study aims to contribute to the scientific understanding of the hydrological and ecological dynamics of the Song and Nayar River catchments. By assessing the underlying factors influencing streamflow variations, water availability, and ecosystem health, the findings will help inform data-driven policies for sustainable river basin management. The study will also provide actionable insights for policymakers, water resource managers, and local communities to implement effective conservation strategies, thereby ensuring the long-term preservation of these vital river systems.

The rejuvenation of the Song and Nayar Rivers is not only critical for sustaining local water resources but also for maintaining the ecological integrity of the region. A holistic approach that integrates scientific research, community participation, and policy support will be essential in achieving sustainable outcomes. Through strategic planning and evidence-based decision-making, this initiative will contribute to the broader goal of safeguarding Uttarakhand’s riverine ecosystems while promoting water security for future generations.

## 1.2 Objectives

The broad objective of the study is to carry out the analysis for identifying the prioritized sub-catchments within Song and Nayar river catchments. The specific objective of the study are as follows:

a) To assess streamflow dynamics in the Song and Nayar (East and West) catchments, by analyzing the observed / estimated streamflow data to identify trends and patterns over time.

b) To assess the role of governing factors (Rainfall Pattern, Morphometry, LU/LC, Soil Types etc.) on the hydrological behaviour of the selected river catchments and their sub-catchments

c) To prioritize the sub-catchments on the basis of land use / land cover changes and morphometric characteristics and establish a framework for their prioritization considering the societal importance (population residing in the sub-basin and the JJM schemes for providing their domestic water requirements).

## 2. STUDY AREA

The Song River is a spring-fed river that originated from different small rivulets of the mountainous range of Dhanolti, crossing with Sahastradhara streams, flowing downward towards Doon valley basins, and finally assimilates into river Ganga. Apart from the surrounding natural beauty, the Song River of Dehradun is famous for its abundant natural sulphur springs. These springs originate from the cracks of the mountain and flow into the main stream, thus making the river water rich in sulphur content. People come here to take a dip in the mineral rich water. It is believed that sulphur bath is beneficial for various ailments, especially skin diseases. The river Song is located at 30º28’ latitude and 78º8’ longitude, with which peoples of Raiwala, Doiwala, Chiddarwala, and Lacchiwala are very much attached because this river is the only ultimate source of water for them travelling a total distance of approximately 107 km. It merges into river Ganga at 78°14'54" longitude and 30°02'02" latitude just upstream of Haridwar near Satyanarayan G&D station maintained by CWC after crossing Satyanarayana area in Figure 1. The river Suswa is an important tributary of river Song originating from the midst of the clayey depression of the Mussoorie range drains eastern part of Dehradun city and joint river Song at south-east of Doiwala. Dehradun and Doiwala are two major urban settlement situated in the catchment. Rispana and Bindal are two major drainage networks carrying municipal sewage from Dehradun and Doiwala discharges into the Song river through the Suswa river. The average annual rainfall is approximately 1451 mm, with around 1181 mm (81%) occurring during the monsoon season, making July and August the wettest months of the year.

The Nayar River, which flows fully within the Pauri Garhwal region, is the second-largest perennial spring-fed river in the state of Uttarakhand after the Ramganga River. Its two main branches, Purvi Nayar River and Pashchimi Nayar River originates in the dense Dudhatoli Reserved Forest. Purvi Nayar River is approximately 94 km long, while Pashchimi Nayar River is around 91 km long. Near Satpuli, they eventually combine to form the 20 km-long Nayar River. After joining of these two rivers with each other, the river travels to Vyas Ghat where it finally confluences with Ganga River. The Nayar River's watershed is bounded by districts of Uttarakhand, Tehri Garhwal to the north, Chamoli to the east, Almora to the south-east, Nainital to the south, and Dehradun to the west. Horn peaks, serrated canyons, hanging valleys, and waterfalls make it unique. Paithani, Thalisain, Pathisain, Pabo, and Satpuli are signifcant cities in the Nayar watershed. Its latitude and longitude boundaries are, respectively, 29°45'N to 30°15'N and 78°32'E to 79°12'E. The Nayar watershed covers an area of 1956.33 $km^2$, which has elevations ranging from 428 to 3102 m and receives about 1700 mm of rainfall on average annually. Also, the area's yearly average temperature ranges from 25 °C to 30 °C. The location has a pleasant summer time climate.

The Song and Nayar River catchments, located in Uttarakhand, India, are critical hydrological systems that play a vital role in sustaining ecological balance, supporting biodiversity, and meeting the water demands of local communities. These river systems are increasingly experiencing hydrological stress due to a combination of natural and anthropogenic factors, including climate change, land use modifications, and urban expansion. The degradation of riverine ecosystems, declining water availability, and increasing sediment loads necessitate urgent intervention to ensure sustainable water resource management and ecological restoration.

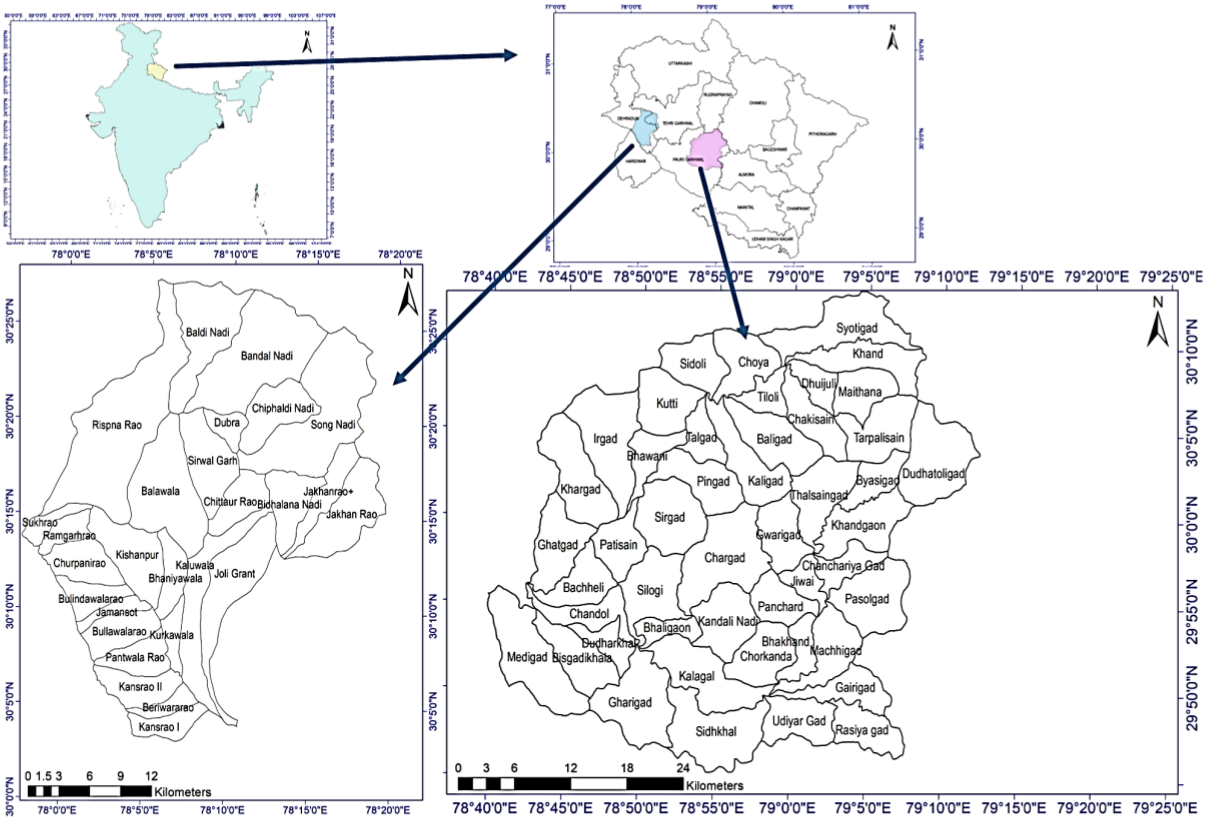



**Figure 1: Study area**

## 3. METHODOLOGY

The methodology for identifying potential areas for watershed management involves the systematic integration of multiple thematic layers using Geographic Information System (GIS) tools. The approach consists of data collection, thematic layer preparation, weighted overlay analysis and classification of potential areas for Watershed management. The study utilizes key spatial datasets, including a Digital Elevation Model (DEM), land use/land cover (LULC) data, soil data and geological data. The methodology ensures a structured analysis to identify zones suitable for watershed management within the Song and Nayar catchment.

### 3.1 Data Collection

The successful delineation of potential areas for watershed management requires the integration of multiple datasets that provide insights into terrain characteristics, soil properties, geological formations, and land use changes. These datasets are essential for designing effective interventions aimed at enhancing groundwater recharge and sustainable water resource management. The key datasets utilized in the study are described in detail below.

### 3.1.1 Topographical Data

In this study, the FAB DEM (Fine-resolution Adaptive Blending Digital Elevation Model) dataset was used to analyze terrain characteristics. This dataset provides a high-resolution elevation model with a 30-meter spatial resolution, ensuring an accurate representation of topographical variations within the study area. The DEM was instrumental in deriving slope gradients, flow direction, drainage networks, and watershed boundaries. Since slope directly influences groundwater recharge potential, the DEM was further processed to classify the study area into different slope categories. Gentle slopes facilitate infiltration, whereas steep slopes promote surface runoff, reducing recharge potential.

### 3.1.2 Soil Data

Soil characteristics play a crucial role in determining infiltration rates, permeability, and water retention capacity, all of which directly affect groundwater recharge. The soil classification data was obtained from the National Remote Sensing Centre (NRSC) and sourced from the GIS server of IIT Delhi (available at http://gisserver.civil.iitd.ac.in/grbmp/downloaddataset.aspx).

### 3.1.3 Geological Data

Geological formations significantly influence subsurface water movement, storage capacity, and permeability. Understanding the lithological characteristics of the study area is critical for groundwater recharge planning. Geological data was obtained from the Geological Survey of India (GSI), providing detailed lithological and structural information. This dataset includes information on rock types, fractures, fault zones, and subsurface permeability.

### 3.1.4 Land Use and Land Cover (LULC) Data

Land use and land cover (LULC) patterns provide critical insights into surface conditions, vegetation cover, impervious surfaces, and anthropogenic influences on groundwater recharge. Changes in land use over time affect infiltration, runoff, and evapotranspiration, making it necessary to analyze historical LULC trends.

The LULC maps were generated using Landsat satellite imagery for different time periods, allowing for a time-series analysis of land use change. The datasets used for LULC classification include:

1995: Landsat 5 (30m resolution)
2005: Landsat 7 (30m resolution)
2015: Landsat 8 (30m resolution)
2023: Landsat 9 (30m resolution)

These datasets were processed using supervised classification techniques, with training samples collected for different land cover classes. The integration of LULC data with slope, soil, and geology information allowed for a more comprehensive assessment of groundwater recharge potential and the identification of priority areas for conservation and intervention.

### 3.2 Preprocessing

The first step in the analysis involved acquiring relevant spatial datasets, which were processed to generate thematic layers for further analysis. The DEM was obtained and used to derive the slope characteristics of the study area. Slope influences the infiltration and runoff of rainwater, thereby affecting the recharge potential. The land use/land cover dataset was collected through satellite imagery and classified into different land cover categories. The soil data was acquired and provided information on soil texture, which play a crucial role in infiltration. Additionally, geological data was incorporated to understand the subsurface lithology, as different rock formations exhibit varying degrees of porosity and permeability. The final dataset included information on priority areas for watershed management, which was useful in identifying regions where conservation efforts are required.

Before further analysis, all datasets were projected into a common coordinate reference system to ensure spatial alignment. The data preprocessing stage also involved correcting spatial inconsistencies, eliminating noise, and filling missing values where necessary.

### 3.3 Generation of Thematic Layers

Each dataset was processed to derive thematic layers that represent different factors affecting groundwater recharge.

#### 3.3.1 Slope analysis

The slope map was derived from the DEM using the Slope Tool in ArcGIS. Slope influences the movement of surface water, with flatter areas allowing more infiltration and steeper slopes facilitating runoff. The slope values were categorized into five classes: flat and gentle slope areas with a gradient of 0-8 percentage were assigned high recharge potential, Rolling slopes between 8-15 percentage were given intermediate recharge potential followed by hilly and mountainous slopes between 15-40 percentage and steep mountainous slopes between 40-60 percentage were classified as low recharge zones due to increased surface runoff and greater than 60 percentage slope were considered as very low recharge zones. Figure 1 presents the slope distribution across the study areas, indicating that significant portions of the basin have moderate to steep slopes, which may limit infiltration in certain regions.

#### 3.3.2 Land use/land cover classification

The land use/land cover map was prepared using remote sensing data and classified into different categories such as forest, agricultural land, urban settlements, water bodies, and barren land. Each land cover type influences groundwater recharge differently. Forested regions, which cover a substantial portion of the study area, promote infiltration due to dense vegetation and minimal surface runoff. Agricultural areas also contribute to recharge, though the extent varies depending on land management practices. Urbanized regions, on the other hand, have impervious surfaces such as roads and buildings that significantly reduce infiltration, leading to low recharge potential. Water bodies, though they contribute to direct recharge, are limited in spatial extent. The classified LULC maps provide a clear representation of the land use patterns within the basin, highlighting regions with varying recharge capacities.

### 3.3.3 Soil analysis

The soil characteristics of the study area were analyzed using a soil map, which categorized different soil types based on soil texture which plays a critical role in groundwater recharge.

### 3.3.4 Geology

Geological formations influence groundwater recharge by determining the storage capacity and movement of water through subsurface layers. Areas with porous rock formations, such as Tal and Balini formation, have a higher potential for recharge, whereas regions with impermeable rock layers, such as Rautgara and Chandpur formation, restrict infiltration. Understanding the geological characteristics is essential for assessing long-term groundwater availability and recharge sustainability.

## 3.4 Identification of Priority Watershed Management Areas

The final thematic layer incorporated into the analysis was the identification of priority areas for watershed management. These areas indicate regions where conservation measures such as check dams, afforestation, and rainwater harvesting could be implemented to enhance recharge. By integrating these priority areas, the study ensured that recharge assessments aligned with ongoing watershed conservation efforts, thereby promoting sustainable water resource management.

## 3.5 Weighted Overlay Analysis

The Weighted Overlay Analysis (WOA) is a GIS-based multi-criteria decision-making technique used to integrate multiple thematic layers and determine the potential areas for watershed management. The different thematic layers prepared were combined using a weighted overlay approach to generate the potential areas for prioritization for watershed management. Each layer was assigned a weight based on its relative influence on recharge. The weighting process was determined based on literature review and expert judgment, ensuring a balanced representation of factors. In this study, land use, soil, slope and geological characteristics was assigned equal weights. The thematic layers were standardized to a common scale and combined using the Weighted Overlay Tool in ArcGIS.

### 3.6 Classification and Visualization of Potential Areas for Watershed Management

The final potential areas for watershed management was classified into five categories: very low, low, moderate, high, and very high potential. Areas with dense forest cover, permeable and deep soils, and gentle slopes exhibited the highest recharge potential, while urbanized zones, steep slopes, and shallow depth soils were categorized as low recharge zones. The classified map was visualized using a color gradient, with darker shades representing higher recharge potential and lighter shades indicating limited recharge capacity. The resulting map provides a spatial representation of groundwater recharge suitability across the study area.

To enhance clarity and to streamline the execution of the work, the results were analyzed and presented at the micro-watershed level designated by the Watershed Management Directorate for the Song and Nayar river basins.

## 4. RESULTS AND DISCUSSION

### 4.1 Trend Analysis of Rainfall Patterns in Nayar and Song Catchments

Detection of trends in long term series of climatic data is of paramount importance and is of practical significance. Studies of change are also of importance because of our need to understand the anthropogenic and climate change impacts on the "natural" world. There are many approaches that can be used to detect trends and other forms of non-stationary in climatic and hydrological data. In deciding which approach to take, it is necessary to be aware of which test procedures are valid (i.e. the data meets the required test assumptions) and which procedures are most useful. The Mann-Kendall Test (MK Test) has been widely applied for detection of trends in hydro-meteorological variables due to following reasons:

a) MK test does not require the assumption of normality or the assumption of homogeneity of variance.
b) It compares medians rather than means and, as a result, if the data have one or two outliers, their influence is negated.
c) In MK test, prior transformations are not required, even when approximate normality could be achieved.
d) Greater power is achieved for the skewed distributions in MK test.

However, the MK tests are based on the assumption that the time series is serially independent in nature i.e. uncorrelated. In many cases, the observed climatic data are either serially correlated or auto-correlated. This autocorrelation leads to misinterpretation of the results. Therefore, in this study, the original MK test is used. MK test determines the change in the central value or median with time keeping the spreading of the distribution to be constant.

### 4.1.1 Mann-Kendall test

The MK test, also called Kendall's tau test due to Mann (1945) and Kendall (1975), is the rank based nonparametric test for assessing the significance of a trend, and has been widely used in hydrological trend detection studies. It is based on the test statics S defined as below:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \qquad \text{….(1)}$$

Where, $x_1$, $x_2$, … $x_n$ represent n data points where $x_j$ represents the data point at time j.

A very high positive value of S is an indicator of an increasing trend, and a very low negative value indicates a decreasing trend.

$$\mathrm{sgn}(x_j - x_i) = \begin{Bmatrix} 1 \ldots\ldots\ldots \text{ if } (x_j - x_i) > 0 \\ 0 \ldots\ldots\ldots \text{ if } (x_j - x_i) = 0 \\ -1 \ldots\ldots\ldots \text{ if } (x_j - x_i) < 0 \end{Bmatrix} \qquad \text{….(2)}$$

It has been documented that when n ≥10, the statistic S is approximately normally distributed with the mean

$$E(S) = 0$$

And its variance is

$$VAR(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \qquad \text{….(3)}$$

Where n is the number of data points, m is the number of tied groups (a tied group is a set of sample data having the same value), and $t_i$ is the number of data points in the $i^{th}$ group.

The standardized test statistic Z is computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} \text{ if } S < 0 \end{cases} \quad ....(4)$$

The null hypothesis, H0, meaning that no significant trend is present, is accepted if the test statistic Z is not statistically significant, i.e. $-Z_{\alpha/2} < Z < Z_{\alpha/2}$, where $Z_{\alpha/2}$ is the standard normal deviate. In this study, three different significance levels i.e. 1%, 5% and 10% were considered.

***Slope***

Slope of the lines fit to the time series of climatic data provides a picture of changes that have occurred at any location over an extended period. The slope of the data set can be estimated using the Thiel-Sen Approach. This equation is used instead of a linear regression because it limits the influence that the outliers have on the slope (Hirsch et al, 1982).

$$\beta = Median\left[\frac{X_j - X_i}{j-i}\right] \; For\ all\ i < j \quad ....(5)$$

where $X_j$ and $X_i$ are data values at times j and i (i>j), respectively.

### 4.1.2 Trend analysis of rainfall and number of rainy days in Nayar and Song catchments (1951-2022)

The present study focuses on the long-term trend analysis of rainfall and the number of rainy days (NRD) in the Nayar and Song catchments over the period 1951–2022. Understanding the historical changes in rainfall patterns is essential for water resource management in the catchments. This study assesses trends in seasonal and annual rainfall, the associated NRD changes, and their implications for sustainable hydrological management.

### 4.1.2.1 Trend analysis of rainfall patterns in Nayar catchment

***Season I (Monsoon Season)***

The rainfall trend analysis for the Nayar catchment indicates a consistent decline in monsoon rainfall at most locations. The slope of the trend varies between -7.117 mm/season and +2.511 mm/season, highlighting both declining and increasing rainfall trends in different locations. The total change in monsoon rainfall ranges from -512.39 mm to +180.81 mm over the study period. This decline in monsoon precipitation has a significant impact on surface water availability and groundwater recharge potential, which are critical for sustaining water resources in this region. Table 1 presented distribution and trend of the rainfall in and around catchment. Figure 2 and 3 exhibited average rainfall and trend of rainfall in the catchment.

**Table 1: Average Monsoon season Rainfall along with Trend, Slope and Total Change during 1951-2022**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/season) | Total Change (mm) |
|---|---|---|---|---|---|
| 29.75 | 78.75 | 1050.52 | -1 | -7.117 | -512.39 |
| 29.75 | 79 | 1008.34 | -1 | -6.650 | -478.83 |
| 29.75 | 79.25 | 927.19 | -1 | -4.844 | -348.77 |
| 30 | 78.75 | 855.40 | -5 | -3.295 | -237.23 |
| 30 | 79 | 839.57 | 0 | -1.237 | -89.04 |
| 30 | 79.25 | 850.65 | 0 | -0.645 | -46.40 |
| 30.25 | 78.75 | 806.08 | 0 | 1.648 | 118.68 |
| 30.25 | 79 | 834.82 | 0 | 1.628 | 117.21 |
| 30.25 | 79.25 | 875.37 | 0 | 2.511 | 180.81 |

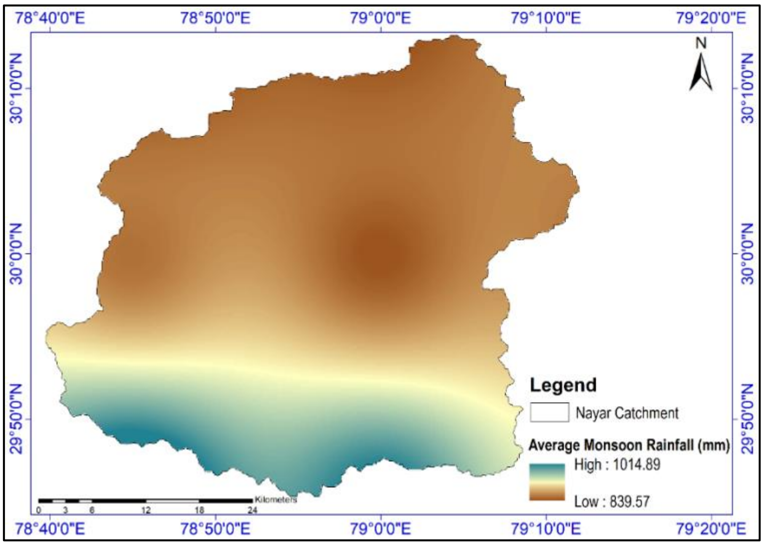



**Figure 2: Average monsoon rainfall of Nayar catchment during 1951-2022**

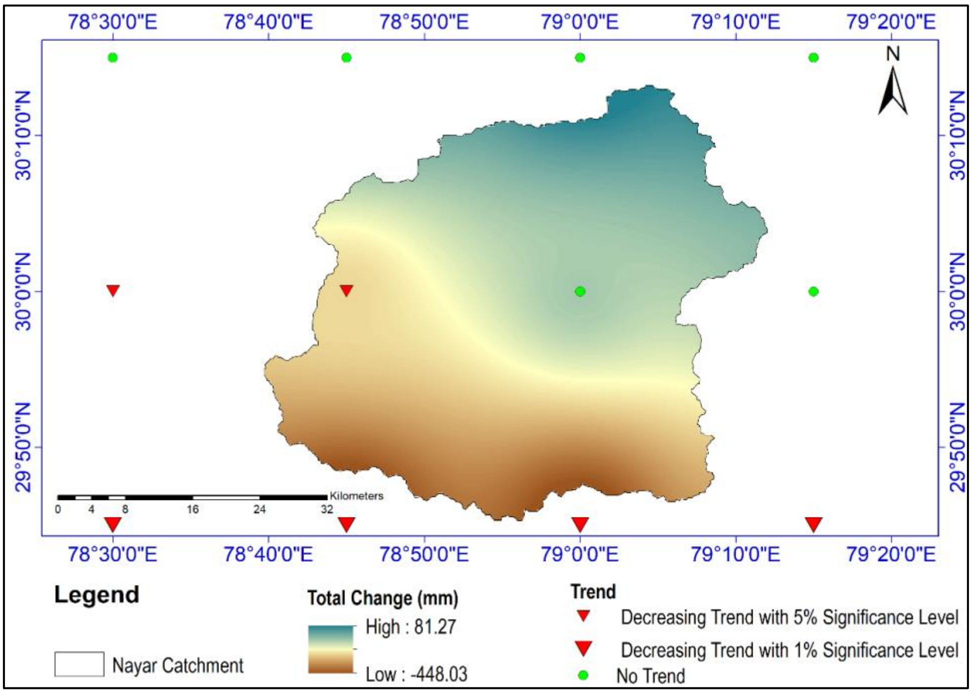



**Figure 3: Trend and total change of monsoon rainfall in Nayar catchment during 1951-2022**

***Season II (Winter Season)***

The Winter rainfall in and around the Nayar catchment shows relatively minor changes, with reductions ranging between -9.16 mm and -30.98 mm. The slope of the trend varies between -0.430 mm/season and -0.127 mm/season, indicating a generally declining trend in winter precipitation. Although these changes are not drastic, they indicate a weakening of winter precipitation, which can affect water supply in the dry season. Table 2 presented distribution and trend of the rainfall in and around catchment. Figures 4 and 5 exhibited distribution and trend of rainfall in the catchment.

**Table 2: Average Winter season Rainfall along with Trend, Slope and Total Change during 1951-2022**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/season) | Total Change (mm) |
|---|---|---|---|---|---|
| 29.75 | 78.75 | 96.32 | 0 | -0.386 | -27.79 |
| 29.75 | 79 | 111.35 | 0 | -0.416 | -29.97 |
| 29.75 | 79.25 | 113.02 | 0 | -0.430 | -30.98 |
| 30 | 78.75 | 97.11 | 0 | -0.185 | -13.31 |
| 30 | 79 | 104.93 | 0 | -0.202 | -14.57 |
| 30 | 79.25 | 107.94 | 0 | -0.198 | -14.22 |
| 30.25 | 78.75 | 102.77 | 0 | -0.261 | -18.78 |
| 30.25 | 79 | 112.05 | 0 | -0.127 | -9.16 |
| 30.25 | 79.25 | 117.62 | 0 | -0.244 | -17.59 |

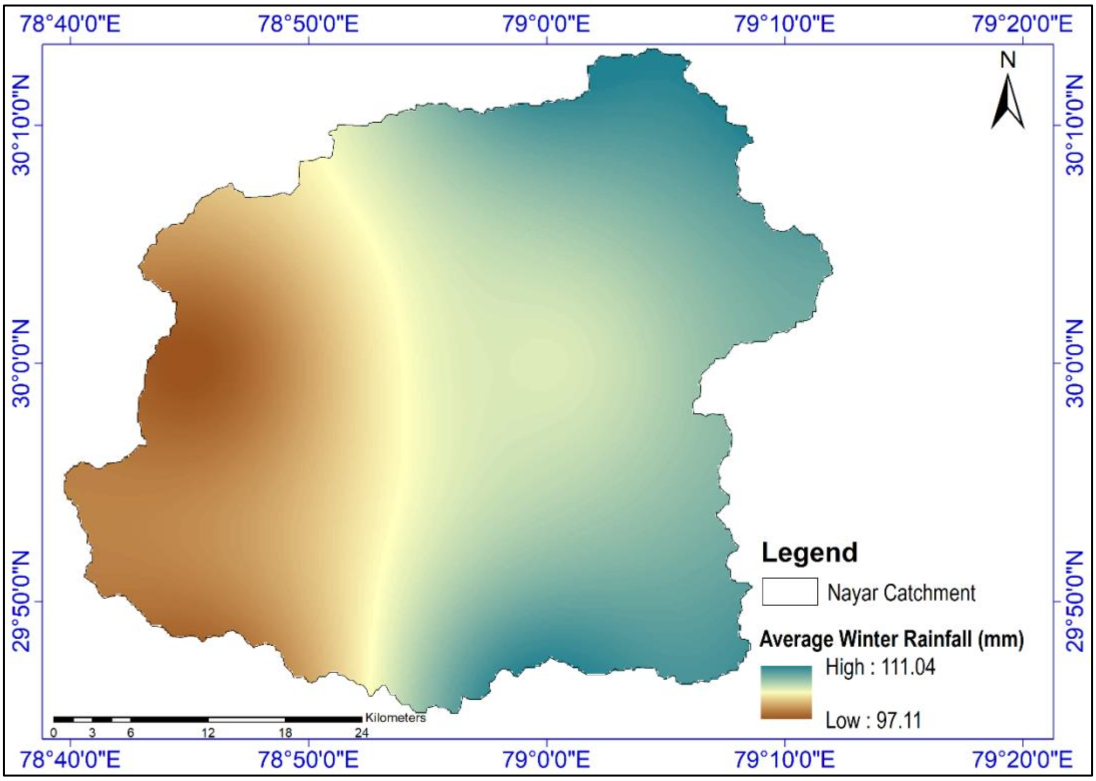



**Figure 4: Average winter rainfall of Nayar catchment during 1951-2022**

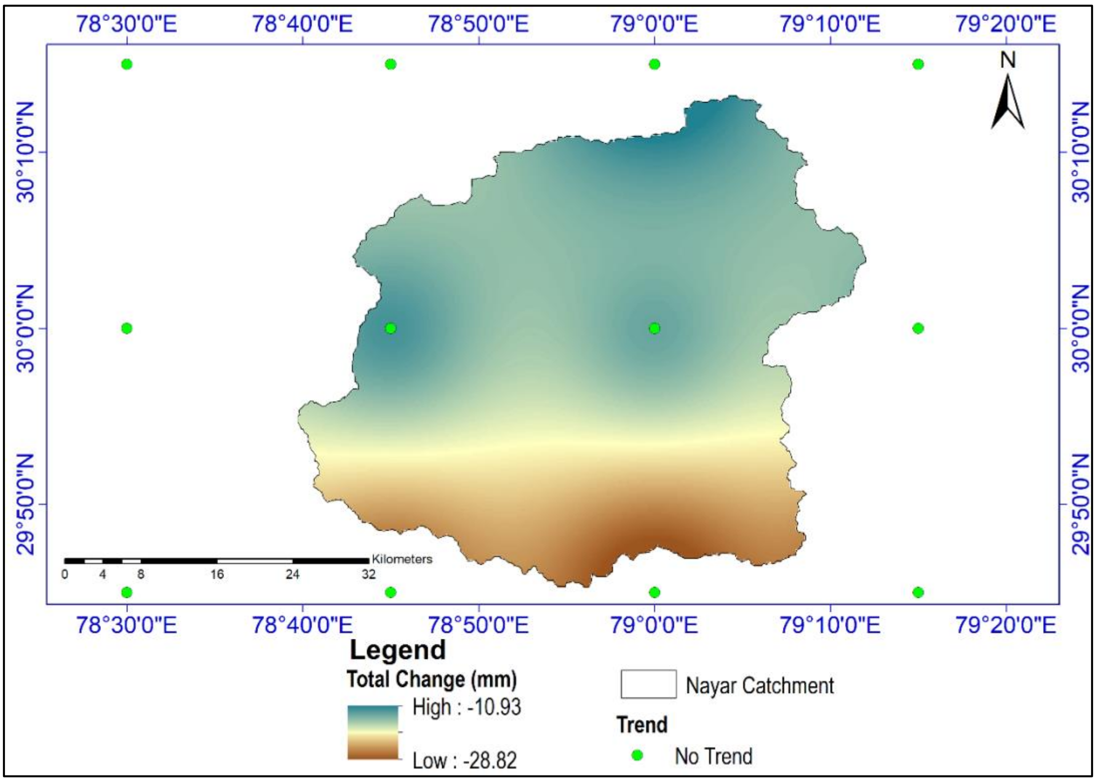



**Figure 5: Trend and total change of winter rainfall in Nayar catchment during 1951-2022**

***Season III (Summer Season)***

The summer season presents a mixed pattern in and around catchment with non-significant trend with slope values ranging from -0.657 mm/season to +0.778 mm/season. The total change in summer rainfall varies between -47.29 mm and +56.03 mm, suggesting that local convective systems may influence summer rainfall trends, leading to spatial heterogeneity in precipitation. Table 3 presented distribution and trend of the rainfall in and around catchment. Figures 6 and 7 exhibited distribution and trend of rainfall in the catchment.

**Table 3: Average Summer season Rainfall along with Trend, Slope and Total Change during 1951-2022**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/season) | Total Change (mm) |
|---|---|---|---|---|---|
| 29.75 | 78.75 | 122.42 | 0 | -0.657 | -47.29 |
| 29.75 | 79.00 | 144.63 | 0 | -0.404 | -29.07 |
| 29.75 | 79.25 | 166.11 | 0 | -0.318 | -22.87 |
| 30.00 | 78.75 | 161.70 | 0 | 0.227 | 16.37 |
| 30.00 | 79.00 | 173.21 | 0 | 0.162 | 11.64 |
| 30.00 | 79.25 | 181.24 | 0 | 0.055 | 3.98 |
| 30.25 | 78.75 | 183.83 | 0 | 0.778 | 56.03 |
| 30.25 | 79.00 | 201.74 | 0 | 0.685 | 49.32 |
| 30.25 | 79.25 | 221.33 | 0 | 0.478 | 34.44 |

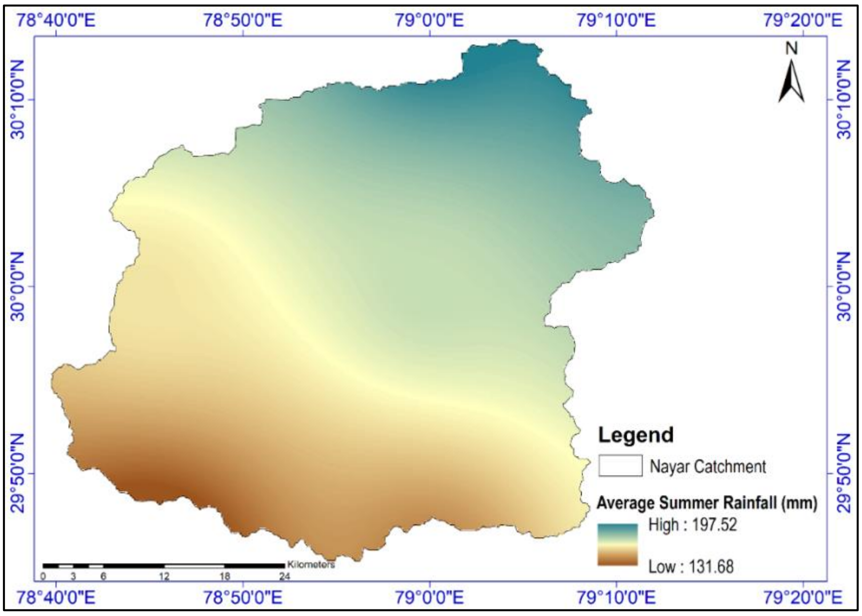



**Figure 6: Average Summer Rainfall of Nayar Catchment during 1951-2022**

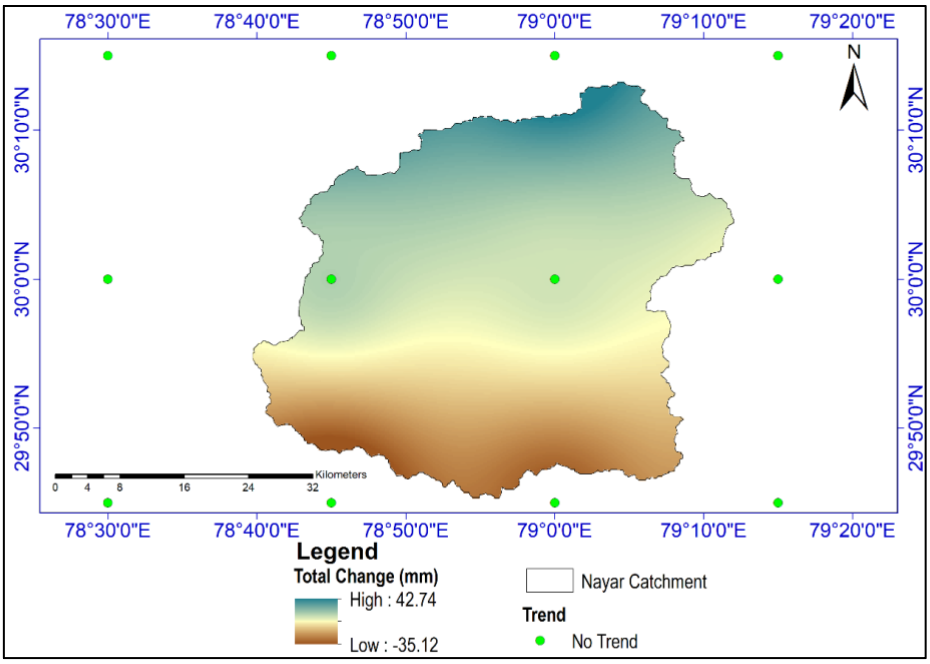



**Figure 7: Trend and Total change of Summer Rainfall in Nayar Catchment during 1951-2022**

### *Annual Rainfall*

The annual rainfall trend in and around the catchment indicates a substantial decline in precipitation, with total changes ranging from -557.64 mm to +140.05 mm. Table 4 presented distribution and trend of the rainfall in and around catchment. Figures 8 and 9 exhibited distribution and trend of rainfall in the catchment. The slope of the annual rainfall trends varies between -7.745 mm/year and +1.945 mm/year. The declining trend is more pronounced at lower latitudes, implying that the southern regions of the catchment may face increasing water stress.

**Table 4: Average Annual Rainfall along with Trend, Slope and Total Change during 1951-2022**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/year) | Total Change (mm) |
|---|---|---|---|---|---|
| 29.75 | 78.75 | 1269.26 | -1 | -7.745 | -557.64 |
| 29.75 | 79.00 | 1264.32 | -1 | -7.501 | -540.04 |
| 29.75 | 79.25 | 1206.33 | -1 | -6.735 | -484.92 |
| 30.00 | 78.75 | 1114.21 | -5 | -4.468 | -321.66 |
| 30.00 | 79.00 | 1117.71 | -10 | -2.847 | -204.96 |
| 30.00 | 79.25 | 1139.84 | 0 | -2.358 | -169.74 |
| 30.25 | 78.75 | 1092.68 | 0 | 1.179 | 84.91 |
| 30.25 | 79.00 | 1148.62 | 0 | 0.615 | 44.27 |
| 30.25 | 79.25 | 1214.32 | 0 | 1.945 | 140.05 |

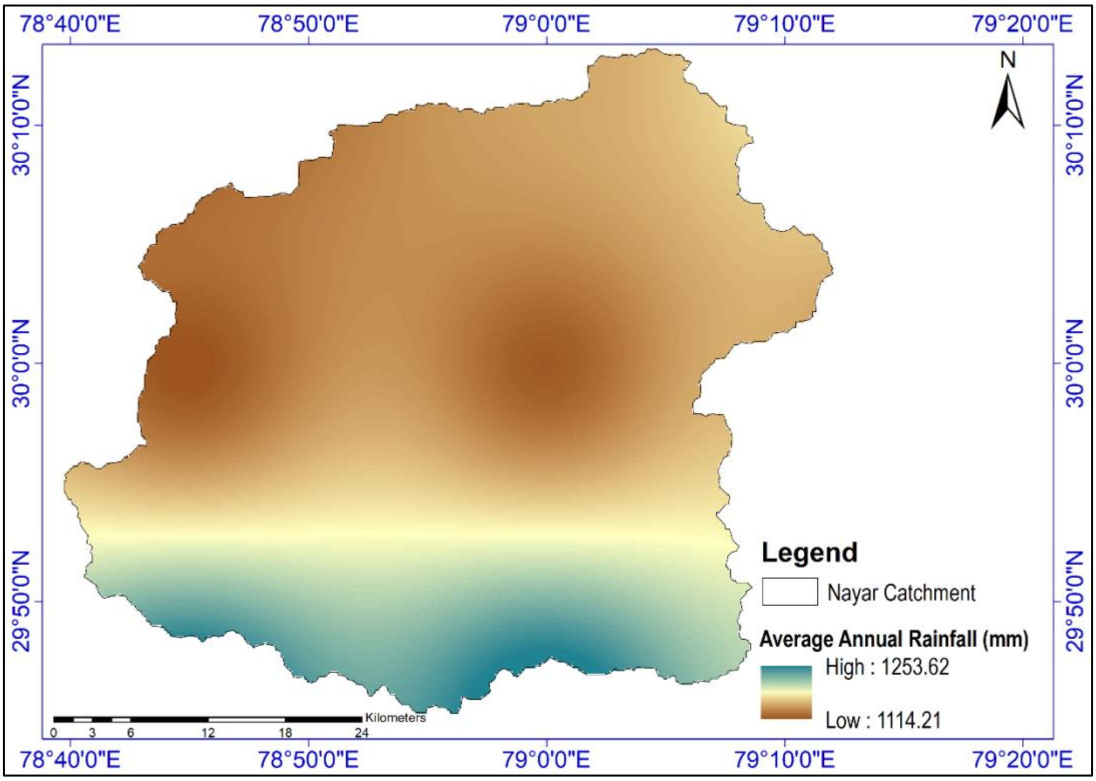



**Figure 8: Average Annual Rainfall of Nayar Catchment during 1951-2022**

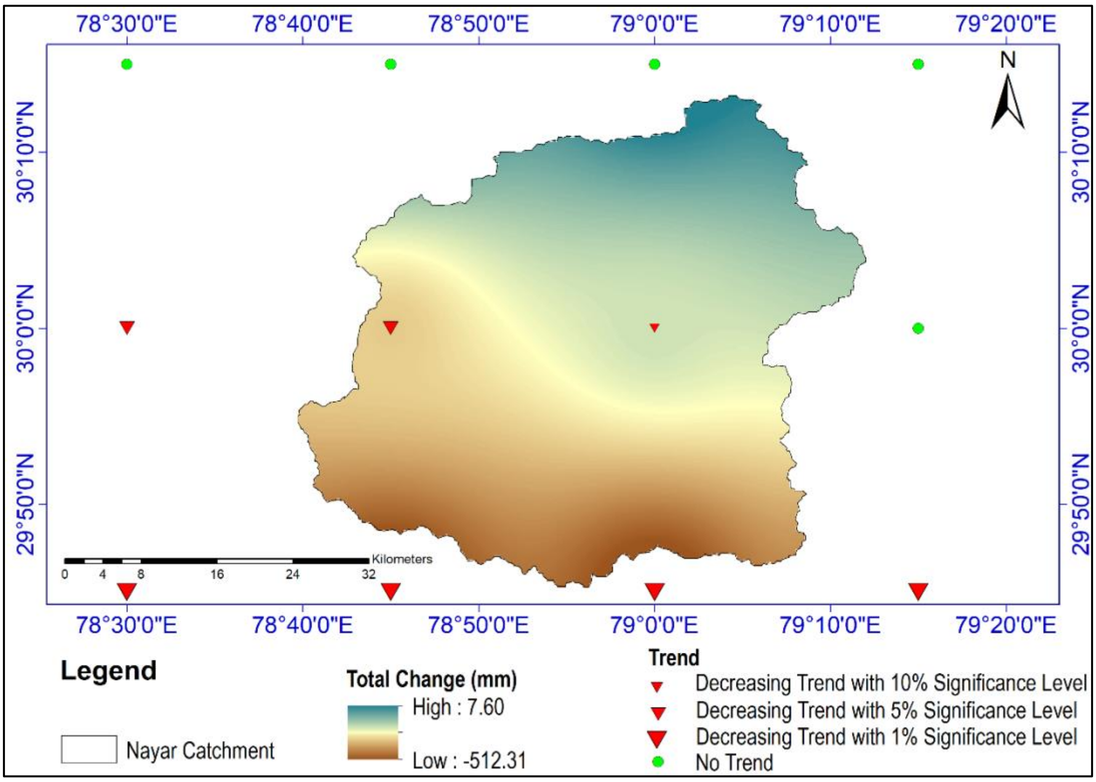



**Figure 9: Trend and Total change of Annual Rainfall in Nayar Catchment during 1951-2022**

***Number of Rainy Days (NRD)***

The analysis of NRD trends in and around catchment reveals a strong correlation with the observed changes in total rainfall. Table 5 presented distribution and trend of the NRD in and around catchment. Figures 10 and 11 exhibited distribution and trend of NRD in the catchment. In the Nayar catchment, a general decline in NRD is observed, with reductions reaching -27 days at some locations. The slope of NRD trends varies between -0.378 days/year and +0.150 days/year, indicating an overall declining pattern. The total change in NRD ranges from -27 days to +11 days. The declining NRD suggests that the reduction in total rainfall is accompanied by fewer precipitation events, which may indicate a shift toward more intense but less frequent rainfall. This shift could lead to increased surface runoff and reduced infiltration, ultimately affecting groundwater recharge.

**Table 5: Average Annual Number of Rainy Days along with Trend, Slope and Total Change during 1951-2022**

| Latitude | Longitude | Avg. NRD | Trend | Slope of trend (days/year) | Total Change (days) |
|---|---|---|---|---|---|
| 29.75 | 78.75 | 73 | -1 | -0.306 | -22 |
| 29.75 | 79.00 | 74 | -1 | -0.263 | -19 |
| 29.75 | 79.25 | 72 | -1 | -0.378 | -27 |
| 30.00 | 78.75 | 74 | -5 | -0.166 | -12 |
| 30.00 | 79.00 | 78 | 0 | -0.067 | -5 |
| 30.00 | 79.25 | 79 | 0 | -0.083 | -6 |
| 30.25 | 78.75 | 73 | 0 | -0.042 | -3 |
| 30.25 | 79.00 | 69 | 0 | 0.150 | 11 |
| 30.25 | 79.25 | 81 | 0 | 0.132 | 10 |

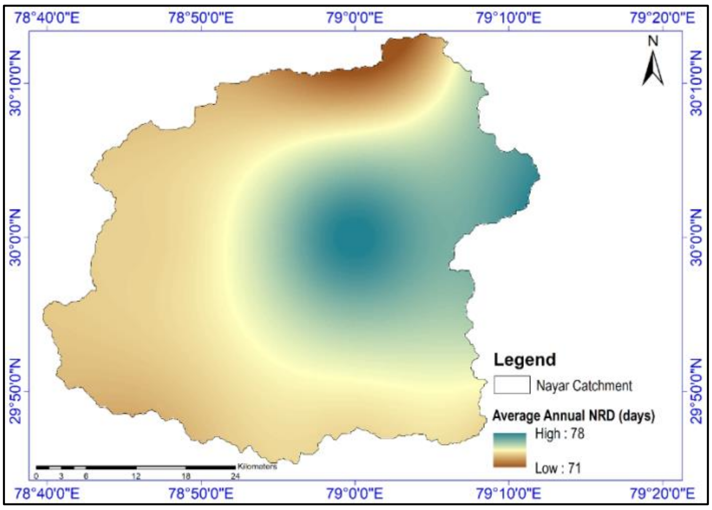



**Figure 10: Average annual number of rainy days in Nayar catchment during 1951-2022**

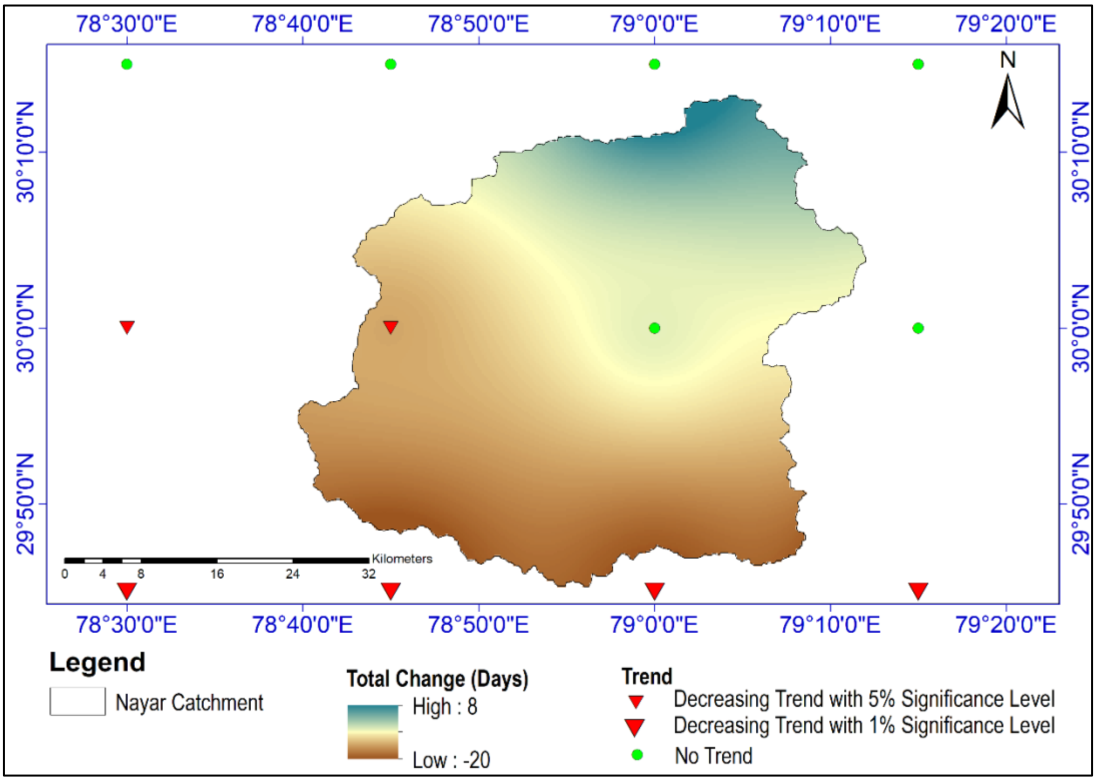



**Figure 11: Trend and Total change of Annual Number of Rainy Days in Nayar Catchment during 1951-2022**

The declining trend in monsoon rainfall and NRD suggests increasing water scarcity risks, necessitating effective watershed management strategies. Key interventions should include rainwater harvesting, check dams, and managed aquifer recharge to enhance groundwater storage. Soil and water conservation measures such as contour bunding and afforestation can help reduce surface runoff and improve infiltration.

The reduction in winter rainfall highlights the need to optimize water storage structures to sustain dry-season flow. Enhancing traditional water conservation structures such as ponds and step-wells can improve water availability during lean periods. Additionally, irrigation scheduling should be adjusted to match the evolving climatic conditions, ensuring efficient water use.

#### 4.1.2.2 Trend analysis of Rainfall in Song Catchment

***Season I (Monsoon Season)***

Table 6 presented distribution and trend of the rainfall in and around catchment. Figures 12 and 13 exhibited distribution and trend of rainfall in the catchment. The rainfall trend analysis in and around Song catchment reveals a more spatially variable pattern compared to the Nayar catchment. The monsoon season rainfall has decreased significantly at several locations, with reductions up to -420.29 mm. The slope of monsoon rainfall trends varies between -5.837 mm/season and +1.136 mm/season, indicating both declining and increasing trends. The total change in monsoon rainfall ranges from -420.29 mm to +81.81 mm over the study period. These contrasting trends suggest spatial variability in monsoonal precipitation, likely influenced by local topographic effects and atmospheric circulation patterns.

**Table 6: Average Monsoon season Rainfall along with Trend, Slope and Total Change during 1951-2022 in Song River catchment**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/year) | Total Change (mm) |
|---|---|---|---|---|---|
| 30.00 | 78.00 | 1159.99 | 0 | 1.136 | 81.81 |
| 30.00 | 78.25 | 1182.92 | -1 | -4.558 | -328.16 |
| 30.25 | 78.00 | 1530.02 | -5 | -5.837 | -420.29 |
| 30.25 | 78.25 | 1087.75 | 0 | -2.351 | -169.30 |
| 30.50 | 78.00 | 1426.08 | -5 | -5.172 | -372.41 |
| 30.50 | 78.25 | 1025.98 | 0 | -2.944 | -211.98 |

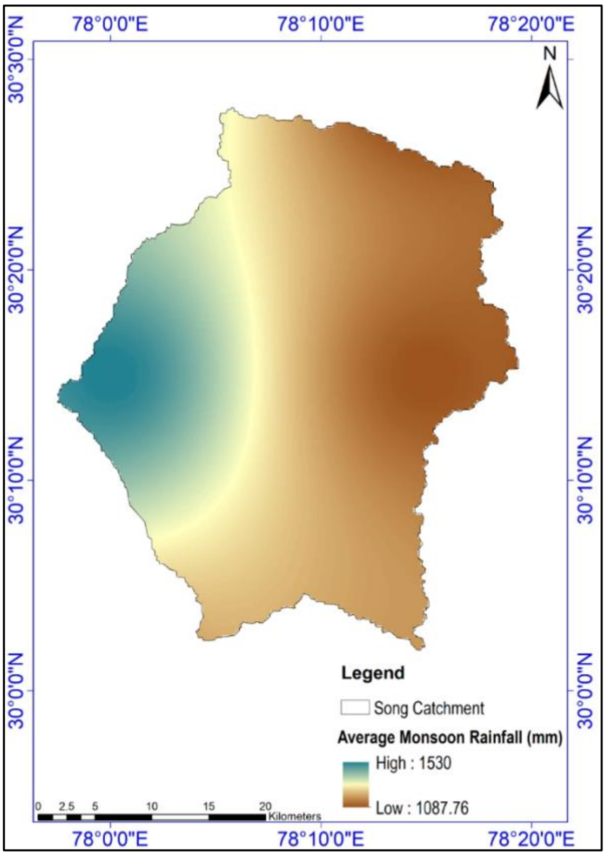



**Figure 12: Average Monsoon Rainfall of Song Catchment during 1951-2022**

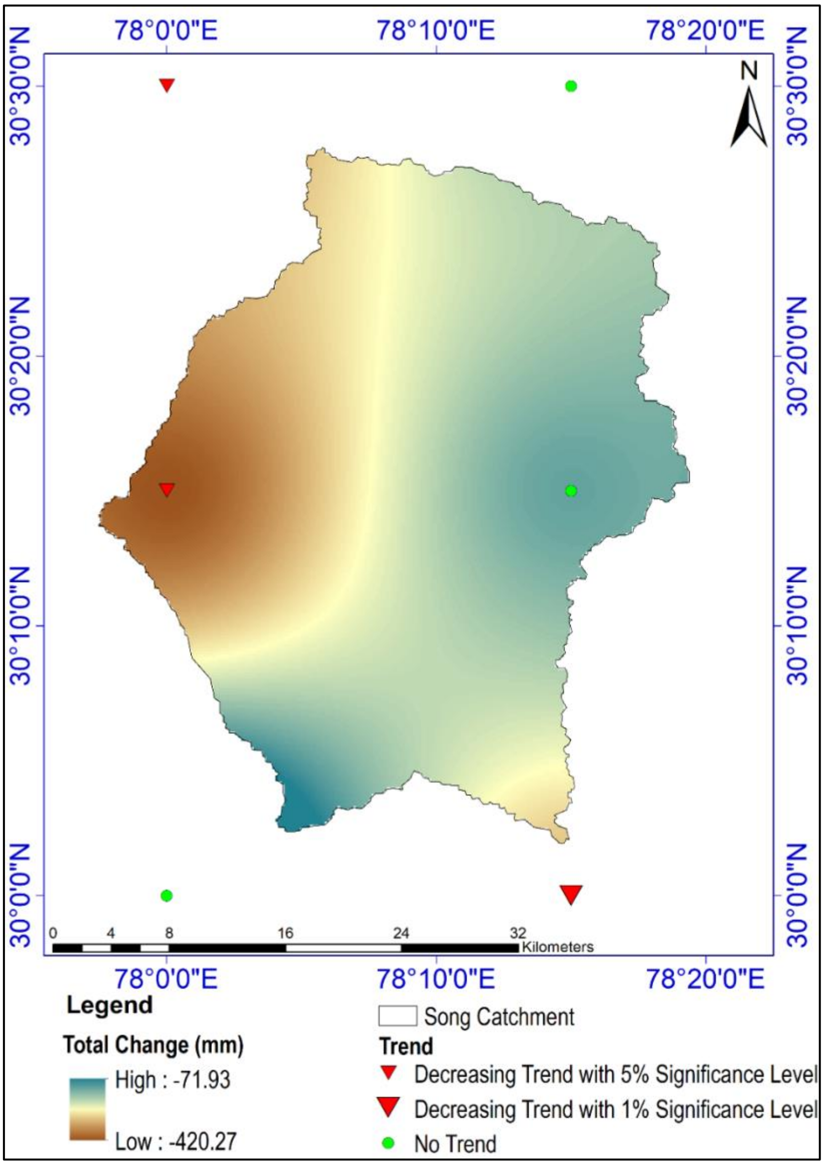



**Figure 13: Trend and Total change of Summer Rainfall in Song Catchment during 1951-2022**

***Season II (Winter Season)***

Table 7 presented distribution and trend of the rainfall in and around catchment. Figures 14 and 15 exhibited distribution and trend of rainfall in the catchment. Winter season rainfall shows a consistent decline in and around Song catchment, with total changes ranging from -38.79 mm to -1.31 mm. The slope of winter rainfall trends varies between -0.539 mm/season and -0.106 mm/season, suggesting a uniform reduction in precipitation. The reduction in winter rainfall, though not as severe as the monsoon decline, indicates a progressive decrease in seasonal water availability, which may have implications for dry-season hydrology for example, the decline could reduce the baseflow contribution to streams, affecting perennial river flow and groundwater recharge.

**Table 7: Average winter season rainfall along with trend, slope and total change during 1951-2022 in Song river catchment**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/year) | Total Change (mm) |
|---|---|---|---|---|---|
| 30.00 | 78.00 | 84.45 | 0 | -0.106 | -7.64 |
| 30.00 | 78.25 | 94.16 | 0 | -0.018 | -1.31 |
| 30.25 | 78.00 | 97.53 | 0 | -0.272 | -19.55 |
| 30.25 | 78.25 | 104.57 | 0 | -0.255 | -18.37 |
| 30.50 | 78.00 | 119.28 | 0 | -0.534 | -38.46 |
| 30.50 | 78.25 | 127.19 | 0 | -0.539 | -38.79 |

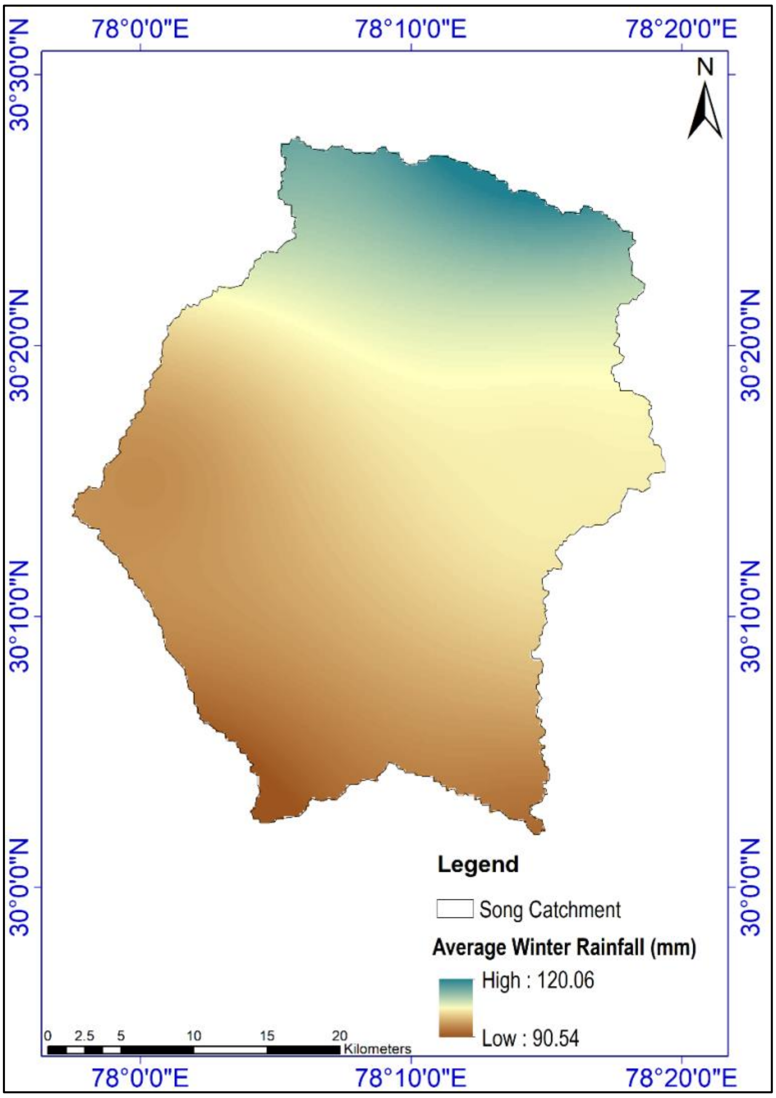



**Figure 14: Average winter rainfall of Song catchment during 1951-2022**

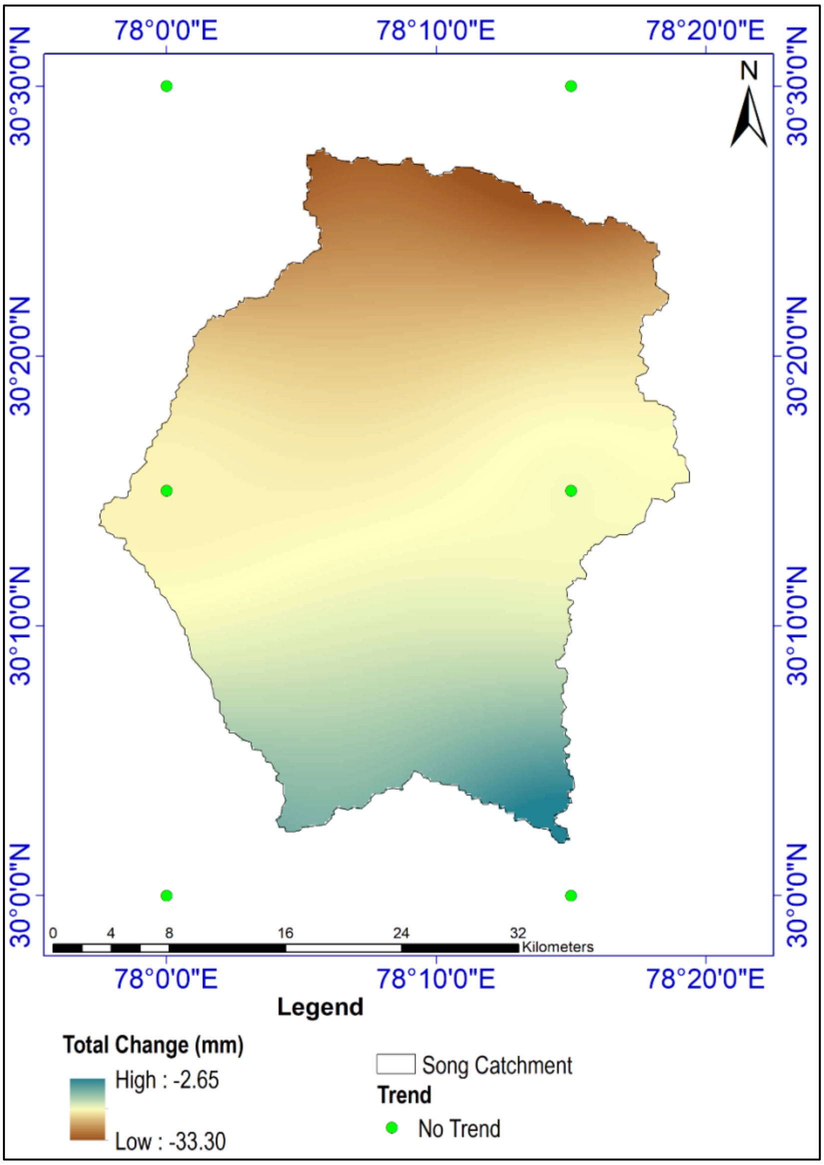



**Figure 15: Trend and total change of winter rainfall in Song catchment during 1951-2022**

***Season III (Summer Season)***

Table 8 presented distribution and trend of the rainfall in and around catchment. Figures 16 and 17 exhibited distribution and trend of rainfall in the catchment. Summer season rainfall trends show a notable increase at some locations, particularly at 30.5°N, 78.25°E (+92.92 mm). The slope of summer rainfall trends varies between 0.509 mm/season and +1.291 mm/season, and the total change in summer rainfall ranges from 36.63 mm to 92.92 mm. The positive trend in summer rainfall may be attributed to localized convective storms, nevertheless, the overall impact of such events on annual water balance remains limited due to the total contribution of summer season is very less.

**Table 8: Average summer season rainfall along with trend, slope and total change during 1951-2022 in Song river catchment**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/year) | Total Change (mm) |
|---|---|---|---|---|---|
| 30.00 | 78.00 | 121.01 | 1 | 1.267 | 91.19 |
| 30.00 | 78.25 | 141.20 | 0 | 0.595 | 42.83 |
| 30.25 | 78.00 | 145.64 | 0 | 0.509 | 36.63 |
| 30.25 | 78.25 | 186.15 | 5 | 1.047 | 75.40 |
| 30.50 | 78.00 | 207.12 | 0 | 0.852 | 61.32 |
| 30.50 | 78.25 | 243.18 | 5 | 1.291 | 92.92 |

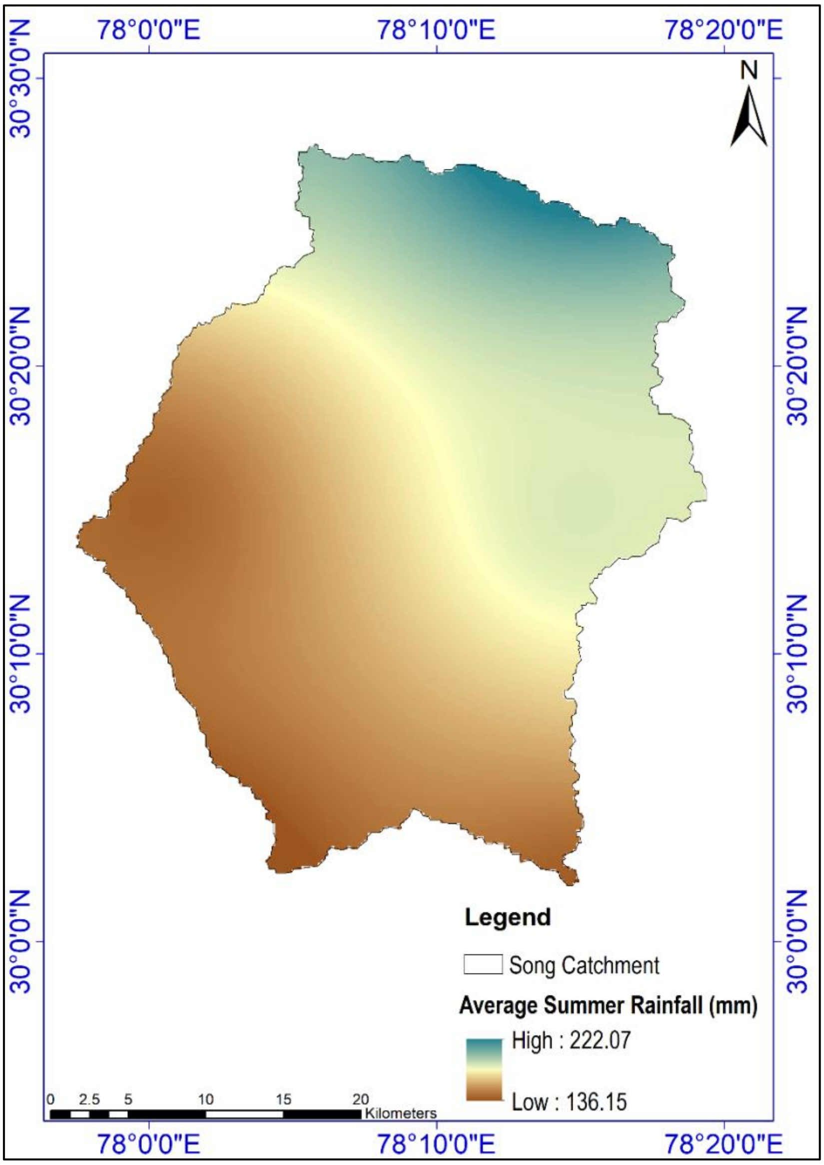



**Figure 16: Average Summer Rainfall of Song Catchment during 1951-2022**

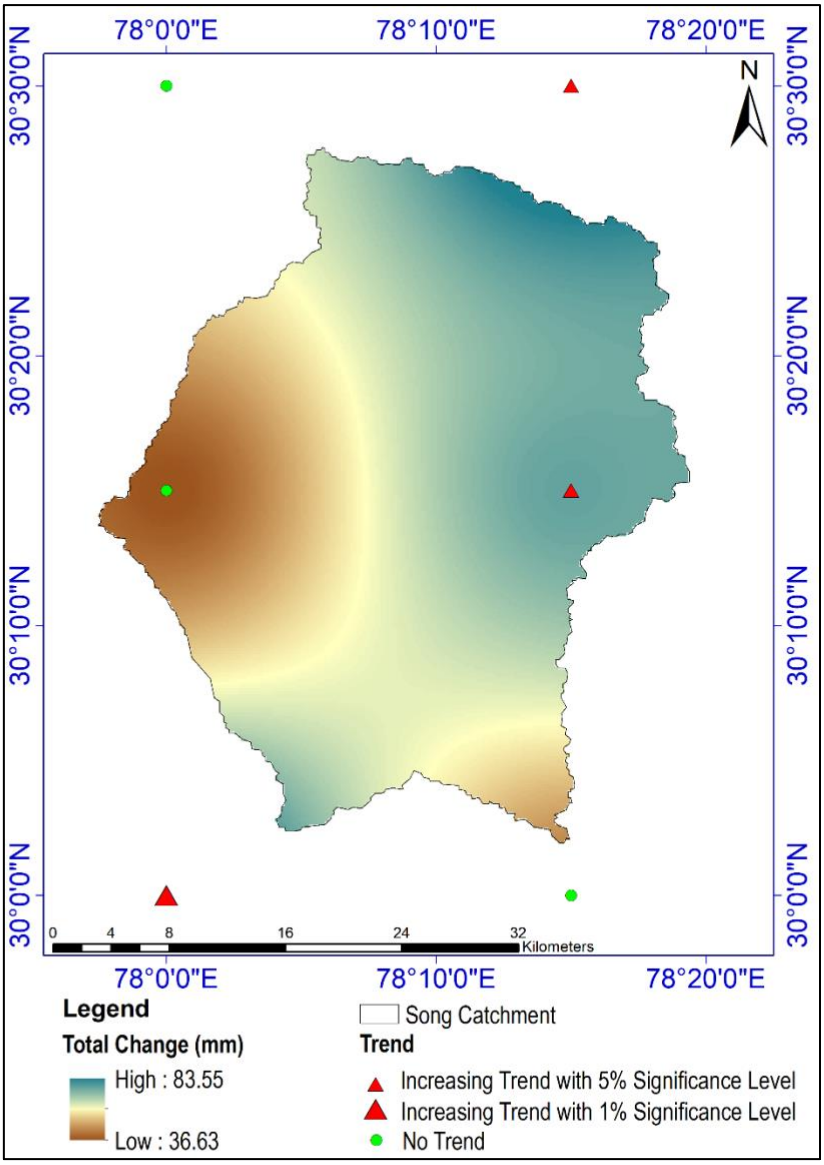



**Figure 17: Trend and Total change of Summer Rainfall in Song Catchment during 1951-2022**

### *Annual Rainfall*

Table 9 presented distribution and trend of the rainfall in and around catchment. Figures 18 and 19 exhibited distribution and trend of rainfall in the catchment. Annual rainfall trends in and around Song catchment indicate both increasing and decreasing trends at different stations. Some locations exhibit significant declines (-409.44 mm), while others show modest increases (+169.32 mm). The slope of annual rainfall trends varies between -5.687 mm/year and +2.352 mm/year. The spatial heterogeneity in rainfall trends highlights the need for localized water management strategies tailored to the specific hydrological conditions of different sub-regions within the catchment.

**Table 9: Average annual Rainfall along with trend, slope and total change during 1951-2022 in Song River catchment**

| Latitude | Longitude | Avg. Rainfall (mm) | Trend | Slope of trend (mm/year) | Total Change (mm) |
|---|---|---|---|---|---|
| 30.00 | 78.00 | 1365.45 | 0 | 2.352 | 169.32 |
| 30.00 | 78.25 | 1418.28 | -5 | -3.887 | -279.87 |
| 30.25 | 78.00 | 1773.19 | -5 | -5.657 | -407.30 |
| 30.25 | 78.25 | 1378.48 | 0 | -0.761 | -54.76 |
| 30.50 | 78.00 | 1752.48 | -5 | -5.687 | -409.44 |
| 30.50 | 78.25 | 1396.35 | -10 | -3.319 | -238.99 |

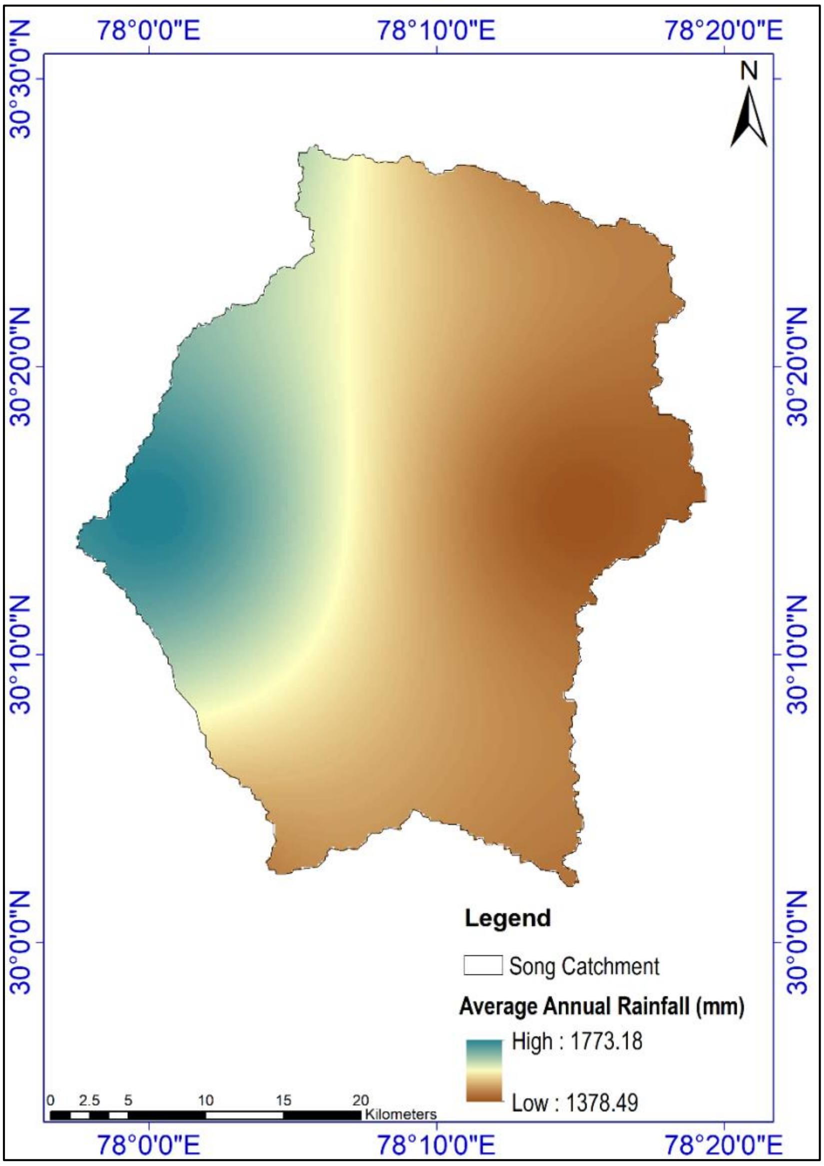



**Figure 18: Average Annual Rainfall of Song Catchment during 1951-2022**

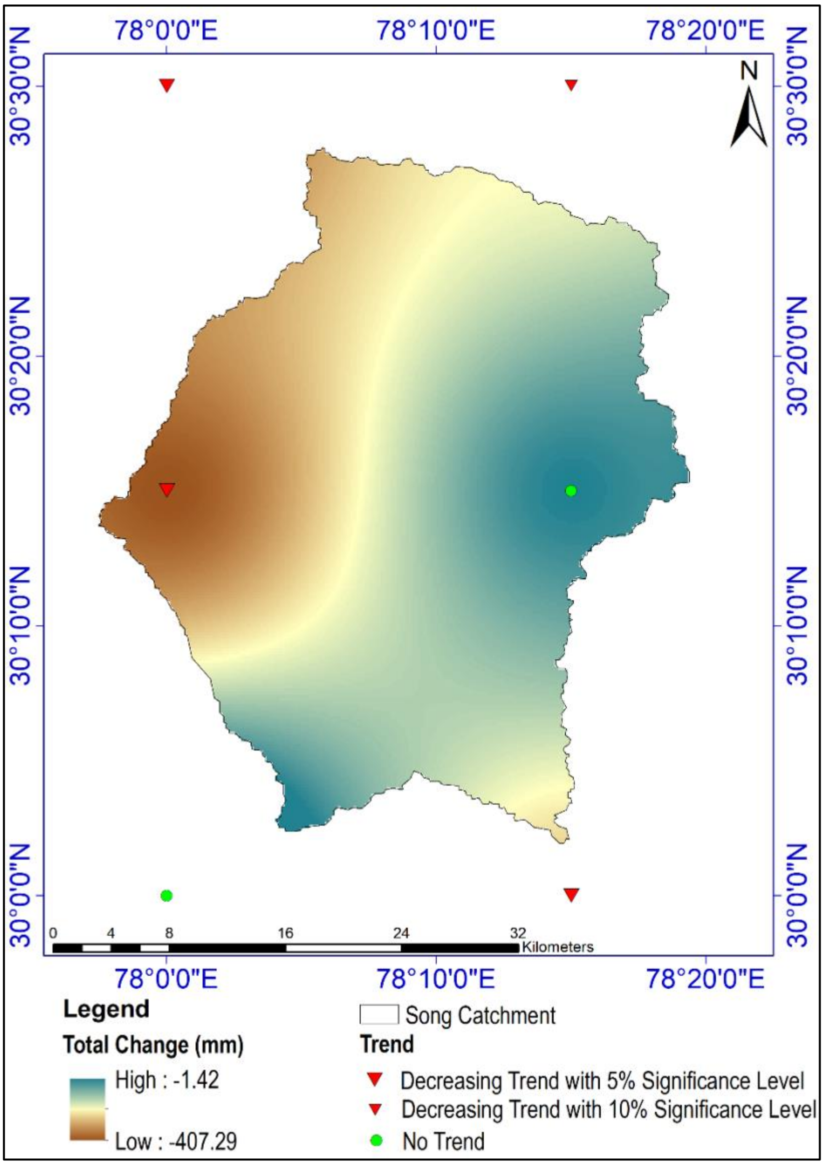



**Figure 19: Trend and Total change of Annual Rainfall in Song Catchment during 1951-2022**

### *Number of Rainy days (NRD)*

Table 10 presented distribution and trend of the NRD in and around catchment. Figures 20 and 21 exhibited distribution and trend of NRD in the catchment. The Song catchment exhibits a mixed trend in NRD, with some locations experiencing decreases of up to -15 days, while others show slight increases (+8 days). The slope of NRD trends varies between -0.208 days/year and +0.106 days/year, and the total change in NRD ranges from -15 days to +8 days. The stations with increasing NRD tend to correspond with areas experiencing rising summer rainfall, suggesting that additional rainy days may be associated with short-duration convective events. However, the overall decline in NRD in several parts of the catchment indicates a shift toward more erratic rainfall patterns, which could pose challenges for water resource management.

**Table 10: Average annual number of rainy days along with trend, slope and total change during 1951-2022 in Song river catchment**

| Latitude | Longitude | Avg. NRD | Trend | Slope of trend (days/year) | Total Change (days) |
|---|---|---|---|---|---|
| 30.00 | 78.00 | 62 | 0 | 0.106 | 8 |
| 30.00 | 78.25 | 79 | 0 | -0.127 | -9 |
| 30.25 | 78.00 | 86 | 0 | -0.118 | -8 |
| 30.25 | 78.25 | 81 | 0 | -0.085 | -6 |
| 30.50 | 78.00 | 95 | -5 | -0.167 | -12 |
| 30.50 | 78.25 | 82 | -1 | -0.208 | -15 |

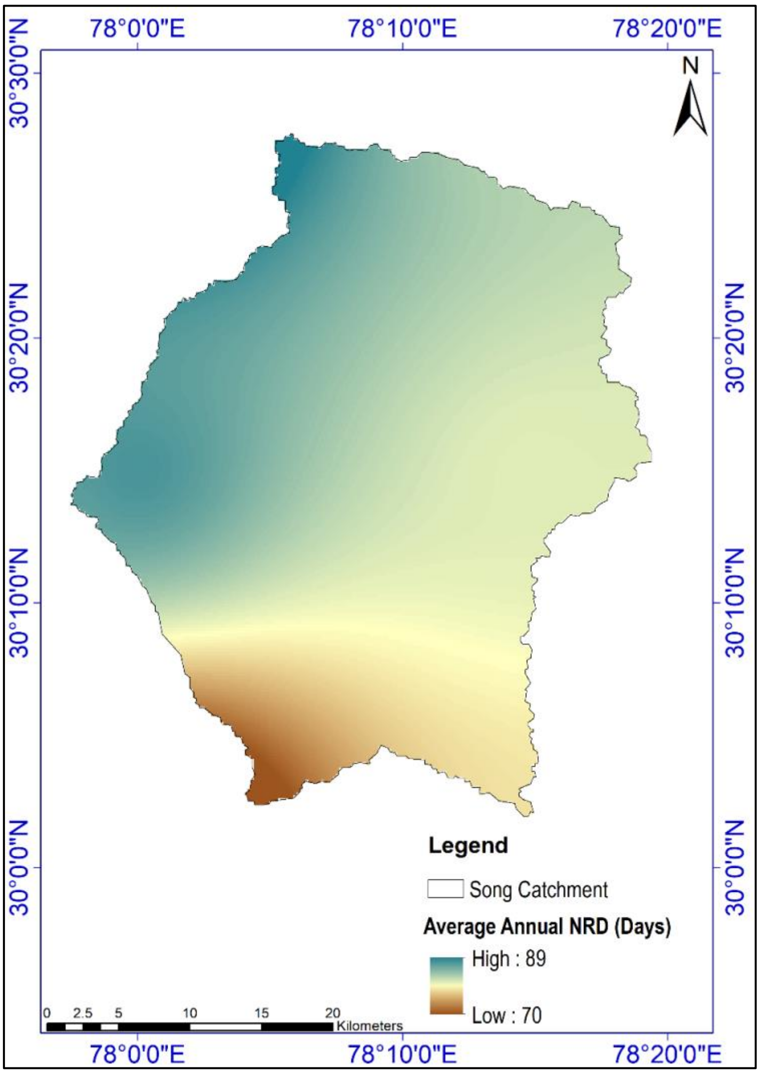



**Figure 20: Average Annual Number of Rainy Days in Song Catchment during 1951-2022**

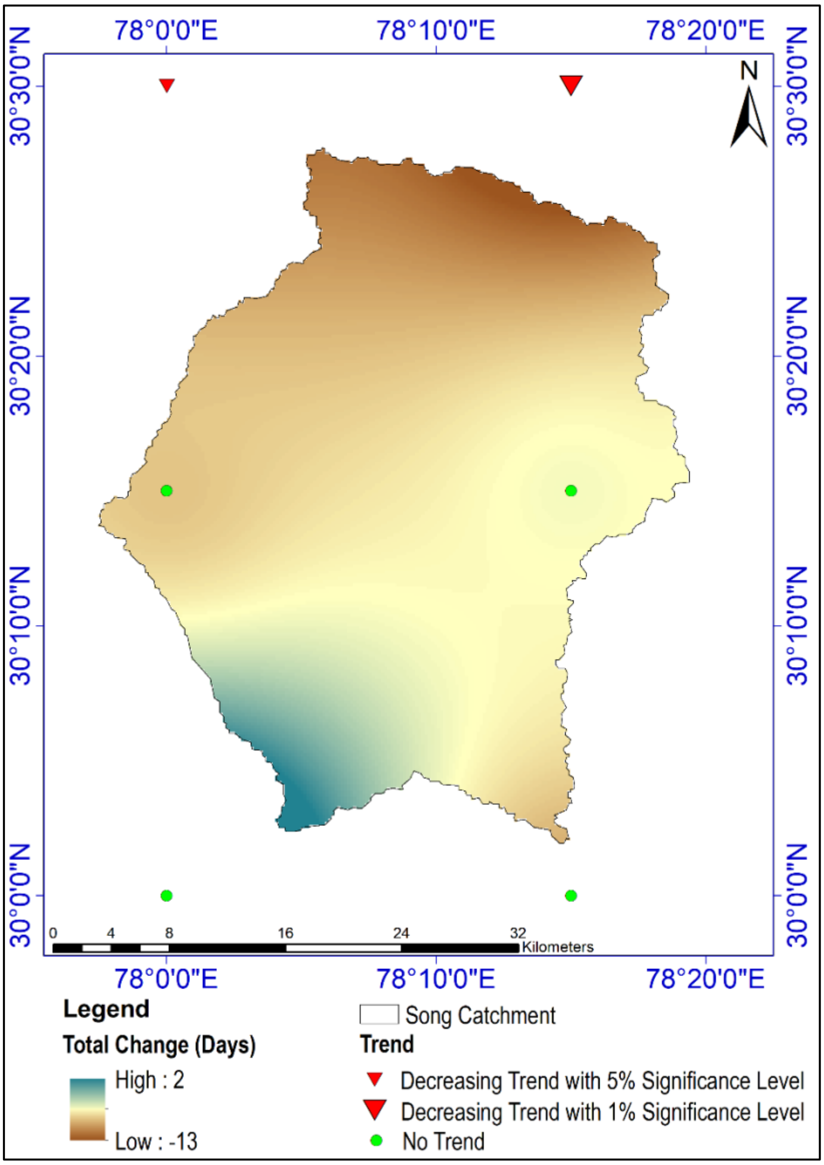



**Figure 21: Trend and total change of annual number of rainy days in Song catchment during 1951-2022**

The spatial variability in rainfall trends necessitates a region-specific approach to watershed management in the Song catchment. Areas experiencing declining rainfall and NRD should focus on integrated watershed management enhancing artificial recharge techniques, to mitigate sub-surface storage depletion. The observed increase in summer rainfall in certain regions suggests that localized water storage solutions such as rooftop rainwater harvesting and small reservoirs can help capture and utilize excess precipitation.

## 4.2 Land Use and Land Cover Change Analysis

The transformation of land use and land cover (LULC) plays a significant role in shaping the hydrological and ecological landscape of river basins. Over the years, natural and anthropogenic influences have altered land use patterns, impacting the delicate balance between vegetation cover, water availability, and urban development. The Song and Nayar River Basins, vital sources of water and ecological stability in their respective regions, have witnessed distinct LULC changes over the last three decades. Understanding these shifts provides insights into how land use transitions may influence broader environmental and water resource dynamics. For this study, supervised classification using the Random Forest algorithm was employed in Google Earth Engine (GEE), leveraging its robust processing capabilities to analyze satellite imagery from multiple time periods. The classification results offer a comprehensive view of how land cover has evolved in these basins, shedding light on trends such as afforestation, urban expansion, shrinkage of water bodies, and changes in agricultural land use.

### 4.2.1 Land use and land cover changes in the Song river catchment (1995-2023)

The Song River Basin has undergone significant land cover modifications over the years, reflecting both natural succession and human interventions. Table 11 and Figures 22 to 25 exhibit the changes in land use and land cover categories in the Song River Basin over four time periods (1995, 2005, 2015, and 2023). The most notable trend observed is the increase in forest cover, which has expanded from 624.34 km² in 1995 to 728.93 km² in 2023. This increase suggests active afforestation efforts or natural regrowth, potentially influenced by conservation policies or changing land management practices. While forest expansion contributes to soil stabilization and enhances groundwater infiltration, its effects on water availability must be considered, as denser vegetation can lead to higher evapotranspiration rates.

**Table 11: Land use / land cover changes in the Song River Basin**

| Class/Year | 1995 (Area-km$^2$) | 2005 (Area-km$^2$) | 2015 (Area-km$^2$) | 2023 (Area-km$^2$) |
|---|---|---|---|---|
| **Forest** | 624.34 | 660.76 | 660.64 | 728.93 |
| **Water** | 48.22 | 26.86 | 43.25 | 19.93 |
| **Shrub** | 103.65 | 73.79 | 44.48 | 10.62 |
| **Built Up** | 77.66 | 90.39 | 110.84 | 115.79 |
| **Crop** | 114.28 | 116.33 | 108.93 | 92.87 |

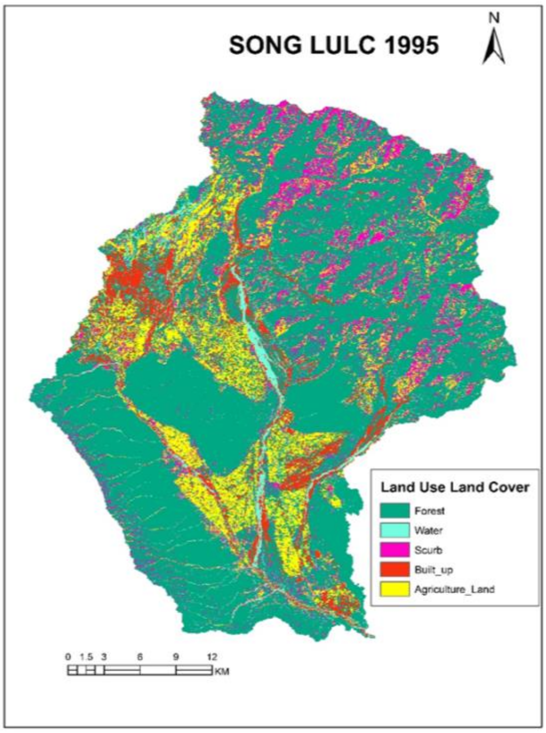



**Figure 22: Land use Land Cover for Song River Basin (1995)**

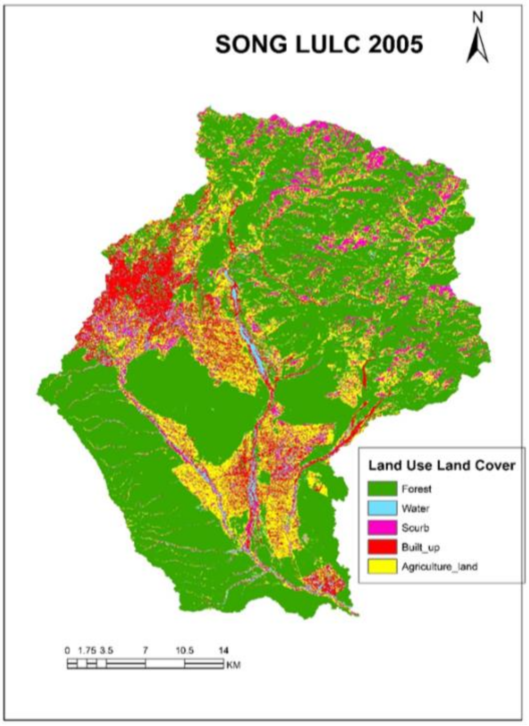



**Figure 23: Land use Land Cover for Song River Basin (2005)**

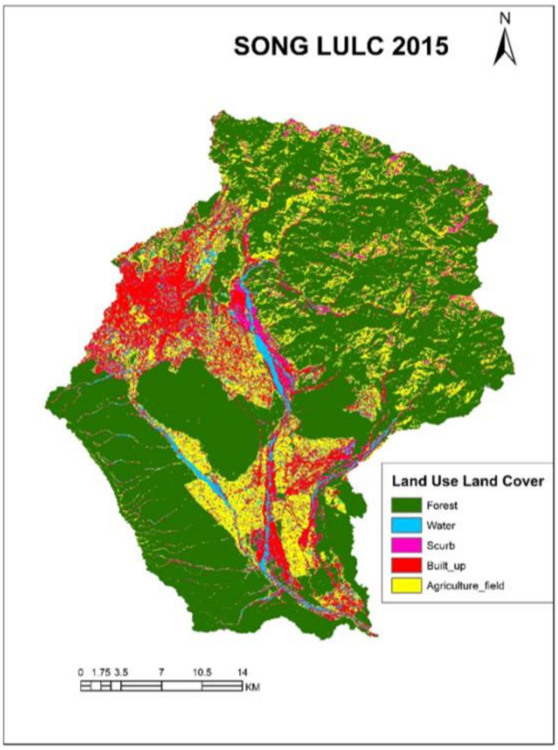



**Figure 24: Land use land cover for Song river basin (2015)**

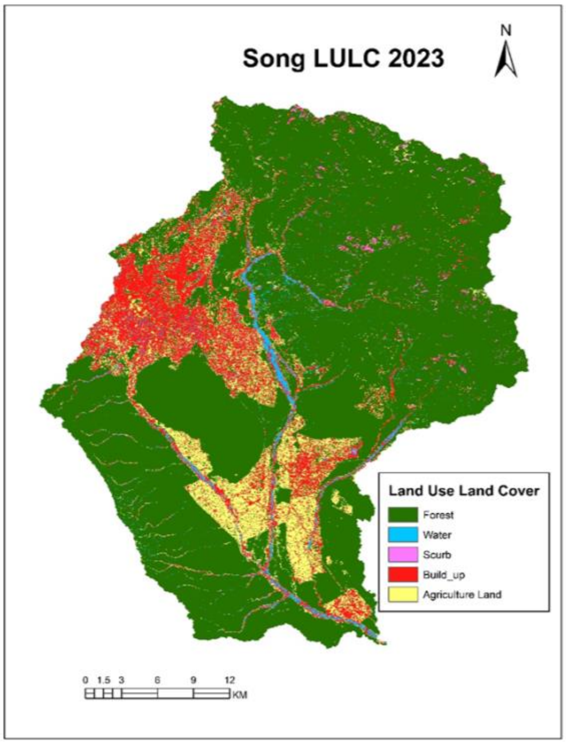



**Figure 25: Land use land cover for Song river basin (2023)**

Water bodies, in contrast, have diminished significantly, with their extent reducing from 48.23 km² in 1995 to only 19.93 km² in 2023. This trend highlights a shift in surface water distribution, which could be associated with reduced baseflows, increased sedimentation, or encroachment into wetland areas. The decline in water bodies suggests possible long-term hydrological changes, where surface runoff patterns and aquifer recharge dynamics may be evolving in response to land use alterations. Shrubland cover has also seen a drastic reduction, shrinking from 103.65 km² in 1995 to merely 10.62 km² in 2023. This nearly complete loss of shrubland indicates that much of this land has transitioned into either dense forest or built-up areas. The transition from shrubland to forest suggests a gradual ecological succession, whereas the conversion to built-up areas signals ongoing urbanization. The built-up area itself has expanded, increasing from 77.66 km² in 1995 to 115.79 km² in 2023. The steady growth of urban settlements, especially in and around Dehradun, aligns with broader patterns of population increase and infrastructure development. The spread of built-up areas alters land surface permeability, influencing runoff patterns and groundwater recharge potential. A landscape once dominated by open land and agricultural fields is increasingly marked by impermeable surfaces, modifying natural hydrological processes over time. Agricultural land, on the other hand, has decreased from 114.28 km² in 1995 to 92.87 km² in 2023. This reduction suggests a gradual shift in land use priorities, where some farmland may have been converted into urban spaces, while other portions could have transitioned into forested zones. The decline in agricultural extent over time reflects changes in land management practices, possibly influenced by economic, environmental, or policy-driven factors.

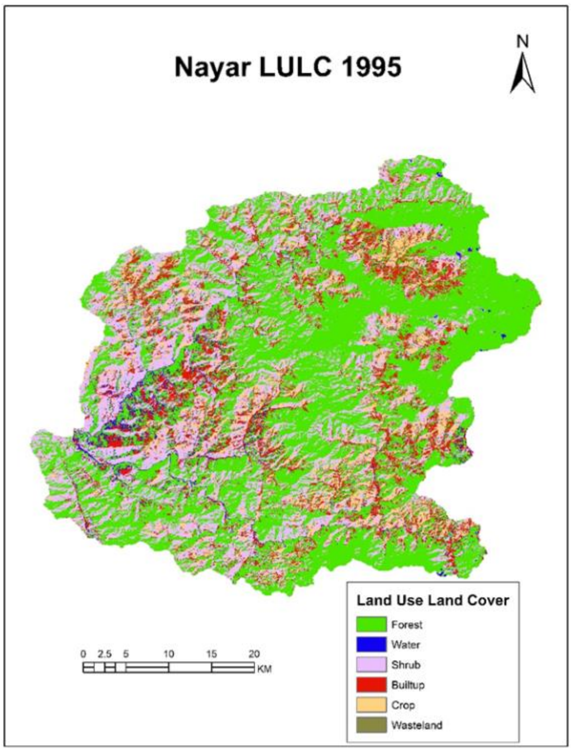
The Land Use/Land Cover (LULC) Map of the Song Catchment (2023) highlights the spatial distribution of forests, shrublands, built-up areas, croplands, and water bodies. The dominance of forest cover suggests a well-vegetated landscape, but the presence of urban expansion and declining water bodies indicates increasing human interventions. The expansion of built-up areas, particularly around Dehradun, has modified natural drainage patterns, increasing surface runoff and reducing groundwater recharge potential. The reduction in agricultural land suggests a shift in land use priorities, possibly influenced by economic changes or urban sprawl.

### 4.2.2 Land Use and Land Cover Changes in the Nayar River Basin (1995–2023)

Table 12 and Figures 26 to 29 show the changes in land use and land cover categories in the Nayar River Basin over four time periods (1995, 2005, 2015, and 2023). Forest cover has shown a steady increase, rising from 852.72 km² in 1995 to 938.60 km² in 2023. This expansion suggests ongoing forest regeneration or afforestation efforts, reinforcing the ecological importance of forested regions in maintaining slope stability and influencing water balance. However, such trends should also be examined for their effects on local hydrology, as increased vegetation density can shift the distribution of available water resources. Water bodies in the Nayar Basin have slightly expanded, increasing from 46.03 km² in 1995 to 51.13 km² in 2023. This growth may be attributed to watershed management efforts, hydrological interventions, or natural variations in precipitation patterns. Shrubland, however, has followed a downward trajectory, reducing from 480.14 km² in 1995 to 357.95 km² in 2023.

**Table 12: Land use / land cover changes in Nayar River Basin during 1995-2023**

| Class/Year | 1995 (Area-km$^2$) | 2005 (Area-km$^2$) | 2015 (Area-km$^2$) | 2023 (Area-km$^2$) |
|---|---|---|---|---|
| **Forest** | 852.72 | 887.92 | 920.53 | 938.60 |
| **Waterbody** | 46.03 | 39.67 | 46.91 | 51.13 |
| **Shrub** | 480.14 | 470.09 | 399.24 | 357.95 |
| **Built-up** | 180.85 | 198.63 | 221.83 | 274.23 |
| **Crop** | 134.94 | 102.81 | 105.17 | 87.78 |
| **Wasteland** | 31.21 | 27.77 | 32.04 | 15.33 |



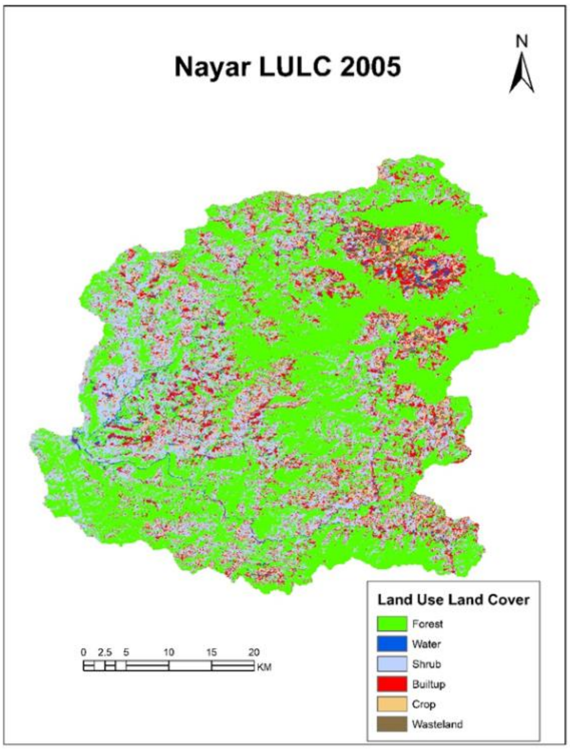
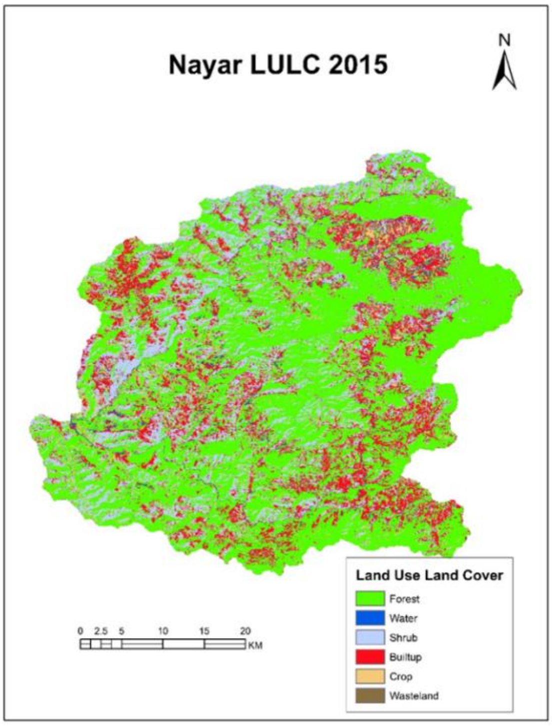




**Figure 26: Land use land cover for Nayar basin (1995)**

**Figure 27: Land use land cover for Nayar basin (2005)**



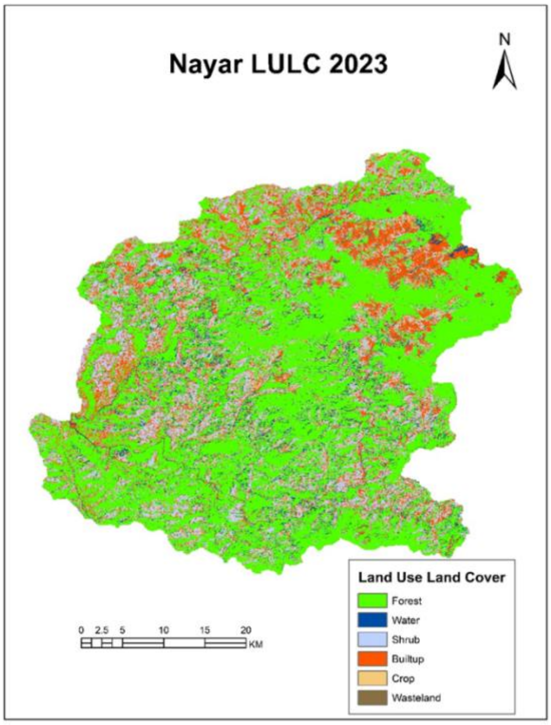




**Figure 28: Land use land cover for Nayar basin (2015)**

**Figure 29: Land use land cover for Nayar basin (2023)**

This reduction reflects broader land use changes, where open landscapes are being replaced by either forested regions or human settlements. The gradual loss of shrubland could indicate shifts in ecosystem composition, where vegetation dynamics are responding to both climatic factors and land management practices. Urban expansion has been pronounced in the Nayar Basin, with built-up areas increasing from 180.85 km² in 1995 to 274.23 km² in 2023. This increase underscores the ongoing transformation of the basin into a more urbanized landscape, driven by infrastructure growth and population expansion. Urbanization alters natural drainage networks, increases surface runoff, and influences local climate conditions, gradually reshaping the basin's hydrological characteristics. Agricultural land in the Nayar Basin has also experienced a decline, dropping from 134.94 km² in 1995 to 87.78 km² in 2023. This shift may suggest evolving agricultural practices or land use conversion for non-agricultural purposes. As agricultural land contracts, the spatial distribution of cultivated areas changes, influencing both groundwater extraction patterns and food production systems. One of the more notable trends in the Nayar Basin is the reduction in wasteland, which has decreased from 31.21 km² in 1995 to 15.33 km² in 2023. This decline suggests that previously unproductive land has either been repurposed for agriculture, afforestation, or urban development, reflecting broader land rehabilitation efforts or shifts in land use demand.

The patterns of LULC change observed in both river basins highlight evolving interactions between natural landscapes and human activities. The expansion of forest cover in both basins suggests an increasing focus on conservation or natural succession, but it also calls for attention to potential hydrological shifts due to changing evapotranspiration dynamics. The contrasting trends in water bodies between the two basins reflect differing hydrological conditions, where factors such as sedimentation, watershed management interventions, and climate variability play key roles in shaping surface water availability. The steady urban expansion in both basins underscores the growing influence of human settlements on the landscape. As built-up areas continue to spread, land surface permeability decreases, modifying groundwater recharge processes and increasing runoff intensity. The decline in shrubland and agricultural land in both basins signals a transition in land use priorities, where open landscapes are either forested or urbanized over time. While some of these changes align with conservation goals, others indicate shifts in land availability for cultivation, potentially influencing local livelihoods and food security.

The LULC Map of the Nayar Catchment (2023) reveals a significant proportion of forested areas, indicating the ecological importance of this basin. However, urbanization and infrastructural development are gradually encroaching into natural landscapes. The persistence of cropland in certain regions suggests ongoing agricultural dependence, though the contraction of these areas hints at possible land abandonment or conversion to other uses. The presence of water bodies, though limited, underscores the need for conservation efforts to sustain hydrological balance.

The evolving land cover patterns in the Song and Nayar River Basins reflect a complex interplay of ecological processes, human interventions, and environmental factors. These transformations not only reshape the physical landscape but also influence long-term water resource sustainability, necessitating an integrated approach to land and water management that considers both conservation objectives and human development needs.

## 4.3 Slope Analysis

### 4.3.1 Slope analysis of Song Catchment

The Slope Map of the Song Catchment illustrates the varying topographical gradients across the basin (Figure 30). The Song Catchment exhibits a mix of steep slopes in the upper reaches and gentler slopes in the downstream areas. The slope ranges between 0 to 85 percentage. The upper hilly regions experience rapid runoff, leading to low groundwater recharge potential but high susceptibility to erosion and landslides. The gentler slopes in the lower basin facilitate infiltration, supporting groundwater recharge and agricultural activities.

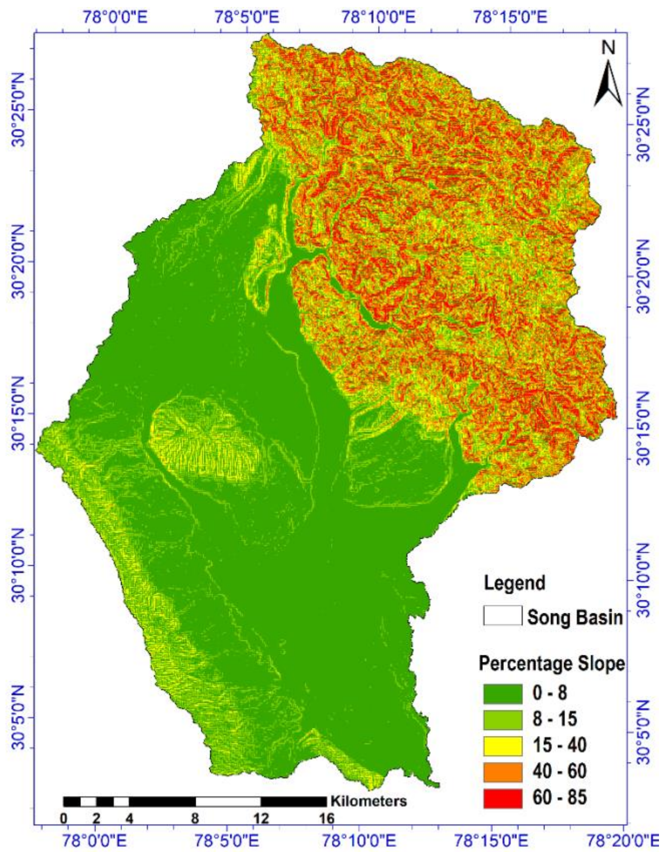



**Figure 30: Slope Map of the Song Catchment**

### 4.3.2 Slope analysis of Nayar catchment

The slope map of the Nayar catchment shows a topography characterized by steep gradients in the mountainous terrain and moderate slopes in the middle and lower reaches (Figure 31). The slope varies between 0-89 percentage. The presence of rugged terrain in the upstream areas results in high runoff rates and low infiltration, necessitating soil conservation measures to prevent degradation. Downstream, the moderate slopes offer better recharge potential, making them more suitable for agricultural expansion and water retention projects.

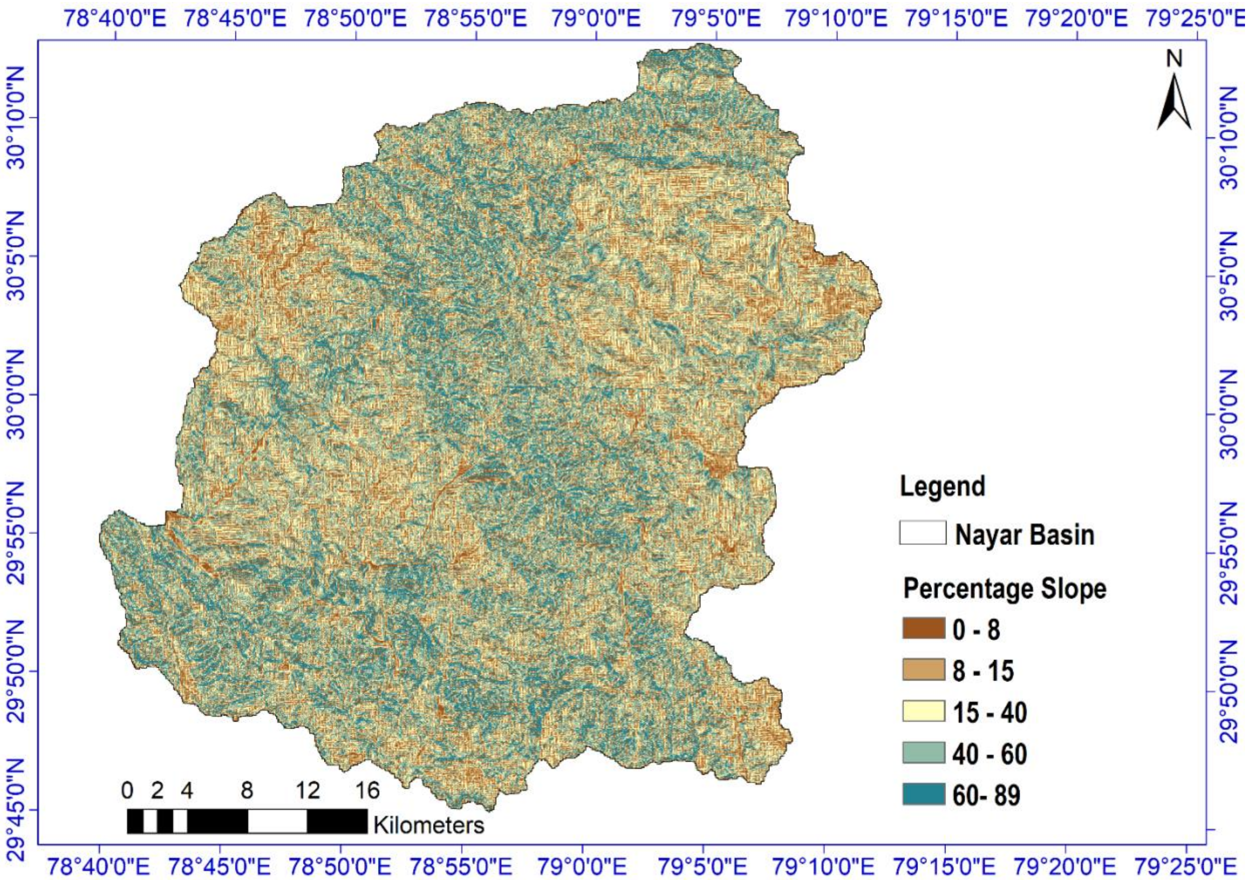



**Figure 31: Slope Map of the Nayar Catchment**

## 4.4 Soil Characteristics

### 4.4.1 Soil characteristics of song catchment

The soil map of the Song Catchment categorizes the basin based on soil texture (Figure 32). The presence of deep Silty loam and loamy soils in certain areas indicates high infiltration rates, making them suitable for groundwater recharge. Conversely, some loamy soil with shallow layers in other sections exhibit low permeability, leading to surface water accumulation and increased runoff. The distribution of alluvial soils in the floodplain areas suggests fertile lands favorable for agriculture, though these regions might also be susceptible to seasonal flooding and erosion.

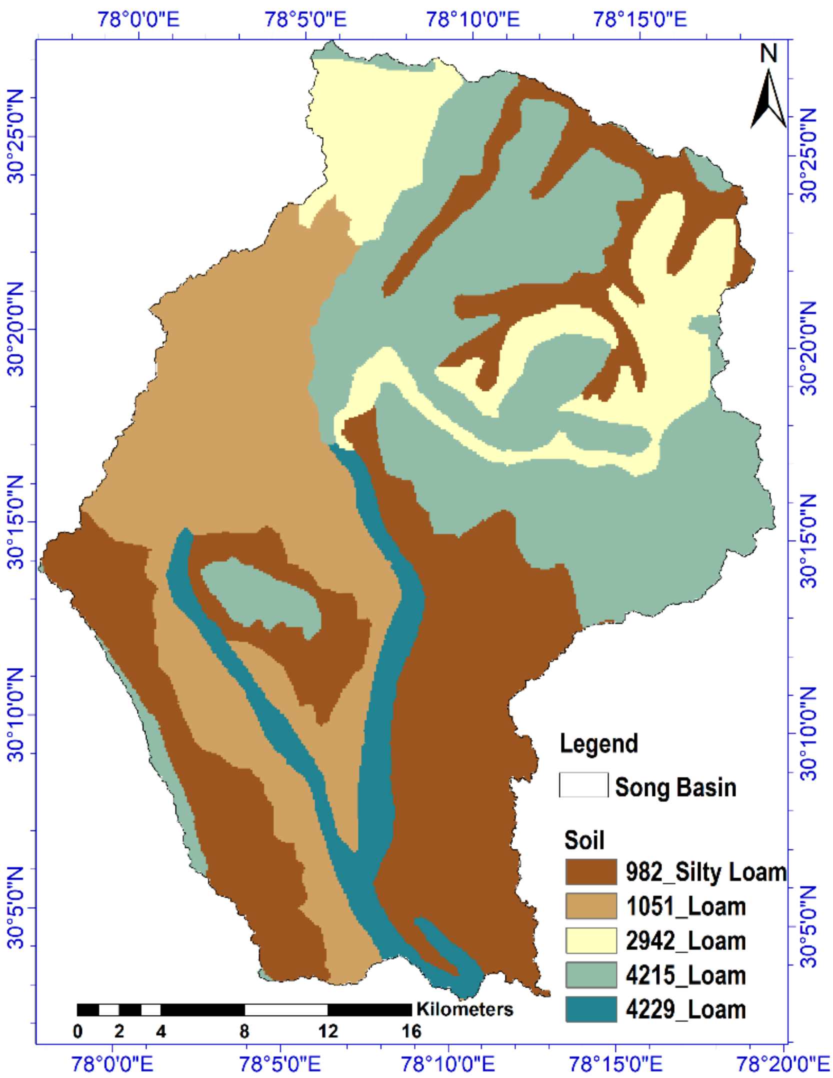



**Figure 32: Soil Map of the Song Catchment**

### 4.4.2 Soil Characteristics of Nayar Catchment

The Soil Map of the Nayar Catchment categorizes the basin based on soil texture (Figure 33). The presence of deep Silty loam and loamy soils in certain areas indicates high infiltration rates, making them suitable for groundwater recharge. Conversely, some loamy soil with shallow layers in other sections exhibit low permeability, leading to surface water accumulation and increased runoff. The distribution of alluvial soils in the floodplain areas suggests fertile lands favorable for agriculture, though these regions might also be susceptible to seasonal flooding and erosion.

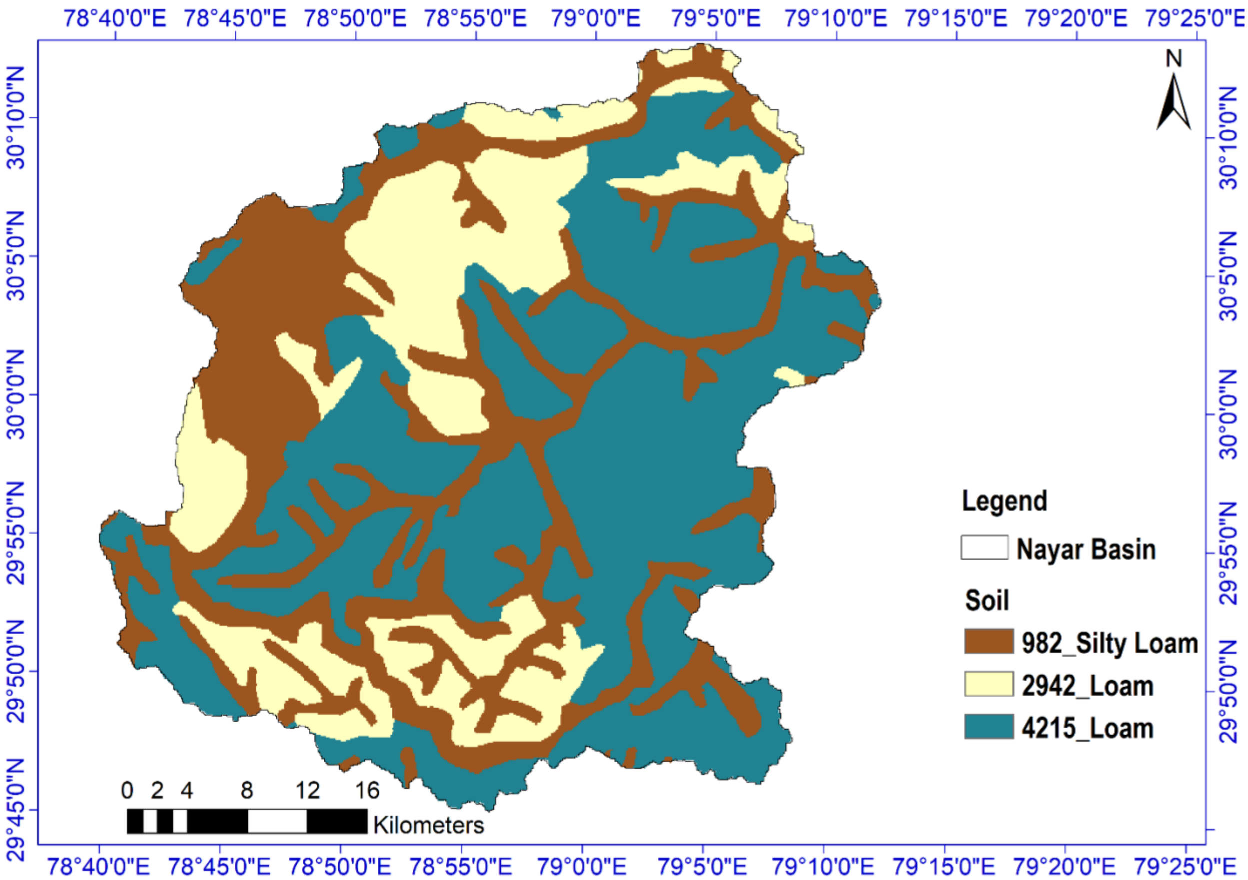



**Figure 33: Soil Map of the Nayar Catchment**

## 4.5 Geology

### 4.5.1 Geology of song Catchment

The Geology Map of the Song Catchment provides valuable insights into the lithological formations and structural geology that influence groundwater storage and movement (Figure 34). The catchment area is divided into Shivalik group Doon gravel, Naghat-Berinag formation, Blaini Formation, Krol Formation, Saryu-Gumalikhat-Munsiyari formation, Tal formation, Chandpur formation, Nathuakhan Betalghat, Bhatwari, Bansi subathu and Chakrata formation. The Blaini Formation, Shivalik group Doon gravel and Tal formation have a higher potential for water storage followed by Krol, Chakrata Formation, Bansi subathu, Nathuakhan Betalghat, Chandpur, Saryu-Gumalikhat-Munsiyari formation.

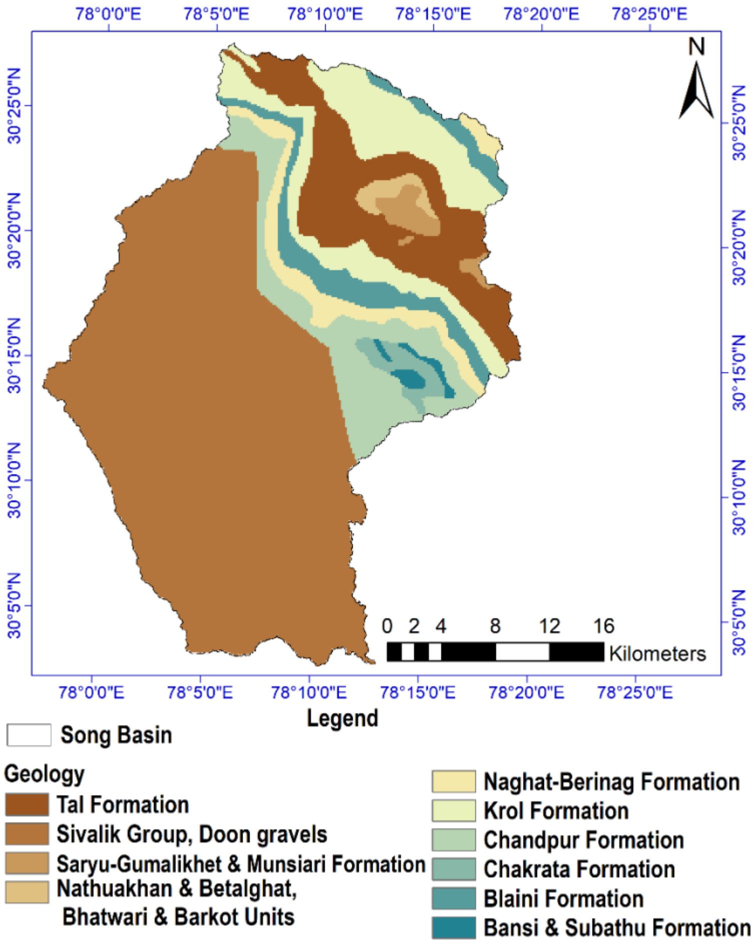



**Figure 34: Geology map of the Song Catchment**

### 4.5.2 Geology of Nayar catchment

The Geology Map of the Song Catchment provides valuable insights into the lithological formations and structural geology that influence groundwater storage and movement (Figure 35). The catchment area is divided into Chandpur, Saryu-Gumalikhat-Munsiyari, Rautgara, Deoban, Nathuakhan Betalghat, Naghat-Berinag, Chakrata, Tal, Blaini and Krol formation. The Deoban, Tal, Blaini and Krol formations have a higher potential for water storage followed by Naghat-Berinag, Chakrata, Nathuakhan Betalghat, Rautgara, Chandpur and Saryu-Gumalikhat-Munsiyari formation.

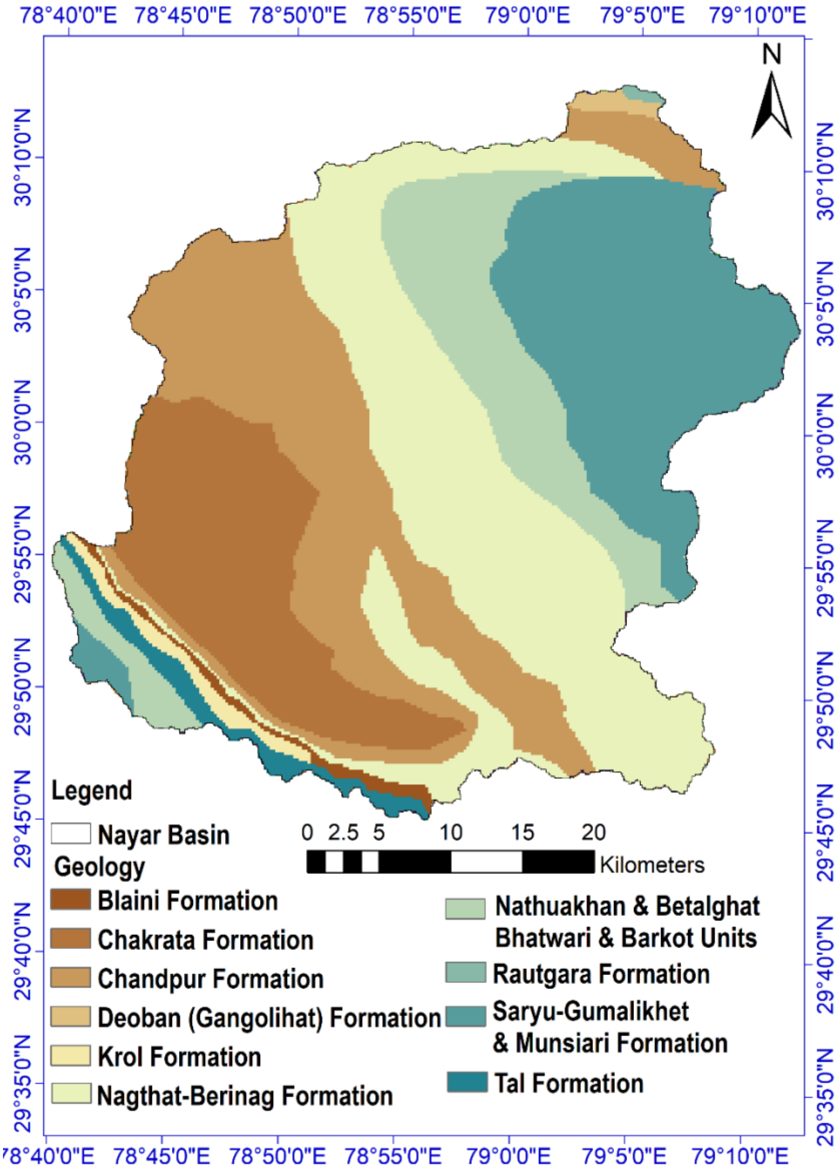



**Figure 35: Geology map of the Nayar Catchment**

## 4.6 Priority Areas for Watershed Management

### 4.6.1 Priority areas of Song catchment for watershed management

The identification of potential areas for priority watershed management in the Song Catchment highlights the need for targeted conservation interventions to mitigate environmental degradation and restore hydrological balance. Given the catchment's ecological importance and its role in sustaining regional water availability, the Watershed Management Directorate of Uttarakhand has delineated the catchment into 29 microwatersheds: Balawala, Baldi Nadi, Bandal Nadi, Beriwararao, Bhaniyawala, Bidhalana Nadi, Bulindawalarao, Bullawalarao, Chiphaldi Nadi, Chittaur Rao, Churpanirao, Dubra, Golapani Rao, Jakhan Rao 1, Jakhan Rao 2, Jaman Sot, Joli

Grant, Kaluwala, Kansrao 1, Kansrao 2, Kisanpur, Kurkawala, Pantwala Rao, Ramgarh Rao, Rispana Rao, Satyanarayan, Sirwalgarh, Song Nadi, and Sukh Rao. These microwatersheds serve as distinct hydrological units for prioritization based on various watershed management criteria. Figure 36 and Table 13 exhibited the rank of different subwatershed based on the priority for watershed management within the Song catchment. The findings indicate that about 64.85% of the Song Catchment falls under the high-priority category. About 24.57% of the catchment is classified as medium-priority and the remaining about 10.57% falls under the low-priority category. The prioritized sub-watersheds in Song river catchment are shown in Figure 37.

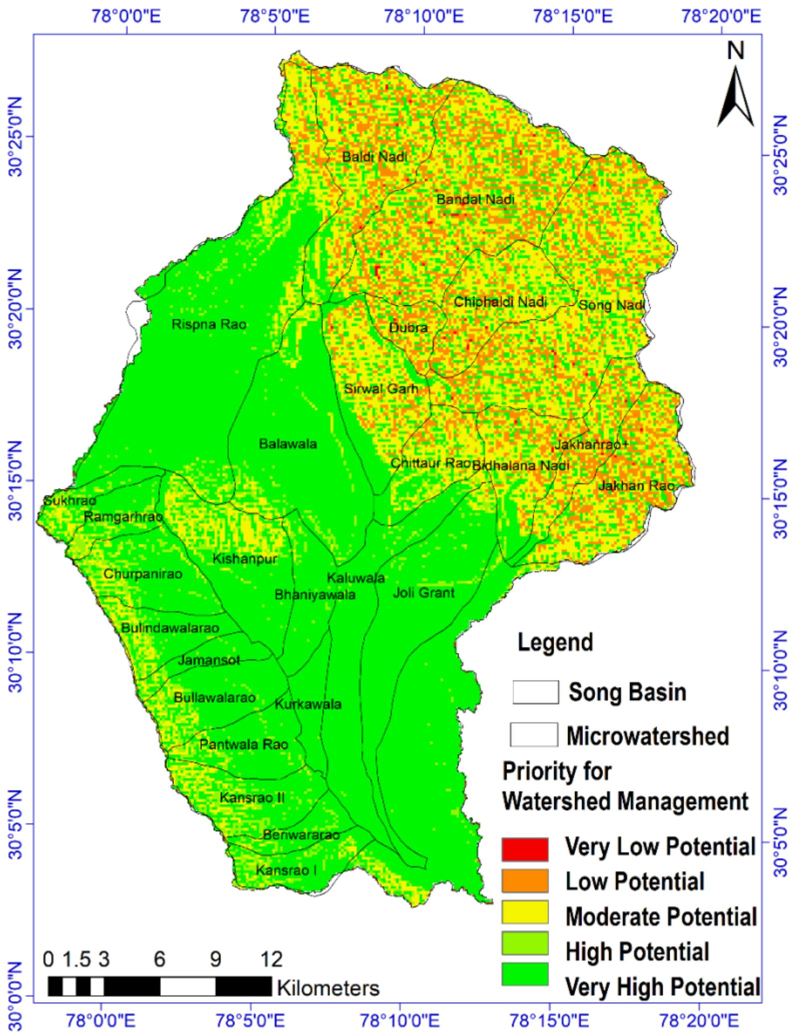



**Figure 36: Potential areas of subwatersheds for watershed management in the Song catchment**

**Table 13: Priority ranking of subwatersheds for watershed management in the Song catchment**

| High Priority | | | Medium Priority | | | Least Priority | | |
|---|---|---|---|---|---|---|---|---|
| Microwatershed | Area km$^2$ | Rank | Microwatershed | Area km$^2$ | Rank | Microwatershed | Area km$^2$ | Rank |
| Rispana Rao | 117.54 | 1 | Jakhan Rao 1 | 39.53 | 11 | Kansrao 1 | 14.61 | 21 |
| Song Nadi | 86.33 | 2 | Churpanirao | 24.19 | 12 | Jakhan Rao 2 | 19.83 | 22 |
| Balawala | 63.88 | 3 | Chiphaldi Nadi | 30.29 | 13 | Ramgarh Rao | 11.46 | 23 |
| Golapani Rao | 59.18 | 4 | Bullawalarao | 22.45 | 14 | Kurkawala | 9.66 | 24 |
| Bandal Nadi | 83.75 | 5 | Kansrao 2 | 22.23 | 15 | Sukh Rao | 9.38 | 25 |
| Joli Grant | 48.56 | 6 | Bidhalana Nadi | 25.59 | 16 | Satyanarayan | 9.12 | 26 |
| Kaluwala | 40.45 | 7 | Pantwala Rao | 19.19 | 17 | Beriwararao | 9.02 | 27 |
| Kisanpur | 37.29 | 8 | Chittaur Rao | 20.61 | 18 | Jaman Sot | 8.48 | 28 |
| Baldi Nadi | 50.98 | 9 | Bhaniyawala | 16.51 | 19 | Dubra | 10.04 | 29 |
| Sirwalgarh | 35.25 | 10 | Bulindawalarao | 15.55 | 20 | | | |

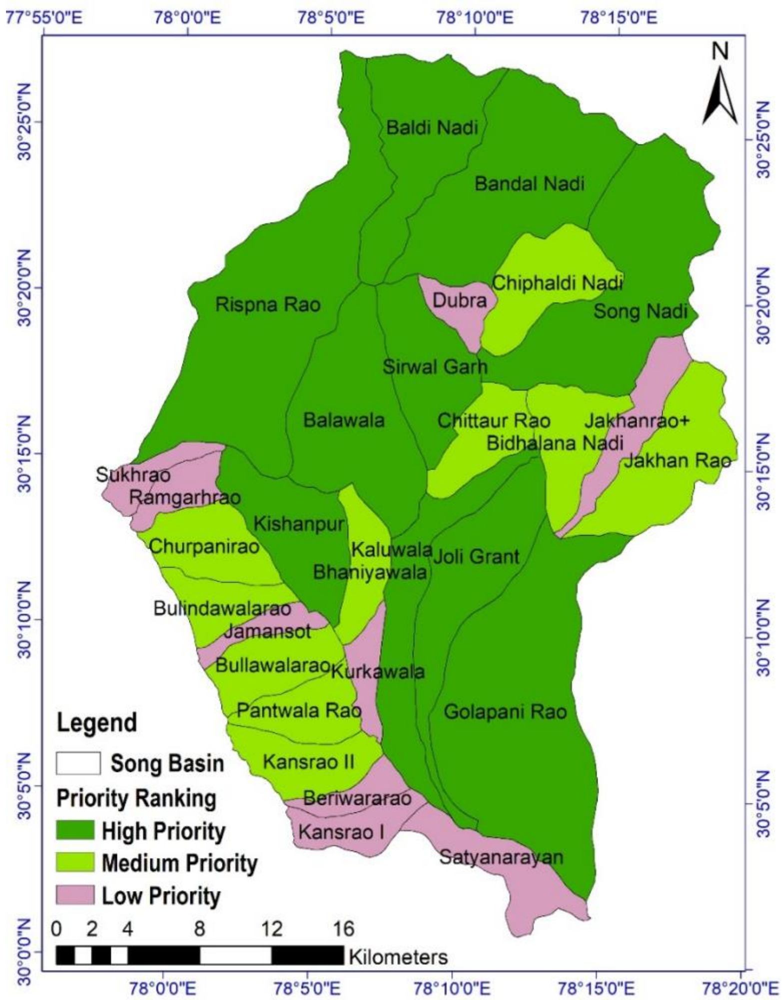



**Figure 37: Prioritized sub-watersheds in Song river catchment**

### 4.6.2 Priority Areas of Nayar catchment for watershed management

The identification of potential areas for priority watershed management in the Nayar Catchment underscores the need for urgent conservation measures to restore hydrological balance and ensure long-term water sustainability. In alignment with the recommendations of the Watershed Management Directorate, Uttarakhand, the Nayar Catchment has been systematically delineated into 47 microwatersheds: Chargad, Medigad, Irgad, Sidhkhal, Dudhatoligad, Gharigad, Khargad, Syotigad, Kalagal, Pasolgad, Sirgad, Silogi, Khandgaon, Tarpalisain, Khand, Thalsaingad, Kaligad, Baligad, Kandali Nadi, Machhigad, Bisgadikhala, Pingad, Ghatgad, Chorkanda, Udiyargad, Kutti, Chakisain, Bachheli, Gwarigad, Rasiya Gad, Sidoli, Gairigad, Patisain, Chandol, Panchard, Choya, Maithana, Byasigad, Chanchariya Gad, Bhawani, Dudharkhal, Talgad, Bhakhand, Bhaligaon, Jiwai, Dhuijuli, and Tiloli. These microwatersheds represent distinct hydrological units, each requiring specific interventions based on their priority ranking for watershed management. Figure 38 and Table 24 exhibited the rank of different subwatershed based on the priority for watershed management within the Nayar catchment. The assessment revealed that approximately 48.78% of the Nayar Catchment falls within the high-priority category. Around 32.43% of the catchment is classified as medium priority and the remaining 18.79% of the catchment is categorized as low priority. The prioritized sub-watersheds in Song river catchment are shown in Figure 39.

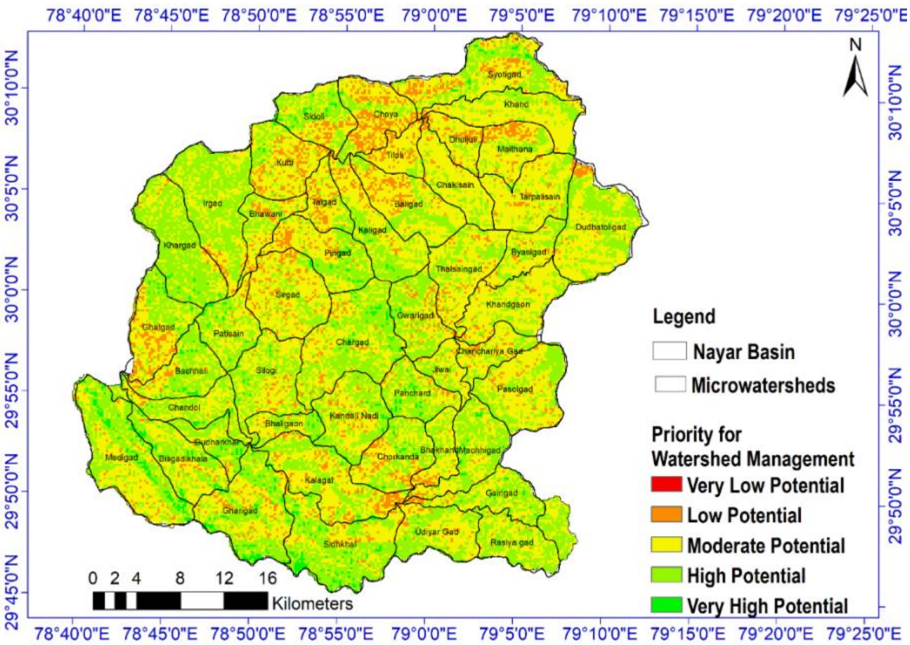



**Figure 38: Potential areas for priority for watershed management in Nayar Catchment**

**Table 14: Priority ranking of micro-watersheds for watershed management in the Nayar catchment**

| High Priority | | | Medium Priority | | | Least Priority | | |
|---|---|---|---|---|---|---|---|---|
| Microwatershed | Area ($km^2$) | Rank | Microwatershed | Area $km^2$ | Rank | Microwatershed | Area $km^2$ | Rank |
| Chargad | 67.88 | 1 | Kaligad | 39.78 | 17 | Patisain | 27.81 | 33 |
| Medigad | 65.73 | 2 | Baligad | 42.56 | 18 | Chandol | 26.63 | 34 |
| Irgad | 61.44 | 3 | Kandali Nadi | 39.19 | 19 | Panchard | 25.91 | 35 |
| Sidhkhal | 62.11 | 4 | Machhigad | 35.73 | 20 | Choya | 34.34 | 36 |
| Dudhatoligad | 56.25 | 5 | Bisgadikhala | 35.82 | 21 | Maithana | 27.81 | 37 |
| Gharigad | 57.39 | 6 | Pingad | 37.21 | 22 | Byasigad | 21.66 | 38 |
| Khargad | 52.33 | 7 | Ghatgad | 38.47 | 23 | Chanchariya Gad | 19.97 | 39 |
| Syotigad | 53.56 | 8 | Chorkanda | 35.23 | 24 | Bhawani | 20.82 | 40 |
| Kalagal | 52.25 | 9 | Udiyargad | 32.78 | 25 | Dudharkhal | 16.69 | 41 |
| Pasolgad | 47.49 | 10 | Kutti | 36.15 | 26 | Talgad | 19.43 | 42 |
| Sirgad | 48.46 | 11 | Chakisain | 30.38 | 27 | Bhakhand | 16.9 | 43 |
| Silogi | 42.73 | 12 | Bachheli | 30.21 | 28 | Bhaligaon | 14.62 | 44 |
| Khandgaon | 42.26 | 13 | Gwarigad | 31.1 | 29 | Jiwai | 14.62 | 45 |
| Tarpalisain | 41.72 | 14 | Rasiya gad | 28.7 | 30 | Dhuijuli | 16.35 | 46 |
| Khand | 38.51 | 15 | Sidoli | 30.59 | 31 | Tiloli | 16.35 | 47 |
| Thalsaingad | 40.49 | 16 | Gairigad | 28.27 | 32 | | | |

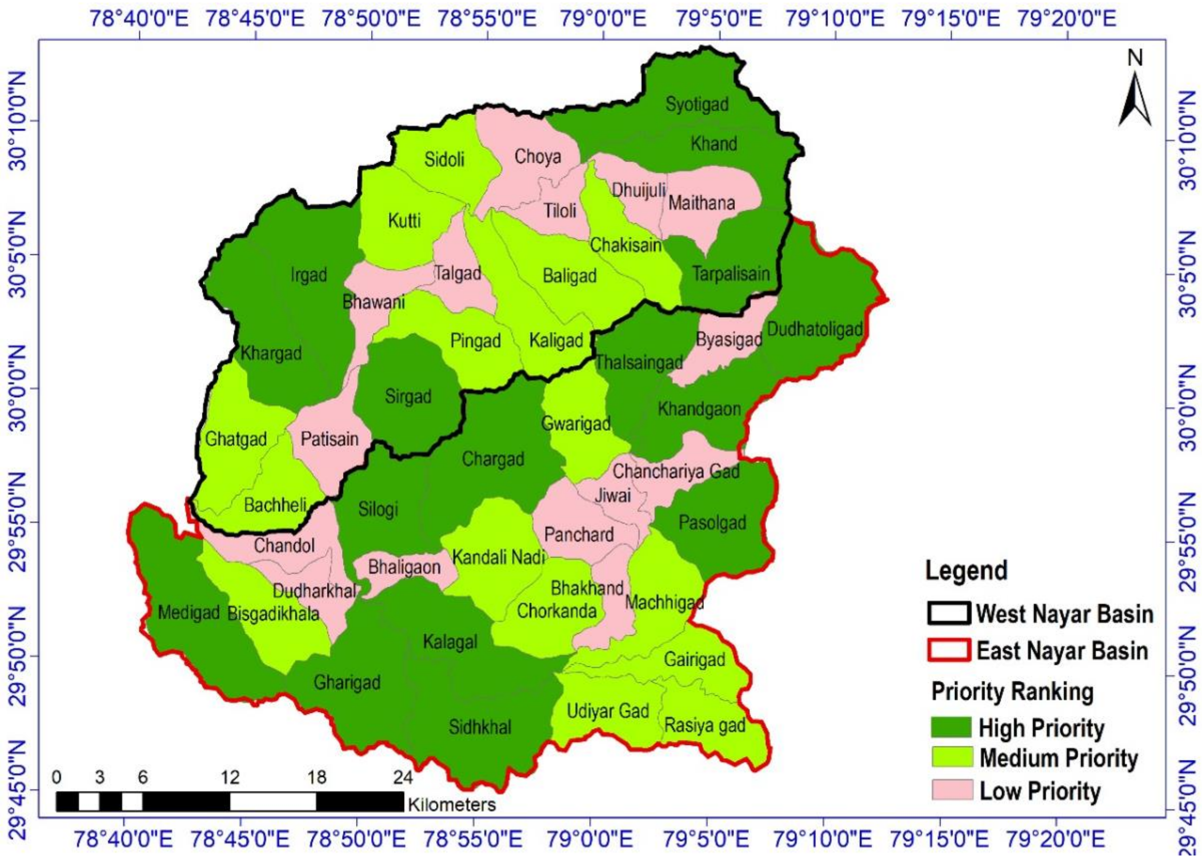



**Figure 39: Prioritized sub-watersheds in Nayar river catchment**

The watershed prioritization framework serves as a strategic guideline for implementing targeted conservation measures in the Nayar Catchment. By integrating nature-based solutions and sustainable land management practices, the resilience of the watershed can be enhanced, ensuring improved water availability, reduced sedimentation, and better adaptation to climatic variations. Addressing these priority areas with well-planned interventions will contribute to the long-term sustainability of the catchment, benefiting both ecological and socio-economic systems within the region.

By focusing conservation efforts on identified priority areas, resource allocation can be optimized to achieve maximum environmental and hydrological benefits. The integration of soil conservation, afforestation, and water retention strategies will enhance ecosystem resilience, mitigate flood risks, and improve groundwater sustainability.

### 4.7. Potential watershed management measures

A variety of watershed management measures for conservation of monsoon rainfall and augmentation of non-monsoon water availability are proposed in literature. For the present scope of study, these technologies have been classified in four groups:

1. Vegetative measures (plantation of trees, grass barriers and bushes etc. across the slopes)
2. Semi-structural measures (contour bunds, terracing, trenching, gully plugging, gabion structure, etc.)
3. Groundwater recharge structures (ponds, pits, percolation tanks, bunds, etc.)
4. Engineering/structural measures (masonry check dams / stop dams, in-stream storage structures etc.) for water retention and ground water recharge.

#### 4.7.1. Vegetative measures

Vegetative measures for soil and water conservation work by their protective impact on the vegetation cover. These measures prevent splash erosion; reduce the velocity of surface runoff; increase surface roughness which reduces runoff and increases infiltration; the roots and organic matter stabilise the soil aggregates and increase infiltration.

### 4.7.2. Semi-Structural Measures

In gully control, temporary structural measures such as woven-wire, brushwood, logs, loose stone and boulder check dams proposed to be used to facilitate the growth of permanent vegetative cover. Mostly in the first order streams, gully checks can be constructed across the gully bed to reduce the velocities of flowing water induced by the rainfall by reducing the original gradient of the gully channel, hence, the flowing water gets more time for infiltration. Semi-permanent check dams, which have a life-span of three to eight years, collect and hold soil and moisture in the bottom of the gully.

To obtain satisfactory results from these structural measures, a series of check dams should be constructed for each portion of the gully bed wherever feasible locations are available. Because they are less likely to fall, low check dams are more desirable than high ones. Check dams should be combined with retaining walls parallel to the gully axis in order to prevent the scouring and undermining of the gully banks.

Stabilized watershed slopes are the best assurance for the continued functioning of gully control structures. Therefore, attention must be given to keeping the gully catchment well vegetated. If this fails, the structural gully control measures may fail as well.

After visualizing the longitudinal profile of the gully, the number of check dams for each portion of the main gully channel can be calculated so as the bottom elevation of first check dam should be equal to the crest elevation of second check dam and so on.

The first check dam should be constructed on a stable point in the gully such as a rock outcrop, the junction point of the gully to a road, the main stream or river, lake or reservoir. If there is no such stable point, a counter-dam must be constructed. The distance between the first check dam and the counter-dam must be at least two times the effective height of the first check dam.

Loose boulder check dams made of relatively small rocks are placed across the gully. The main objectives for these dams are to control channel erosion as well as the runoff along the gully bed and to stop waterfall erosion by stabilising gully heads. Loose stone check dams are used to stabilize the incipient and small gullies and the branch gullies of a continuous gully or gully network. The length of the gully channel should not be more than 100 metres and the gully catchment area should be two hectares or less.

An illustrative diagram of the loose boulder check dam is shown in Figure 40.

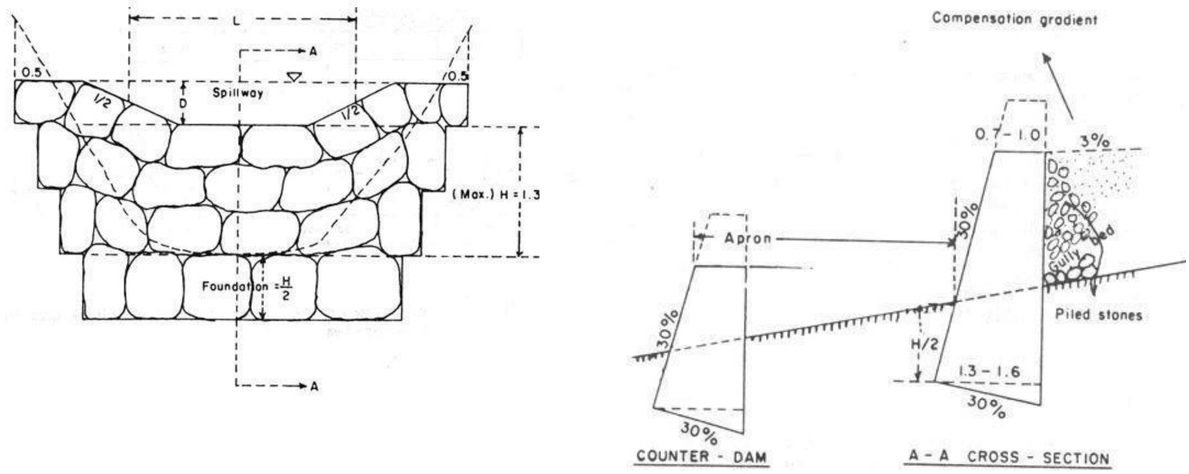



**Figure 40: Illustrative diagram of loose boulder check dam**

**Gabions (wire crate check dams)**

Gabion check dams are small barriers constructed of a series of gabion baskets bound together to form a flexible row that acts to slow down the water flow in drainage ditches or storm water runoff channels. They are commonly used with moderate slopes up to 10% and positioned in series with a typical spacing of 25 -100 m apart. These dams are either constructed straight across the channel or in a crescent shape with its open end upstream. It is proposed to prefer the construction of gabion check dams in the second order streams. Depending on the site suitability, the gabion check dams can be constructed in 3rd order streams too. An illustrative diagram of gabion structures is shown in Figure 41.

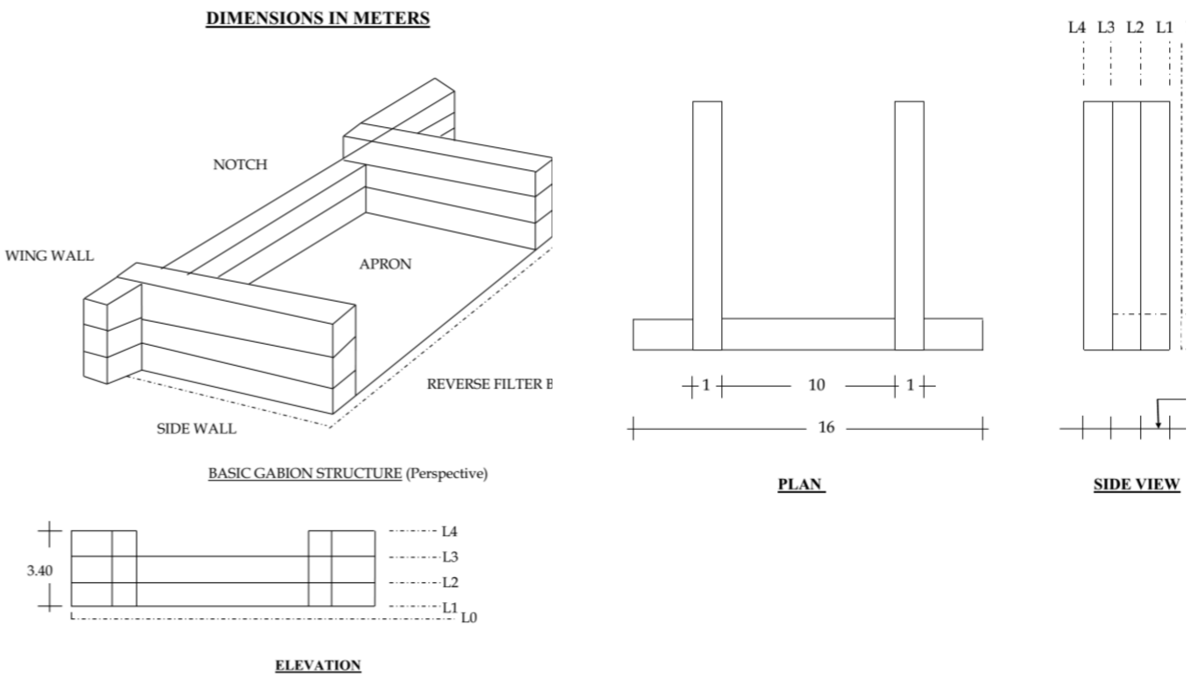



**Figure 41: Illustrative diagram of gabion structure**

### 4.7.3. Groundwater Recharge Structures

The ground water recharge structures generally refers to creation of some depression areas which hold the runoff from the nearby areas and let it infiltrate into the ground thus contributing to the ground water. According to the slope map of the catchment, the sites for contour trenches, percolation tanks and ponds have been identified.

***Staggered Trenches***

Staggered trenching is excavating shallow pits of rectangular shape in a row with shorter lengths across the slope and as nearly on contour as possible in the upper reaches of the catchment with interspace between them. The trenches in successive rows will be staggered, while in alternate rows the trenches will be located directly below one another. Suitable vertical intervals between the rows are restricted to impound the runoff expected from above, without overflow. The depth and top width of the trenches may be taken as 0.3 m and 0.6 m with side slopes as 0.5:1 or 1:1. The excavated soil from the trench should be placed parallel to the downstream edge of the trench with 6 inches clearance from the downstream edge of the trench. Plantation on the bund may be preferred to stabilize the bund. The trenches retain the runoff and help in establishment of the plantations made on the bund. The main idea is to create more favourable moisture conditions and thus accelerate growth of vegetation. These trenches also break the velocity of runoff. The rainwater percolates through the soil slowly and travels down, and benefits the better types of land in the middle and lower reaches of the catchment. Where the lower fields are bunded, these trenches also protect the bunds from the runoff from upper reaches of the catchment.

An illustrative diagram of staggered trenches is shown in Figure 42.

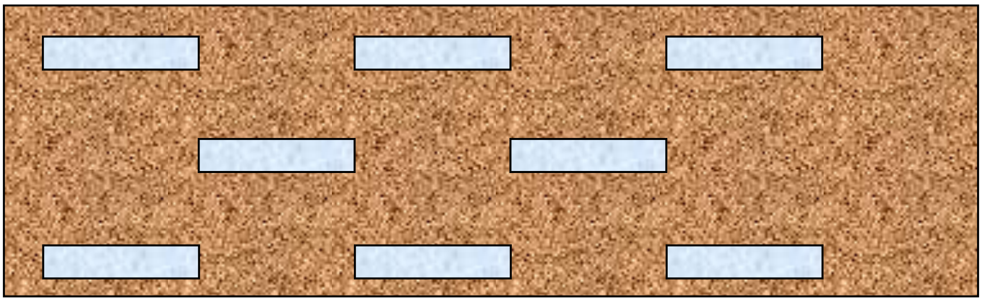


**Figure 42: Illustration of staggered trenching Layout**

***Percolation Pits and Ponds***

A percolation pit is an artificial reservoir which is constructed in the areas with adequate permeability to facilitate sufficient percolation to collect surface water run-off and allow it to percolate within the permeable land. This is one of the effective methods of groundwater recharge.

A percolation tank is an artificial reservoir which is constructed across streams, submerging a land area with adequate permeability to facilitate sufficient percolation to collect surface water run-off and allow it to percolate within the permeable land. This is one of the effective methods of refilling the groundwater table (also known as groundwater recharge). An illustrative picture of a pond in the forested hilly area is shown in Figure 43.


**Figure 43: Illustrative picture of pond in forested hilly area**

Water conservation ponds prove a strategic adaptation practice, collecting rain water and replenishing groundwater reserves during the monsoon, as well as preventing excessive erosion and surface runoff down landslides slopes.

Conservation ponds may be built in many different ways and sizes to suit the specific purpose. It is strongly encouraged to use local tools, materials and labour in order to facilitate maintenance and reduce costs. A critical feature is the size of the pond, which depends on land availability and slope considerations, as small ponds are better suited for porous soil and over-topping concerns. Location is another important feature, as the pond can hold a potentially troubling runoff in landslide-prone areas and increase soil moisture in strategic places. In the present case, it is recommended to construct the ponds at natural depressions.

### 4.7.4. Structural Measures

The check dams constructed in third or fourth order streams are required to be of permanent nature with much more structural strength than the temporary check dams. For large gullies in which excessive runoff from the top is expected and a high degree of safety and permanence is desirable, permanent gully control structures of masonry and concrete are constructed. These structures have a main function to safely dispose of the peak rate of runoff for a given frequency, from higher elevation to lower elevation. These should have arrangements to dissipate the kinetic energy of discharge within the structure, in a manner and degree that will protect both the structure and downstream channel from damage. These structures are usually made of Reinforced Cement Concrete. The water stored in these structures is mostly confined to the stream course and the height is normally less than 2 m and excess water is allowed to flow over the wall. In order to avoid scouring from excess runoff, water cushions are provided at the downstream side. The site selected should have sufficient thickness of permeable bed or weathered formation to facilitate recharge of stored water within a short span of time. To harness the maximum run off in the stream, a series of such check dams can be constructed to have recharge on a larger scale. An illustrative diagram of structural measures across streams for in-stream water retention is shown in Figure 44.

**Figure 44: Illustrative diagram of structural measures across the streams**

## 5. CONCLUDING REMARKS

The prioritization of microwatersheds of Song and Nayar river catchments has been carried out considering the four important factors viz. LULC, soil type, slope and geology. Subsequently, the respective maps pertaining to LULC, soil type, slope and geology have been prepared for both the catchments. For finalizing the priority, equal weightages (1 to 5) have been given to all four factors and the combined priority at different points of the basin has been worked out. To transfer the results on the micro-watershed level for practical implementation of watershed management works, these spatial priorities have been overlaid on the micro-watershed maps of both the basins and the highest priority micro-watersheds in the Song and Nayar Basins have been finally recommended as follows:

**Table 15: Highest priority micro-watersheds in Song River catchment**

| Micro-watersheds | Area (km$^2$) | Priority Rank |
|---|---|---|
| Rispana Rao | 117.54 | 1 |
| Song Nadi | 86.33 | 2 |
| Balawala | 63.88 | 3 |
| Golapani Rao | 59.18 | 4 |
| Bandal Nadi | 83.75 | 5 |
| Joli Grant | 48.56 | 6 |
| Kaluwala | 40.45 | 7 |
| Kisanpur | 37.29 | 8 |
| Baldi Nadi | 50.98 | 9 |
| Sirwalgarh | 35.25 | 10 |

**Table 16: Highest priority micro-watersheds in Nayar River catchment**

| Micro-watersheds | Area (km$^2$) | Priority Rank |
|---|---|---|
| Chargad | 67.88 | 1 |
| Medigad | 65.73 | 2 |
| Irgad | 61.44 | 3 |
| Sidhkhal | 62.11 | 4 |
| Dudhatoligad | 56.25 | 5 |
| Gharigad | 57.39 | 6 |
| Khargad | 52.33 | 7 |
| Syotigad | 53.56 | 8 |
| Kalagal | 52.25 | 9 |
| Pasolgad | 47.49 | 10 |
| Sirgad | 48.46 | 11 |
| Silogi | 42.73 | 12 |
| Khandgaon | 42.26 | 13 |
| Tarpalisain | 41.72 | 14 |
| Khand | 38.51 | 15 |
| Thalsaingad | 40.49 | 16 |

After the prioritization of sub-catchments/micro-watersheds is finalized, the plan for watershed management measures covering the type, location, number and size of interventions is developed. A variety of watershed management interventions for conservation of monsoon rainfall and augmentation of non-monsoon water availability are proposed in literature which covers vegetative measures, semi-structural measures, groundwater recharge structures and engineering/structural measures. These measures should be planned and implemented in integrated manner (mixing the measures on the stream as well in the catchment) for getting maximum outcomes.

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