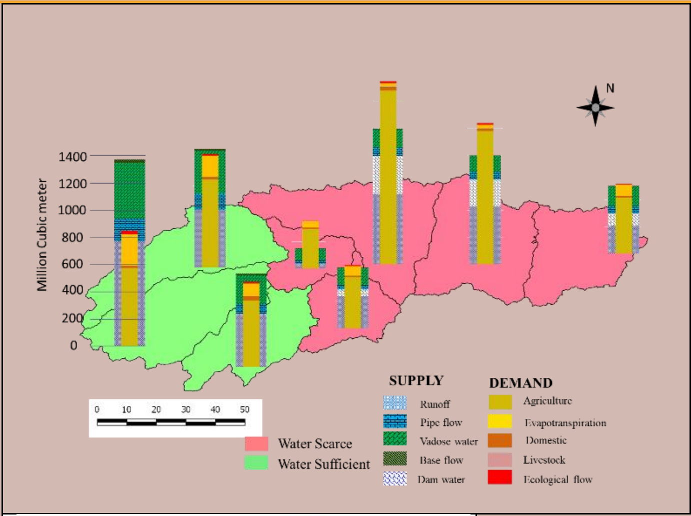
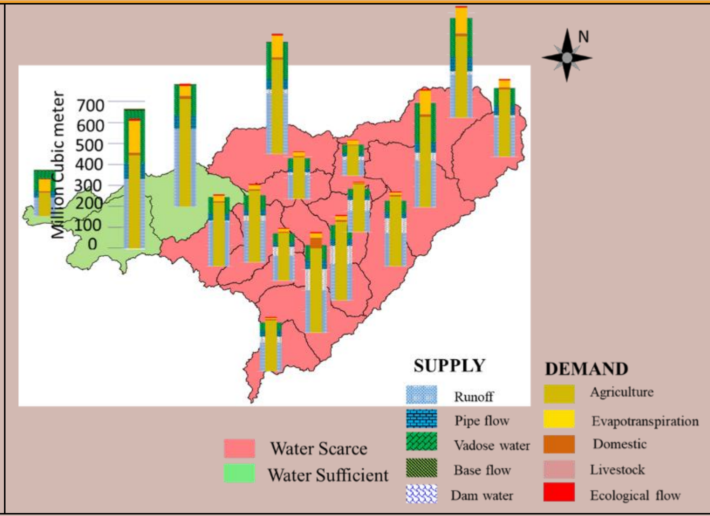
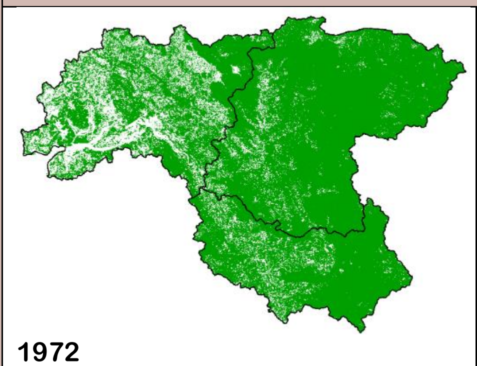
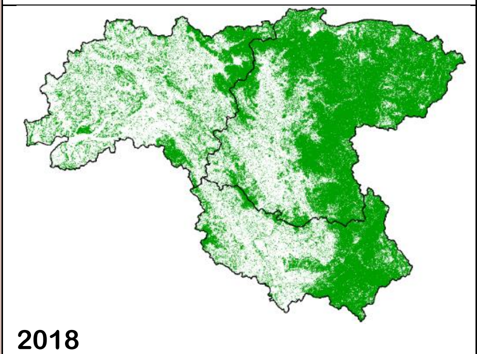
Eco-Hydrologic Footprint in Ghataprabha, Malaprabha, and Mahadayi Rivers with Landscape Dynamics

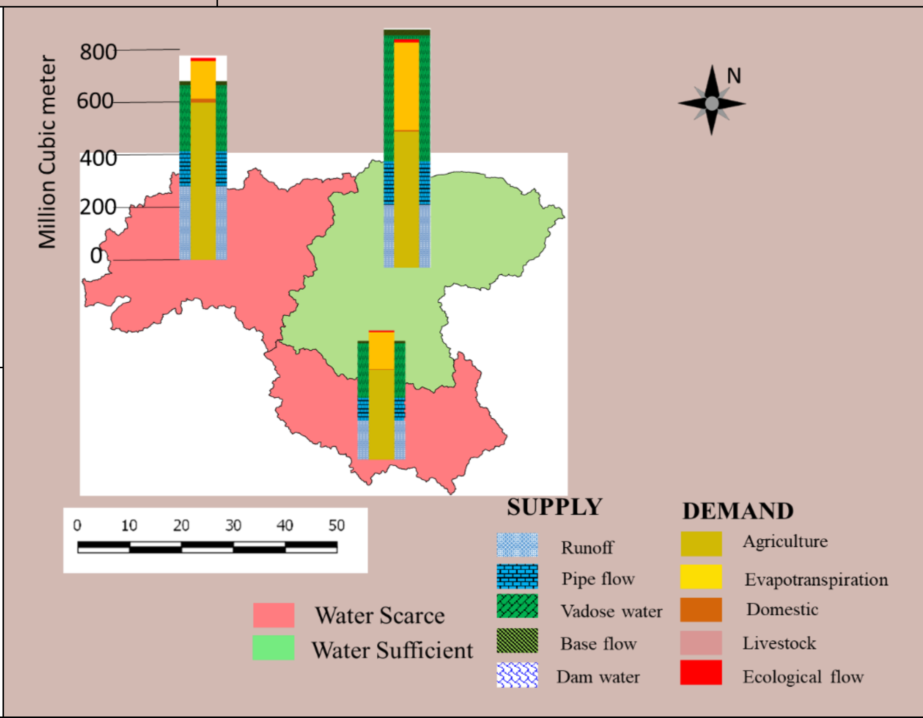
T V Ramachandra   Sai Omkari P   Vinay s











Sahyadri Conservation Series: 108,

ENVIS Technical Report: 178

August 2021

Energy & Wetlands Research Group
Centre for Ecological Sciences, CES TE 15
Indian Institute of Science
Bangalore-560012, INDIA

Web: http://ces.iisc.ernet.in/energy/
http://ces.iisc.ernet.in/biodiversity
Email: tvr@ iisc.ac.in; energy.ces@ iisc.ac.in

ECO-HYDROLOGIC FOOTPRINT IN GHATAPRABHA, MALAPRABHA, AND MAHADAYI RIVERS WITH LANDSCAPE DYNAMICS

T V Ramachandra Sai Omkari P Vinay s

ENVIS Technical report 178

Sahyadri Conservation Series 108

Citation**:** Ramachandra T V, Sai Omkari P, Vinay S, 2021**,** Eco-Hydrologic Footprint in Ghataprabha, Malaprabha, and Mahadayi Rivers with Landscape Dynamics**,** ENVIS Technical report 178, Sahyadri Conservation Series 108, Environmental Information System, CES, Indian Institute of Science, Bangalore 560012

Sahyadri- Western Ghats Biodiversity, Ecology and Environment
Environmental Information System [ENVIS-RP],
Centre for Ecological Sciences, TE 15
New Bioscience Building, Third Floor, E Wing
Indian Institute of Science
Bangalore 560012, India
http://ces.iisc.ernet.in/energy, http://ces.iisc.ernet.in/biodiversity
Email: tvr@iisc.ac.in, energy.ces@iisc.ac.in, envis.ces@iisc.ac.in

ECO-HYDROLOGIC FOOTPRINT IN GHATAPRABHA, MALAPRABHA, AND MAHADAYI RIVERS WITH LANDSCAPE DYNAMICS

***Citation*:** Ramachandra T V, Sai Omkari P, Vinay S, 2021**,** Eco-Hydrologic Footprint in Ghataprabha, Malaprabha, and Mahadayi Rivers with Landscape Dynamics**,** ENVIS Technical report 178, Sahyadri Conservation Series 108, Environmental Information System, CES, Indian Institute of Science, Bangalore 560012

ENVIS Technical report 178

Sahyadri Conservation Series 108

Sahyadri- Western Ghats Biodiversity, Ecology and Environment
Environmental Information System [ENVIS-RP],
Centre for Ecological Sciences, TE 15
New Bioscience Building, Third Floor, E Wing
Indian Institute of Science
Bangalore 560012, India
http://ces.iisc.ernet.in/energy, http://ces.iisc.ernet.in/biodiversity
Email: tvr@iisc.ac.in, energy.ces@iisc.ac.in, envis.ces@iisc.ac.in

Hydrologic Footprint in Ghataprabha, Malaprabha, and Mahadayi Rivers with Landscape Dynamics

Research Highlights

- Investigates Ghataprabha, Malaprabha, and Mandovi/Mahadayi catchments in northern Karnataka to understand eco-hydrological linkages with landscape dynamics across the agro-climatic zones.
- Land use analyses reveal the declining trend of forest cover (which includes evergreen, semi-evergreen, deciduous, scrublands, and grasslands) during 1972 and 2018,
- The decline of forests by 39.45% in Ghataprabha catchment, 33.35% in Malaprabha catchment, and 35.31% in Mandovi catchment
- The study highlights the supportive role played by native vegetation in sustaining the water in the catchment.
- Eco-hydrological footprint assessments reveal that the sub-catchments with native forest cover have a higher ability to retain water, which can easily meet the water demands across the year, against degraded sub-catchments with acute shortages.
- Three sub-basins of eight sub-basins in Ghataprabha catchment during the study period (1972-2018) had sufficient water to meet the requirements (Aquatic & Terrestrial E-flows, societal demands) while the rest faced water shortages for about seven months (2018), while estimates in the 1970s showed the same sub-catchments had water deficiency about 5 months
- Similarly, in Malaprabha catchment of 17 basins, five basins were sufficient in meeting the societal and ecological requirements in 1972, which has reduced to 3 basins in 2018.
- In, Mandovi catchment presence of native forests met all the water requirements in 1972, and the degradation transformed to a water-scarce condition in 2018 up to 3 months (2 out of 3 sub-catchments).

Hydrologic Footprint in Ghataprabha, Malaprabha, and Mahadayi Rivers with Landscape Dynamics

Abstract

Water is one of the essential natural resources sustaining life on Earth. Human evolution with increasing resource demands has altered the natural landscape impairing the catchments' ability to retain water, which has created resource scarcity. Unplanned anthropogenic activities have been changing the structure of catchment, altering functional capabilities of the ecosystem, which has influenced the sustainability of ecology, hydrology, biodiversity, etc. The present study emphasizes understanding the linkages between the landscape, blue water demands, green water demands, and hydrology components of the ecosystem.

The current study investigates Ghataprabha, Malaprabha, and Mandovi/Mahadayi catchments in northern Karnataka to understand eco-hydrological linkages with landscape dynamics across the agro-climatic zones (Coastal, Ghats, Transition zones, and Plains). Landscape dynamics in the catchments of Ghataprabha, Malaprabha and Mandovi have been quantified using spatial data (remote sensing data) of 1972 and 2018, with collateral data such as Survey of India topographic maps (1:50000), virtual global data (Google earth, Bhuvan), etc. Land use analyses reveal the declining trend of forest cover (including evergreen, semi-evergreen, deciduous, scrublands and grasslands) during 1972 and 2018, evident from 39.45% decline in Ghataprabha catchment, 33.35% in Malaprabha catchment and 35.31% in Mandovi catchment.

Eco-hydrological footprint assessments reveal that the sub-catchments with native forest cover have higher ability to retain water, which can easily meet the water demands across the year, against degraded sub-catchments with acute shortages. Three sub basins of eight sub-basins in Ghataprabha catchment during the study period (1972-2018) had sufficient water to meet the requirements (Aquatic & Terrestrial E-flows, societal demands) while the rest faced water shortages for about seven months (2018). Compared to this, estimates in the 1970s showed the same sub-catchments had water deficiency about 5 months. Similarly, in Malaprabha catchment of 17 basins, five basins were sufficient in meeting the societal and ecological requirements in 1972 which has reduced to 3 basins in 2018. In, Mandovi catchment presence of native forests met all the water requirements in 1972, and the degradation transformed to a water-scarce condition in 2018 up to 3 months (2 out of 3 sub-catchments). The study highlights the supportive role played by native vegetation in sustaining the water in the catchment. The decision-makers have to take immediate actions to implement integrated watershed conservation approaches through catchment treatment options of soil and water conservation.

Contents

List of figures

List of tables

Chapter 1 : Introduction

1.1 Environmental flows

Water elixir of life is considered one of the most essential and crucial elements for the existence, sustenance, development, well-being of life, and sustenance of natural resources. The quality of ecosystems has been compromised to meet human demands across the globe. During the past few decades, the increase in population has led to increasing demands for food, resources, etc. Due to which there are large-scale land-use changes with increasing agriculture expanse and escalations in the infrastructural activities such as roads, reservoirs, industries, etc., which have led to a decrease in native vegetation (forest) cover [1]. Reduction in forests, increase in carbon emissions have led to global warming, changes in climate at regional and global level, altering the hydrological regime with increasing floods, droughts, etc. Understanding the environment, hydrologic regime, geology, soil, etc., of the landscape, helps understand the catchment's hydrological responses. These hydrological responses (also known as the flow regimes) decide the habitat condition, ecosystems, and sustenance of dependent life forms. In order to preserve and sustain the quality and diversity in the ecosystems, i.e. biotic component, there is a need to ensure the integrity of abiotic components and ensure minimum flows in the system. The flows that sustain the biota of an ecosystem are also known as natural flows.

Preserving water to sustain biota during all seasons would serve an instream water right for biota (fish, etc.) [2]. Instream flow refers to "*The amount of water flowing through a natural stream course that is needed to sustain, rehabilitate, or restore the ecological functions of a stream in terms of hydrology, geomorphology, biology, water quality and connectivity at a particular level*" by the Instream Flow Council, jointly formed by USA and Canada. This concept of minimum instream flow gave the foundation to define the ecological flow.

Further, the Ministry of environment, New Zealand [3] defined the ecological flow as "*The flows and water levels required in a water body to provide for the ecological function of flora and fauna present within that water body and its margins*." The three terms, namely instream flows, ecological flows, and environmental flows, together constitute the ecological water requirement or environmental demands or environmental flow needs (Figure 1.1).

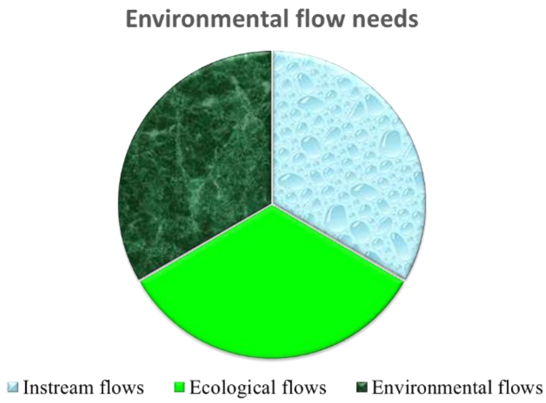


Figure 1.1: Environmental flow needs

Deliberations on instream flow and flow regimes led to two terms i.e., ecological flow and environmental flow. Dyson et al. (2003) [4] considered environmental flow as the "*Water regime provided within a river, wetland or coastal zone to maintain the ecosystems and their benefits*". According to Annear et al. (2004) [5], terms ecological and environmental flows are synonyms.

Lytle and Poff (2004) [2] emphasized that "*There is a wide recognition that a dynamic, variable water regime is required to maintain the biodiversity and ecological processes*".

Brisbane Declaration (2007) [2] defines Environmental flows as "*the quantity, quality and timing of the water flows, which is required to sustain the freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems*".

National water policy (2012) section 3.3 [6] highlights that "*A portion of river flows should be kept aside to meet ecological needs ensuring that the low and high flow releases are proportional to the natural flow regime, including base flow contribution in the low flow season through regulated ground water use*". Environmental flows, i.e., the natural flow regimes during all seasons, are influenced by varied factors such as land use, topography, soil, catchment, vegetation, climate, and other factors, as explained in section 1.2.

1.2 Influential Factors:

Anthropogenic activities through land-use changes are considered the major force that alters the biosphere [7]. **Land use** is defined as "*usage of land for various human purposes or defined as the economic function associated with a piece of land based on requirements*"[8]. Lambin et al., 2003 [9] identified and highlighted the important contribution of evapotranspiration based on the land use type, which also contributes to the flow regime and dependent catchment characteristics, in turn affecting the hydrological cycle. Similarly, the hydrological cycle components such as runoff, infiltration, and landscape changes have been emphasized by Ramachandra et al., (2018) [10]. Earlier studies ([11], [12]) confirm the relationships between the **catchment characteristics** and storm-based indices with the most significant impact on land management. Different catchment characteristics are explained in Figure 1.2.

Size of the catchment helps determine peak runoff volumes and rates, which increases with an increase in size with similar catchment properties. The operation of a specific watershed can be shown effectively on the hydrograph. Hydrograph (Figure 1.4) acts as the best tool in watershed planning which can be achieved by superimposing the rate of precipitation on watershed hydrograph to determine how the watershed reacts with various storms.

Shape of the catchment determines the flow characteristics. Generally, fan-shaped catchments (Figure 1.3) have higher flood intensities since all the tributaries have almost the same length and the time of concentration, long and narrow fern shaped (Figure 1.3) catchments, which have varied time concentration with the discharge being distributed over a longer period of time [13]. The hydrographs (Figure 1.4) explain the variation of runoff based on the shape of the catchment. The time of concentration affects the infiltration rates. The longer time it takes water to leave the watershed, the greater the infiltration capabilities for the water to percolate in the soil.

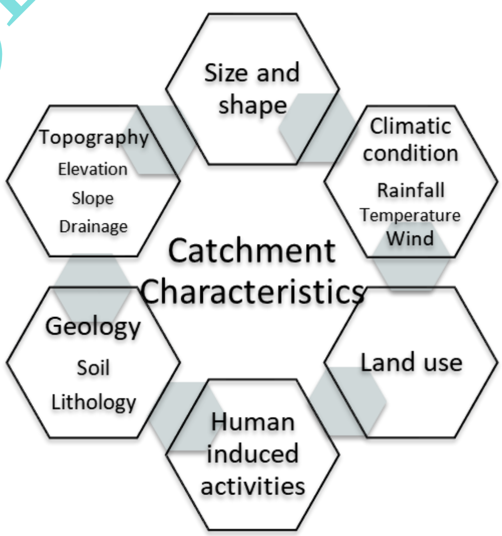


Figure 1.2:Catchment characteristics

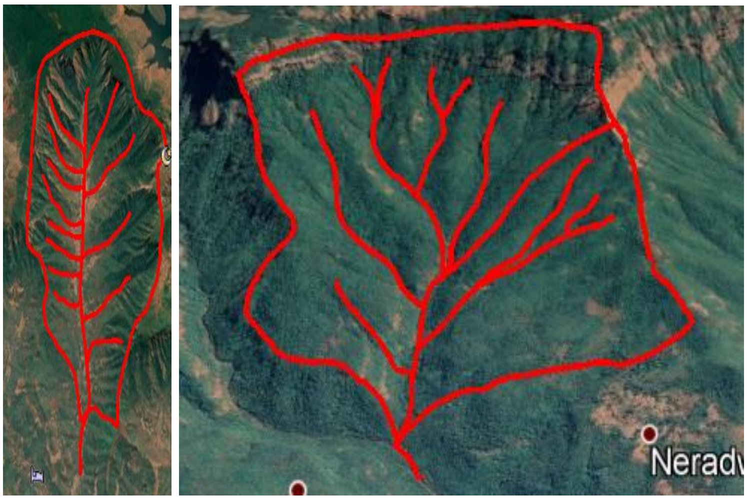


Figure 1.3 Fern and fan shaped catchments
(Source: Google earth pro)

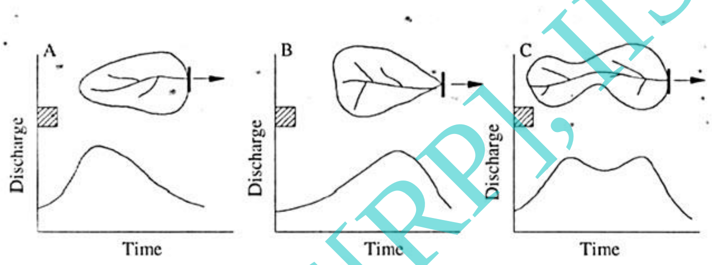


Figure 1.4 Effect of catchment shape on hydrograph
(Source: http://ecoursesonline.iasri.res.in)

Catchment characteristics are described physically through the number of streams, length of streams, stream density, and drainage density. Taylor and Schwartz (1952) explained the importance of drainage density in determination of time lag of the unit hydrograph and peak flow. Drainage densities affect the runoff patterns, which can be determined by equation 1.1.

Error! Reference source not found..

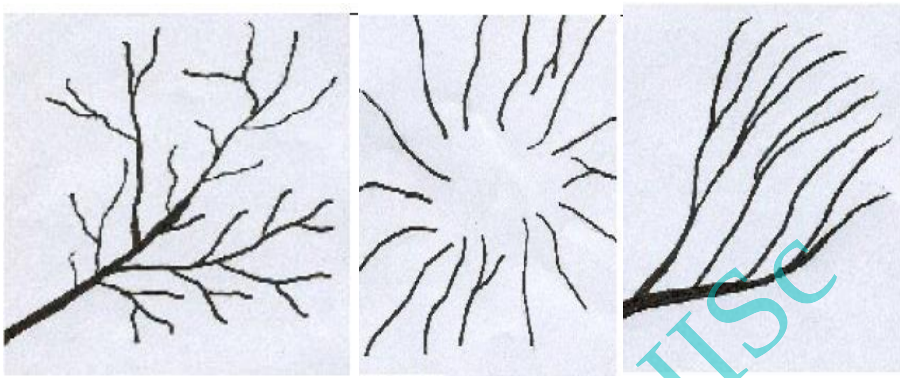
The criteria for drainage densities are listed in

Table 1.1. Drainage densities play a crucial role in surface runof processes, which affects the intensity of torrential floods. For instance, a high value of drainage density indicates a relatively a high-density stream and thus a rapid stream response.

Table 1.1: Drainage density conditions

Drainage densities	Conditions
Fine	≤1
Medium	1.01-3.0
Coarse	>3.0

(Source:https://shodhganga.inflibnet.ac.in/bitstream/10603/68733/18/18_chapter%208.pdf)



Dendritic pattern Radial pattern Parallel pattern

Figure 1.5:Drainage patterns[14]

The **drainage pattern** (Figure 1.5) of the watershed area/catchment/basin is dependent on the steam networks and its tributaries, which are influenced by the slope of the land and the lithological structure. The interpretation of drainage patterns reveals the geomorphic features and in the determination of landform evolution. Fine drainage texture is usually associated with dendritic patterns (Figure 1.5) and indicates impervious rock formations with low permeability. Soils formed in these areas are heavy and slowly permeable. The medium texture is found in rock formations characterized by fractures and joints. Soils formed are moderately deep, permeable, and medium in texture.

Drainage patterns of radial, pinnate, braided are usually observed, as shown in the Figure 1.5. Rectangular, angulate, trellis etc., are associated with coarse drainage texture, having high hydraulic conductivity. Drainage patterns act as guidelines to locate vulnerable areas requiring different kinds and degrees of soil conservation measures.

Soils and geology of the watershed play a key role in determining the infiltration rates, excessive runoff, amount of silt being washed out, etc.[13]. Based on the porosity, the texture of the soil, the corresponding flow rates are established. Soil textures such as coarse-textured soils have larger pores for water to percolate over fine-textured soils. For instance, clays have lower permeability over sandy soils based on the soil matrix. Similarly, geological formations such as aquifers yield a higher volume of water over aquitards and aquicludes.

Topography has major implications on hydrological functions and land use. The rate at which runoff occurs is dependent on the slope of the terrain. The steeper the slopes, the higher is the velocity of flow, which affects the erosion rates. Forested regions have lesser runoff over plain lands because of the soil retention capacity by plants in forest regions over plain lands.

Vegetation and forest cover influence the runoff, infiltration rate, erosion, rate of evapotranspiration, and sediment production. The foliage and the litter maintain the soil's infiltration potential. A denser forest is the most powerful solution for reducing erosion rates and increasing the infiltration rates and storage capacities. For instance, in two similar catchments with the equal area and other similar topographic factors, runoff rates are lower for higher forest density over lower forest density [13].

Among **climatic factors**, intensity, duration, and direction are the important storm characteristics affecting the catchment. Duration and Intensity of rainfall are crucial parameters in the determination of runoff in the catchment. Due to anthropogenic activities, alternations in the landscape have directly impacted the exchange of greenhouse gases, increasing land surface temperature with catastrophic, irreversible effects on biodiversity, affecting the rainfall pattern. These changes together create an imbalance in the ecosystem involving the functional aspects of the ecology and hydrology.

1.3 Flow conditions and their importance

Poff et al. (1997) [2] explained the importance of magnitude, frequency, duration, timing and rate of flow changes to determine the flow regime. Varied flow components link the different responses in the ecosystem, which helps in better understanding to manage flows. Furthermore, different flow conditions contribute to different ecological processes. For instance, low flows help in maintaining the water levels in the flood plains retaining the soil moisture for plants, facilitating the water for the terrestrial animals. Whereas high pulse flows will shape the river channels, and large floods will recharge the floodplain aquifers (IUCN). The details of flows are explained in Figure 1.6 and Table 1.2.

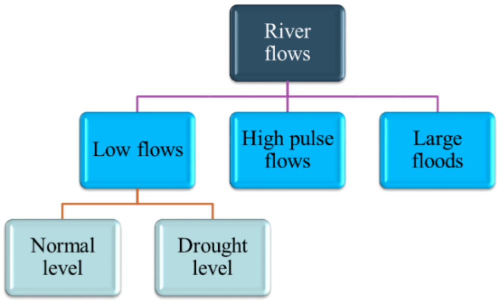


Figure 1.6: River flows

Table 1.2: Ecological functions supported by different river flow levels.

Flow condition	Ecological functions
Low (Base) flows	Normal levels • Provides adequate habitat for aquatic life • Helps in maintaining the water quality such as water temperatures, dissolved oxygen, pH, etc. in the water bodies. Drought levels • It affects aquatic life, leading to a concentration of prey at a particular location
High flows	• It shapes the physical parameters such as river channel • Restores the normal water quality conditions after prolonged low flows, flushing the pollutants.
Large floods	• Beneficial for migration of aquatic life • Recharges the floodplain tables. • Provides new feeding opportunities for the fishes, waterfowl etc.

Source: Securing water for ecosystem and human wellbeing. The importance of environmental flow, Umea University. IUCN & WWF.[15]

Various experts in the field of ecology and hydrology have carried out quantifications of environmental flows. Among these, Tenant method (1957), also known as Montana method, is considered the oldest methodologies developed specially to cater the needs of aquatic life, which was carried out in Nebraska, Wyoming, and Montana based on the stream width, depth, and the water velocity. The Tenant method is considered the ideal condition for the sustenance of aquatic life, which is achieved with the maintenance of 0.45-0.6m depth, and water velocities of 0.45-0.6 m/s. These levels were achieved with the conditions of 10-30 % of mean annual discharge i.e., the average annual flow. Low flows were identified from October to March and high flows during April to September. NGT (National Green Tribunal) of India recommended as 15-20% of the mean annual flow be maintained as environmental flow.

1.4 Water Resource

The global total water resources are estimated to be around 1.36 x 10^{12} M cum (1.36 trillion cubic meter), of which 97.2 % is saline, and 2.8% is freshwater resource [16]. According to Foster, 1998 37 Mkm^3 of freshwater is estimated to be present on the earth, of which 22% exists as groundwater. India has about 4% of the global resource (Figure 1.7), catering to 16 % of the world population (~ 1.2 billion people). The per capita is about 1170 m^3 per person per year (NIH, 2010), just being above the water-stressed criteria of approximately 1000 m^3 per person (Water resources department, Government of India, 1999). Proper management practices have to be encouraged to overcome this situation.

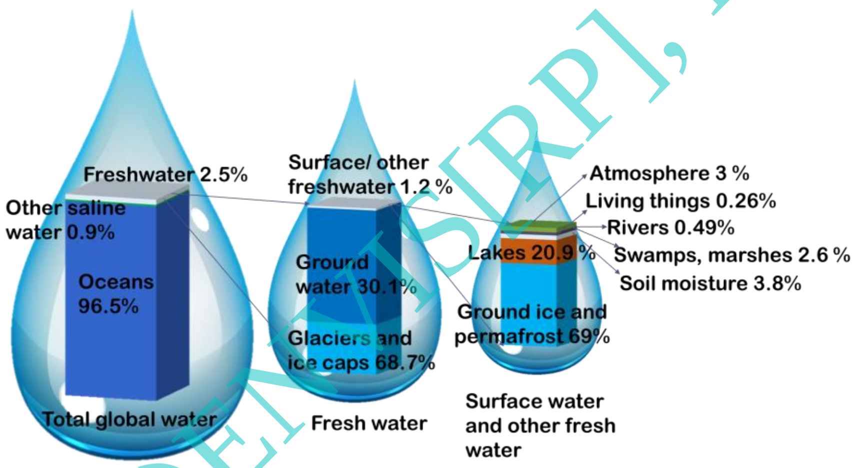


Figure 1.7: World water resources

(Source: https://www.usgs.gov/media/images/distribution-water-and-above-earth-0)

1.4.1 Water resources of Karnataka:

Karnataka State, India, experiences a tropical climate. The state shares the benefit of two monsoons, namely, northeast and southwest, respectively. The whole state is drained with seven major river basins (Karnataka water resources department), as shown in Figure 1.8, with a catchment area of 191733 km^2 with an average estimated flow of around 97800 Mm^3. The Western Ghats is the birthplace of most of the rivers flowing in the state. About 77% of the state's geographical area is drained by Krishna and Cauvery river basins flowing East. Aghanashini, Sharavathi, Nethravathi, Varahi, Kali, Sita, Gangavali, etc., are some of the significant west-flowing rivers in the state. West flowing rivers join the Arabian Sea, and east-flowing rivers join the Bay of Bengal. The mismanagement of water resources in the state has badly affected many villages. Currently, 996 villages and 244 wards of 26 districts face severe crises, namely Tumakuru, Chitradurga, Vijayapura, etc.

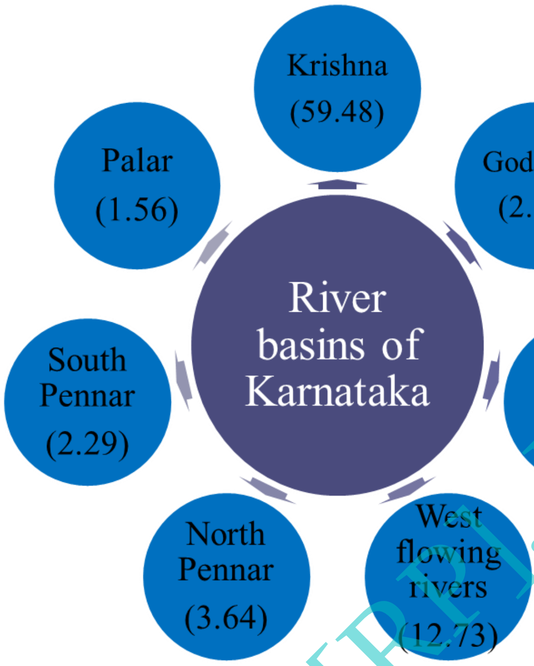


Figure 1.8: Water resources Karnataka
Source: Water resources Karnataka
Note: Numbers within brackets indicate the percentage drained area within the state

United Nations "World water assessment programme 2015" predicted that water demand would increase by 55 % by 2050, leading to an acute shortage of water resources and imbalance in catering the resource across all users, creating a negative hydrological footprint. The current study emphasizes the establishment of Eco-hydrological footprint as explained in section 1.5

1.5 Eco-hydrological footprint

Eco-hydrological footprint refers to the maintenance of hydrological regime for the sustenance of an ecosystem considering the ecological functions and societal requirements. An implicit relationship exists between the hydrologic regime and the biota (living beings) for maintaining the environmental flows and perseverance of ecosystem. The eco-hydrological footprint entails the carrying capacity of a river based on the availability and demand in its catchment. This work considers the dynamic relationships between available water resources, green water requirements, and blue water requirements to understand the societal, terrestrial, and aquatic services provided by water.

Chapter 2 : Literature review

Studies on environmental flows (E-flows) have recently gained importance, considering the acute water shortages due to the extensive anthropogenic activities in the environment. **Jonathan D et al. (2014)**[17] emphasized aspects such as magnitude, frequency, duration, timing, and rate of change of flows to maintain the ecological integrity of rivers. About 156 papers were published on E-flows in Australia between 1995 and 2012, of which 43 % were focused on the methods, modeling, or techniques of E-flows. Still, only 18% focused on the flow-ecology relationship. The basis for the E-flow studies is understanding the hydrological cycle, which depends on rainfall, catchment characteristics etc. The knowledge of the hydrological cycle plays a crucial role in determining the catchment characteristics to evaluate the hydrological status.

Marshall (2014) [18] described the overview of the hydrological cycle. Currently, there is tremendous turnover within the global water cycle. The average residence time of a water molecule in the atmosphere is about 9.2 days. Evaporation is considered one of the most important phases of the hydrological cycle, which accounts for about 86% mainly from oceans. In the overland area, evapotranspiration depends on the availability of soil moisture and the plant's life cycle. On average, about 78% of global precipitation falls over the oceans, with the remaining 22% distributed unevenly over the landscape. The surface or overland flow drains most of the landmass on the planet. Water drains to the subsurface become part of the groundwater system, recharging aquifers and contributing to lateral flow. Decision-makers need to understand the water balance to examine the watershed management of the catchment.

Gu et al., (2010)[19] stated that high quality precipitation data is required for the analysis of the hydrological model system. At present, there are three resources used to estimate rainfall: rain gauge stations, ground-based rainfall radar, and satellite remote sensing devices. Of three, microwave remote sensing observations can be used to retrieve the temporal and spatial rainfall coverage because of their global availability and frequency of measurement.

Gu et al., (2010)[19] analyzed TRMM 3B42V6 (Tropical Rainfall Measuring Mission) rainfall data from the Yangtze River Basin, the longest river and largest basin in China. TRMM carries a rainfall radar (PR), TRMM microwave imager (TMI), visible and infrared scanner (VIRS), lightning imaging sensor (LIS), and earth radiant energy system. The hydrological modeling involved soil hydrological model (SHM), groundwater hydrological model, terrestrial hydrological model (THM), and channel groundwater interaction model (Yu et al. 1992a, 1999b, 2002). The authors developed SHM by Richard's equation; Rainfall data was processed using the inverse distance squared method. Correlation coefficients (Pearson correlation coefficient, Nash-Sutcliffe coefficient) between the interpolated rain gauge data and TRMM data series were calculated. TRMM 3B42V6 data slightly overestimated rainfall during the wet season and underestimated rainfall during the dry season in the Yangtze River Basin. Results suggest that the TRMM 3B42V6 rainfall product can be used as an alternative data source for large-scale distributed hydrological models.

Jing et al., (2014) [20] assessed the rainfall from gauge data of Xicheng district, China. Rainfall interpolation techniques such as Theissen polygon method, inverse distance weightage, kriging and co-kriging were used in the analysis of data. Factors such as gauge numbers, density and gauge position were considered for the spatial interpolation of rainfall data. Trend analysis was carried out using the software ArcGIS 10.1 by adjusting the semi-variogram and cross validation for the rainfall interpolation techniques. The value of RMSE (Root mean square error) showed downtrend for the increase in sampling fraction above 50 percent. The accuracy was enhanced with the increase in sampling number. Thus, results showed that the rainfall was homogenous within the region. Higher accuracy was achieved with high number of gauged stations over sparse stations. Over different rainfall interpolation techniques IDW (Inverse Distance Weightage) and kriging were considered for the optimal results in small areas whereas for larger areas co-kriging is used and it is quiet complex with multiple variables.

Lancashire, UK. Law., (1956)[21] studied the water balance in the region of conifers and compared this study with a smaller area of grasslands.

Hewlett and Nutter, (1969) [21] emphasized the role of canopy structure in determining the storage capacity contributed by interception. The morphometric features of the leaf and bark are the essential factors in determining stem flow and through flow. Large broad-leaved plants such as oak, tend to hold water well on their leaves, while needled plants can hold less per leaf. Seasonal variations make a huge difference within deciduous forests, with the presence and absence of leaves. Table 2.1 illustrated below indicates the interception caused by the different forest types and the ages.

Table 2.1: Interception measurements in different forest types and ages

Tree type	Age	Interception(mm)	% of annual precipitation
Deciduous hardwoods	100	254	12
Pinus strobus (White pine)	10	305	15
Pinus strobus	35	381	19
Pinus strobus	60	533.4	26

Band et al., (1987) [21] described that forests are associated with high amount of rainfall, retaining the moist and coolness in the regions over plain lands because of the aerodynamics that help create higher cloud formation in the regions of forests. However, the effect of forests on rainfall are still under research studies.

Calder. (1990) [21] amalgamated different UK forest interception studies to determine climatic and seasonal variations in their contribution to understanding interception storages. The higher interception ratio (interception loss by canopy rainfall) was found during drier periods over wet climates. The interception values varied from 0.45 at 500 mm to 0.27 at 2700 mm annual rainfall (considering the inter-annual variability).

Putty and Prasad., (2000)[22] worked extensively on western Ghats mountain ranges in southern India to determine different runoff processes and corresponding responses to the catchment. A lumped parameter model was simulated to determine saturated source runoff, lateral flow through pipes, and saturated zone groundwater flow. Table 2.2 below suggests the approximate values for each land use category.

Table 2.2: Suggested range of values for physically based parameters of Sahayadri and for the crop factors.

Land-use	Soil-type	CEPM (mm)	Soil thick (cm)	SZFC (%)	SZWP (%)	CF
Evergreen forest (dense)	Sandy clay organic	4.5–5.5	150–200	25–30	10–12	1.20
Deciduous/open forest(plantations)	Sandy clay	4.0–5.0	125–175	25–30	10–12	1.00

Scrubby	Gravelly sandy loam	2.5–3.5	50–100	15–20	10–12	0.85
Grassed	Gravelly sandy loam	1.8–2.0	50	10–15	10–12	0.85
Paddy (valley)	Gravelly sandy loam	1.8–2.0	50	20–25	10–12	1.10

Note→CEPM: Interception storage capacity, SZFC: Soil zone field capacity,
SZWP: Soil zone wilting point ; CF: Crop factor

This highlights that the significant contribution to stream flows is essentially through pipes. Pipe flows significantly contribute to about 60% only during low intensity, long duration precipitations.

Studies on runoff were carried out by **Horton., (1933)** [21] in the early 18th century. Hydrological effects of natural secondary forest ecosystem were studied by **Wang et al., (2012)** [23] from March to October 2009 in East China. The periodic flooding in Yangtze River and water shortage in Northern china have continuously led to the research progress in China between forest and water. Huang Gongwang forest park was considered for the ecological observations of soil and water. Continuous measurements of microclimatic data and soil moisture data obtained from meteorological and soil moisture DT85 (Data logger) at different depths (5 cm, 10 cm, 20 cm, and 50 cm). Further for the runoff analysis of the two small catchments, were Frequency of the rainfall distribution showed that 42.6% was accounted for light rain. Further, 22.22% and 24.1% were considered to be moderate and heavy rain, respectively, with the leftover portion being accounted for a rainstorm. Dynamic variations of soil moisture depended on precipitation, and the results showed that with an increase in depth, soil moisture tends to be stable. The Month of August showed the highest moisture, about 22.55% at 10 cm depth. Soil moisture variations could mainly depend on roots' strong absorption capacity. Due to increased variations of temperature and strong evaporation, the soil moisture in the topmost layer was found to be lowest. Regression analysis of rainfall(X) and slope runoff(Y) showed linear relationship with equation as $Y=0.0017X-0.0046$ ($R^2=0.994$, $n=54$, $P<0.01$).

Hawkins., (1993)[24] explained the asymptotic determination of runoff curve numbers from the data for three watersheds. This technique preserves the assumption of equal return periods for rainfall and runoff.

Lakhote et al., (2014)[25] analyzed the rainfall-runoff for the agricultural watershed area in Hinghat district, Maharashtra. This study described that the rainfall-runoff characteristics in 8 rain gauge stations in the Vena catchment. The analysis involved comparing runoff with SCS model, modified SCS model, and Mockus model respectively. The relationships established between the three models were well within ±10% variations. The average annual runoff (104.95) was much less compared to annual rainfall (1314.56 mm). Of the three models modified SCS-CN method gave better results for the catchment over the other two methods.

Horton and Hawkins **(1965)** gave the foremost studies concerning the contribution to through-flow to a storm hydrograph [21]**.** They proposed the "Translatory or piston flow mechanism to explain the rapid water movement from subsurface to the stream", based on the principle that the pressure on the top of the piston chamber leads to pressure at the bottom. The role of macro-pores in soil matrix plays a vital role in contributing to pipe flows in hillslope hydrology, which Jones extensively studied **Tanaka., (1981) and (1992)** [21]**.** The role of these macro-pores is not clear, and their contribution to the rapid movement of water to stream flows in non-monsoons, which in turn may lead to piston flow.

Natarajan et al., (2018)[26] estimated the groundwater recharge using empirical methods and water table fluctuation method in Sirumugai, Coimbatore, Tamil Nadu. The rainfall data for the period 1995 to 2014 were collected from 2 rain gauge stations. The results computed from various methods as shown in Table 2.3 varied from 5.51 to 101.20 mm/year using empirical methods and 67.5 to 340 mm/year using the water table fluctuation method.

Ali et al., (2017) [27] compared and evaluated the various empirical and groundwater recharge methods in the Mymesingh district of Bangladesh. During the study (2014-2016), the authors computed groundwater recharge by tracer techniques using chloride as a tracer. The empirical methods were also employed for the comparison. The results showed that the Chaturvedi formula, modified Chaturvedi equation underestimated the values, whereas, Maxey-Eakin overestimated the values concerning tracer techniques. On the other hand, Kirchner formula gave the best results of all the various methods. They further estimated the percent mean relative absolute error, which was less than 11%.

Praveen and Krishnaiah, (2017) [28] compared the empirical models with groundwater recharge estimation in Groundwater recharge in Venkatapura watershed, Karnataka. This analysis was carried out initially by obtaining the average annual rainfall for the study region by the arithmetic mean method for 3 rain gauge stations located at Shirali, Nagavalli, Kogar regions from 1996 to 2015. The data computation revealed that Kogar had the highest rainfall (7516.8 mm) data over the other two. Then, the groundwater recharge estimates were then carried out by Chaturvedhi, U.P.I.R.I, Bhattacharjee, Krishna Rao, Seghal, Kumar, and Sethapathi formulae, respectively in Table 2.3.

Table 2.3: Estimation of ground water recharge by empirical methods

Empirical methods	Equation	Region worked	Outcomes
Chaturvedi Formula (1936)	$R_g = 2\ (P-15)^{0.4}$ R_g: Net recharge in inches P: Annual rainfall, in inches	Ganga-Yamuna doab	Preliminary estimation of ground water recharge from rainfall
Amritsar Formula (1973)	$R_r = 2.5\ (P - 16)^{0.5}$ R_r and P are measured in inches	Doabs in Punjab	The formula was found to hold good for areas were rainfall was between 23.6 and 27.5 inches.
U.P.I.R.I. Formula (1954)	$R_g = 1.35\ (P-14)^{0.5}$ R_g is net recharge, in inches, P is annual rainfall, in inches.	Ganga-Yamuna doab	Modified Chaturvedi Formula
Krishna Rao Formula (1970)	$R_r = K\ (P-X)$ R_r: Groundwater recharge, mm, P: Precipitation, mm and K: Recharge coefficient	Karnataka	K=0.2 (400<P<600 mm) K=0.25(600<P<1000 mm) K=0.35 (P>2000 mm) To determine the ground water recharge in climatological homogenous areas
Bhattacharjee Formula (1954)	$R = 3.47\ (P-38)^{0.4}$ R: Groundwater recharge (cm) P: Precipitation (cm)		
Kumar and Seethapathi Formula (2002)	$Rg = 0.63\ (P-15.28)^{0.76}$	Upper Ganga canal	

	Rg: Groundwater recharge from rainfall in monsoon season (inches) P: Mean rainfall in monsoon season (inches)		
Water table fluctuation method	$R_g = A_w * ÄL * S_y$ R_g : Groundwater recharge A_w: Area of watershed (m^2) S_y: Specific yield (0.25, based on literature data) ÄL: Water table difference (m)		

Evapotranspiration is the major driver for the demands in forests. Determination of evapotranspiration is carried out by various studies like Hamon method, Thornthwaite method, Pristley and Taylor equation etc. Penman-Monteith and Hargreaves are the commonly used equations for these studies. The following literature would give more insight into the assessment of evapotranspiration.

Karl Vanderlinden et al. (2004) assessed the reference evapotranspiration by the Hargreaves method in Southern Spain. The study was carried out in 16 meteorological stations as recommended by the Penman Monteith equation, compared with the Hargreaves method. The results showed that the Hargreaves method was more biased in dry, hot summer seasons over the other climatic conditions, and this equation uses limited parameters over Penman-Monteith estimates.

Berti., (2014)[29] calibrated the usefulness of the Hargreaves equation in plain areas of northeastern Italy. Thirty-five stations with prolonged and continuous data set were used in the present study. Of which 10 were used for calibration and 25 for validation. To measure various climatic parameters such as air temperature and relative humidity, soil temperature, atmospheric pressure, leaf wetness, rainfall, wind speed and direction, solar radiation and pan evaporation. Data was processed using Oracle system called SIRAV (Sistema Informativo Regionale Ambientale del Veneto). The results showed that the Hargreaves equation overestimated the value of Penman-Moniteith by 18.9%.

Nithya and Shivapur (2016) [30] quantified the water requirement for crops under the Tarikere area using CROPWAT software, designed as per FAO guidelines. The study area includes the crops such as areca nut, coconut, cotton, banana, sweet pepper, etc. The water requirement for each crop was analyzed using 30-year climatic data. Reference evapotranspiration was determined using the Penman-Monteith equation. Results showed that the reference evapotranspiration varied from 2.5-3.36 mm/day. Therefore, the gross water requirement for the Tarikere area was 342.2 mm/year for an area of 4466 ha, which could be met with proper management practices.

Anthropogenic activities are the major drivers shaping biodiversity altering the stability in nature. Understanding these changes play a crucial role in effective management systems. The literature pertains to land use, and land cover would certainly, throw light on the effects of change in land use patterns on the environment.

Bharath et al. (2012) [31] analyzed the role of the landscape metrics using multi-resolution (spatial) remote sensing data for quantifying landscape patterns. Landscape metrics have been used in understanding landscape dynamics. Aggregation index, cohesion index etc. were computed to quantify spatial patterns of landscapes. An aggregation index (AI) to quantify spatial patterns of landscapes and exploration is in progress to apply these metrics for various purposes to link with the current scenarios. In this study, Greater Bangalore was chosen as a sample space. Data was compiled from Ikonos (4 m), Landsat series Enhanced Thematic Mapper (28.5) sensor, IRS P6 LISS, and Modis data (500 m). Thirteen widely used landscape spatial metrics were computed using FRAGSTATS software in ASCII format. The spatial metrics include the patch area, edge/border, shape, compact/contagion/ dispersion. Results showed that the overall accuracy of the classification was 88% using Landsat data, 91% accuracy using IRS-P6 data and 74% using Modis data respectively. The results reveal that landscape metrics based on patch are sensitive to spatial resolution whereas metrics that are based on shape and neighborhood are not sensitive and behave similarly across all resolutions.

Ramachandra and Bharath (2018) [32] assessed the spatial patterns of landscape changes in Uttara Kannada district of central Western Ghats in Karnataka, India. Landsat data (1973-2016) were resampled to 30 m to maintain uniform resolution. The analysis involved understanding vegetation cover changes using NDVI (Normalized Difference Vegetation Index) and land-use dynamics through supervised classification technique, i.e., Gaussian maximum likelihood classifier algorithm. The fragmentation of a landscape with space and time is assessed through indices such as clumpy index, aggregation index, etc. were analyzed using Fragstats 3.3(1973

– 2016). Results portrayed the conversion of evergreen forest to semi-evergreen and moist deciduous from 67.73% to 29.5%. Enhanced agriculture activities from 7 % to 14.3% and increase in built-up from 0.38% to 4.97% were reported in the study period. In Sirsi, Siddapur, Haliyal, Yellapur, and Mundgod regions, encroachments have changed the forest cover disturbing local ecology. The study revealed the transition of intact forested landscape (1973) to fragmented landscape with increased patchiness (2016).

Luo et al., (2011) [33] delineated the watershed with the application of SWAT model. In recent days with technological improvisation, the hydrological models have become a research focus. The general trend is manually delineating the catchment-based on terrain conditions. The current study emphasizes delineation techniques. Using "ArcGIS" and "ArcSWAT" improved DEM-based method, and pre-defined method was used in watershed delineation. The first method is based on the Digital channel network (DCN) that was carried out using the "Burn-in" function, and the streams and sub-basins were delineated based on the DEM and DCN. Then using the "ArcGIS" the reach layers could be adjusted accordingly. The second method is the manual delineation of the data. Comparison of results were well with the realistic hydrological models.

Chongwei et al. (2006) [34] studied the landscape pattern and eco-hydrological characteristics at upstream of Minjiang River, China. Initially, the watershed boundary was delineated with the topography map and six hydrology stations, viz., Zhenjangguan, Heishui upside, Heishui down, Zagunao upside, Zagunaodown, and Shouxi. Using ERDAS software 8.7 with fifty points for each land cover type were selected randomly to assess classification results. The precision was 83.1 % and landscape indices such as patch density, total edge density etc., were determined using FRAGSTATS software. A precipitation map was generated with 51 rain gauge stations on an annual basis using ARCINFO software. Finally, an eco-hydrological index was established based on the formula as follows:

$$\boldsymbol{H} = \frac{\sum(\boldsymbol{p}-\boldsymbol{R})}{\sum \boldsymbol{p} \sum \boldsymbol{NDVI}} \quad \textbf{(2.1)}$$

Where p: Precipitation (mm) R: Runoff (mm)

The results showed that the Shouxi catchment had a higher forested cover, about 89.41%, followed by Zagunaodown, Heishui. Shouxi had the lowest patch and edge density about

13.53% and 83.63%, respectively. Zagunao had the highest densities of all, indicating the most fragmented region of the study area. The outcome showed that the water holding capacity increased in the Shouxi catchment with higher forest cover and outlined that landscape pattern plays a crucial role in understanding the eco-hydrology of the region.

Monk et al., (2007) [35] assessed the hydro-ecological changes in England and Wales through river flow indices for 83 sites. Hydrological data for a period of 20 years (1980-1999) were considered based on daily mean flows. The ecological data for a period of 11 years (1989-2000) was collected based on a semi-quantitative 3 min sample method. To assess the macro invertebrate, LIFE (Lotic invertebrate index for Flow evaluation) method was developed by the Environmental agency, England. About 201 indices were developed, which were mainly classified into five categories based on magnitude, duration, timing, frequency of flow events and rate of change of flow conditions. PCA (Principal Component Analysis) was carried out based on the regime shape class for 83 rivers. Variables of PCA were used as step-wise multiple line regression models to predict the LIFE scores.

The research carried out at China and abroad by **Mei et al., (2010)** [36] on ecological water requirement was divided into 4 stages. The embryonic stage of ecological water requirement from 1940s to 1970s was the initial stage in development, which identified the purpose of the ecological flow, followed by the quantitative and procedural studies. Further, in the 1980s the minimum acceptable stream flows were taken into consideration to answer the river pollution, account for shipping, biology and landscape water requirement, and meet the drainage and waste discharge, which formed the core of the eco-environment water requirement study. The research on eco-environmental water requirement was enhanced because of the increase in ecological crisis. Later in 1990s, “Four balance method” was proposed by Liu, in accordance with “Three vital water,” which considered the “live, production and ecology”. Till date, there is continuous progress on ecological water requirement studies based on a regional scale and the scale of all kinds of ecological systems. Regional studies were concentrated on Yellow River, Hai River Basin, and eco-environmental water demand in North China and small-scale studies at islands were reported. So far, the results were summarized in FRIEND (Flow Regimes and Network Data) Action plan report. Since the 21st century, the ecological water requirement is called at its inclined maturity stage, which was studied in four categories:

hydrology methods, hydraulics methods, habitat simulation method, and synthetic method. Currently, the research is in progress to relate the environmental standard with sustainable development.

Fuju et al. (2011) [37] carried out the environmental carrying capacity using an ecological footprint model in the Yellow river delta, China, during 2001-2008. Ecological footprint indexes were established based on land use through the relation as:

$$\mathbf{EF = N * ef} \qquad \mathbf{(2.2)}$$

$$\mathbf{ef = \sum aai = \sum (ci/ pi)} \qquad \mathbf{(2.3)}$$

where *i* is the type of commodity and investment;

p_i is the average production ability of commodity of the *i* type;

c_i is consumption per capita of the *i* type commodity;

aa_i is productive land area of the *i* type of commodity per capita;

N is the population of the area;

ef is the ecological footprint per capita;

EF is the total ecological footprint.

The ecology carrying capacity (EC) was estimated as the product of area (areas of the farmland, the grassland, the forest, building land, and the sea), corresponding balanced factor, and the local output factor as;

$$\mathbf{EC = \sum cj\ N = (\sum a\ j * rj * yj) * N} \qquad \mathbf{(2.4)}$$

Where, j is the land use type;

EC is the total ecology carrying capacity of the region;

N is population;

a_j is productive land area per capita;

r_j is the balanced factor;

y_j is the output factor.

The ecological deficit (ED) size may be expressed as:

ED = EF- EC.

The positive or negative ED indicates ecological deficit or ecological surplus, reflecting the degree of sustainable development in the region. During the study period, it has been observed that the ecological footprint has increased from 0.1855hm^2 in 2001 to 0.4369 hm^2 in 2008.

Some counter-measures were advanced in order to improve the environmental situation of the Yellow River Delta, such as adjusting industrial structure through developing circulate economy vigorously, saving mine resources, and protecting pasture environment through strengthening management, controlling the population, and advocating sustainable lifestyle.

Yang et al., (2012) [38] calculated the instream ecological flow for China's Irtysh river. This river had been highly affected by human activities since the 1960s. Data series of monthly measured flow records of Buran station, Ust-Kamenogorsk station, Omsk station, and Tobolsk station were considered for the analysis. Monthly minimum flow and monthly frequency were calculated and found that during the wet season, the stream had higher ecological flow when compared to dry seasons.

The results showed that the monthly frequency method gave optimal results of ecological flow of 616.6-1027.6 m^3/s for Buran station. Similarly, 765.3-1275.5 m^3/s for Ust-Kamenogorsk station, 1017.3-1695.6 m^3/s for Omsk and 2591.5-4319.2 m^3/s respectively. Further Tenant method was used to compare the seasonal variations and found that it was site-specific and was dependent on climatic conditions, ecological protection, etc.

Dubey et al. (2013) [39] carried out various hydrological index methods at the Narmada river at 4 gauging sites. The trend of environmental flow showed that there is a significant alteration in the ecosystem caused by anthropogenic activities. The various methods such as lookup tables, Tenant method, and modified Tenant method were used in the computation of the hydrological data. The results showed that the four gauging stations had EFR (Environmental Flow Requirements) of 50.6 to 73.5 m^3/s at Sandia gauging site, 42.8 to 52.5 m^3/s for Barman, 0.42 to 9.2 m^3/s for Manot, and 0.71 to 4.05 m^3/s for the Dindori gauging site of the river. The results of the lookup tables were inappropriate over the Tenant method because even the poor flow conditions (10% mean annual flow) were not properly distinguished. The modified Tenant method appears to be more preferred to estimate the environmental flow requirements over other methods.

Vinay et al. (2013) [40] modeled the hydrological regime of Sharavathi river basin considering landscape dynamics. Remote sensing data from IRS P6 LISS IV of 5 m resolution was used for land use classification. Topographic maps (1:50000, 1:250000), vegetation map (French institute, 1985) were used to delineate the drainage network using Cartosat DEM of 30 m resolution. Crop calendar (Agriculture Department of Karnataka, Kisan, National Food Security Mission) was used to understand the crop water requirement each month. The overall hydrological assessment was carried out using water balance studies involving rational formula, Hargreaves equation, crop coefficient determination, etc. The analysis helped in identifying the water-stressed areas. Of the field data, 60% of the data was used to classify, and the rest 40% of the data was used for accuracy assessment of the classified database. Based on the flow, streams were categorized from perennial to seasonal as the catchment of perennial streams was dominated by native vegetation and seasonal streams by monoculture plantations.

Ramachandra et al. (2014) [41] estimated the environmental flow of the Lakshmanatirtha watershed using water balance studies. The article presented the interaction of landscape dynamics with catchment characteristics. Land use in the basin was analyzed using Landsat 8 data of 30 m resolution, using Maximum Likelihood Classifier. Daily rainfall data was obtained from Karnataka statistics Department, Bangalore. Solar Irradiation data was used to calculate the Potential Evapotranspiration, obtained from Food and Agriculture Organization. The accuracy of the classification was 94%, and the kappa coefficient was 0.92. The analysis showed that 4 out of 5 sub-watersheds were under water stress conditions, which was insufficient to cater to the requirements. It was observed that catchments with higher forest cover resulted in high groundwater storage (with an increase in infiltration indices i.e., less runoff), over plantation activities with low groundwater storage.

Amna Butt et al. (2015) [42] worked on land-use change mapping and analysis using remote sensing and GIS in a Simly watershed, Islamabad, Pakistan. Land use classification was carried out by ERDAS imagine using Landsat 5 and SPOT 5 data for the study period between 1992 and 2012. The maximum likelihood algorithm was applied for land use analysis, which had five categories: agriculture, settlements, bare soil, vegetation, and water. The overall accuracy of the classification was 95.32% and 95.13% for the years 1992 and 2012. The resultant land use indicated a drastic shift from vegetation and water to agriculture, bare soil, and settlements, which posed a greater threat to water resources. Over two decades, the main cause for these changes is anthropogenic activities, which led to the conversion of areas near the water body to agriculture for human developmental activities. Therefore, proper watershed planning with afforestation is required to maintain the hydrological and ecological balances in the watershed.

Adhikari et al., (2016) [43] carried out land-use change at a sub-watershed level at Mahadev Khola watershed in Bhaktapur, Nepal. This watershed acts as a major source of water to the people existing in this vicinity. Temporal LULC was analyzed for the years 2005 and 2014, respectively, using RS and GIS techniques. Later on, it was verified with field studies, and household surveys carried out by Arkin and Kolton. The results showed that there was a drastic increment of settlements, about 156.25%, and a decrement of forest cover by 6.25% with an increase in forest fragmentation. The authors concluded that this dynamic in landscape led to the "**urban stream syndrome**, " wherein they found a high correlation between water qualities and increased settlement activities. They further suggested increasing the afforestation by planting native species like *Schima wallichi, Vitex negudo* etc to increase the water holding capacity, thereby passing over the shortcomings.

Ramachandra et al., (2016) [44] estimated the environmental flow of Yettinaholé River in Central Western Ghats by investigating the interaction between land-use dynamics, hydrological yield, and fish diversity in the streams for 18 months. Land use analysis was carried out using the Gaussian Maximum Likelihood Classifier technique, and the hydrological yield was determined using the water balance model. Krishna Rao equation was used to quantify groundwater recharge, Hargreaves method for evaluating potential evapotranspiration. Total water demand across the catchments was obtained as a function of environmental flow, evaporation, livestock, domestic and agriculture requirements. Hydrological yield in the catchment was 9.5 TMC, of which 5.84 TMC was used for domestic purposes and 2 TMC for fish life in the streams. The assessment showed that most streams in the forest catchment are perennial compared to streams in the catchment predominantly covered with monoculture plantations and noticed that the alterations in the catchment integrity would result in, variations in the flow regime affecting the biodiversity.

Vinay et al. (2016)[12] studied the interaction of landscape dynamics using remote sensing and GIS with the integration of hydro-meteorological data across seasons. Sagara taluk of Shimoga district Karnataka was considered the study area to obtain landscape on local hydrology. Landsat and IRS series data from 1973 to 2012 were analyzed using the maximum likelihood classifier technique, which was enhanced with field data. The area velocity method was used to quantify the streamflow (discharge measurements), water depth, etc. Land use analysis portrayed the reduction of forest from 57.3% (1973) to 45.5% (2012) and an increment in the forest plantations from 10.76% (1973) to 37.20% (2012). Groundwater dynamics were assessed in the wells located in catchments and in the vicinity, which indicated the availability of water in wells was positively correlated with its proximity to forests and lakes. Results showed that the groundwater fluctuations varied from <0.6m (along with the downstream of lakes with good forest cover) and 1.2m (with good forests in the upstream) to 1.5 m (in the catchment dominated by degraded forests). This helped in understanding the watershed management strategies to sustain and maintain the desired environmental flow catering to the demands.

Ramachandra et al. (2018) [10] determined the eco-hydrological index of a river basin in the Western Ghats. This index speaks about the crucial status and health of the river. The investigation involved temporal land use analysis using Landsat series remote sensing data obtained from USGS from 1973 to 2016. Demand requirements included agriculture, livestock, domestic and ecological needs. Further, the establishment of eco-hydrological footprint determined the water scarcity or the water sufficient conditions. The results showed a decline in forest activities from 1973 to 2016 from 61.8% to 37.5%. Computation of eco-hydrological index revealed that sub-catchments dominated with forest cover in Ghats had better hydrological index over plain regions. Water footprint portrayed that of 13 basins, 8 were under water scarce condition, inefficient in meeting the requirements. The authors bought out the importance of the eco-hydrological index, stating that native species of forest cover had a better Eco-hydrological index with streams being perennial for almost 12 months, against plain regions with low Eco-hydrological index with streams being seasonal.

Zeiger et al. (2019) [45] quantified the linkages between Missouri streams' watershed characteristics and hydrological indices. Hydro ecological Integrity Assessment Process (HIP) and Ecological Limits of Hydrological Alteration (ELOHA) are the frameworks developed to assess the environmental flow. Cumulative LULC variables, physical soil characteristics, roughness, slope and geomorphic variables were considered for the model fitting. In the present study, 11 of 171 hydro-ecological indices were computed using USGS for Environmental flow analysis. Results showed that urban land was the only parameter strongly correlated to hydro-ecological indices and had a good correlation of $0.77 < R^2 > 0.85$.

Chapter 3 : Study Area

3.1 Ghataprabha

Ghataprabha River is a tributary of Krishna River, which originates at Chakul village, Sawantawadi taluk, in Sindhudurg district (Figure 3.1) Maharashtra state. Originating in the Western Ghats, Ghataprabha flows for a distance of 283 km, towards the east joining Alamatti reservoir at Bilgi taluk and extending between 15°44’11” N to 16°25’28” N latitude and 74°00’00” E to 75°50’48” E longitude. Ghataprabha catchment covers an area of 8771.24km^2. Ghataprabha catchment spreads across two states, namely Karnataka and Maharashtra, covering five districts and 21 taluks, as described in Table 3.1

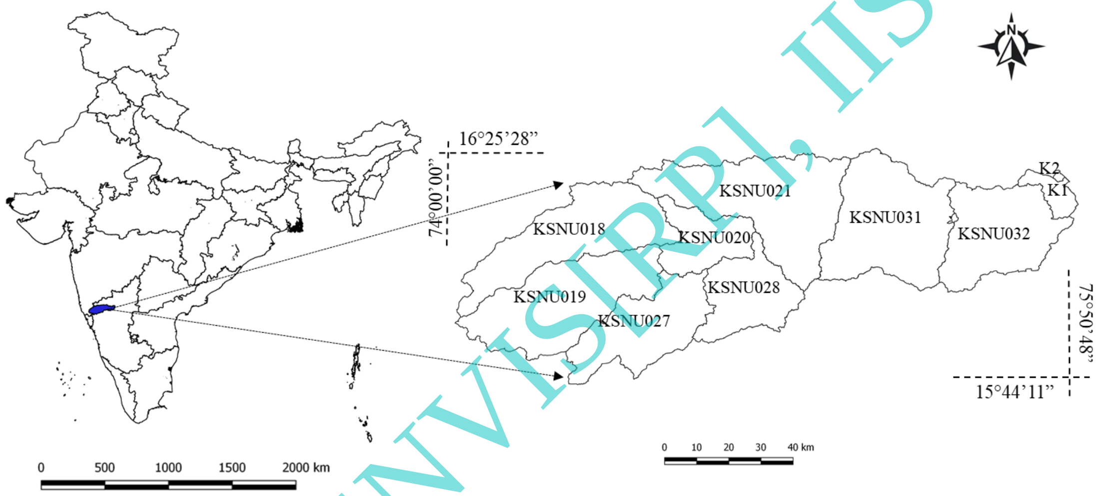


Figure 3.1:Ghataprabha and its sub catchments as per CWC

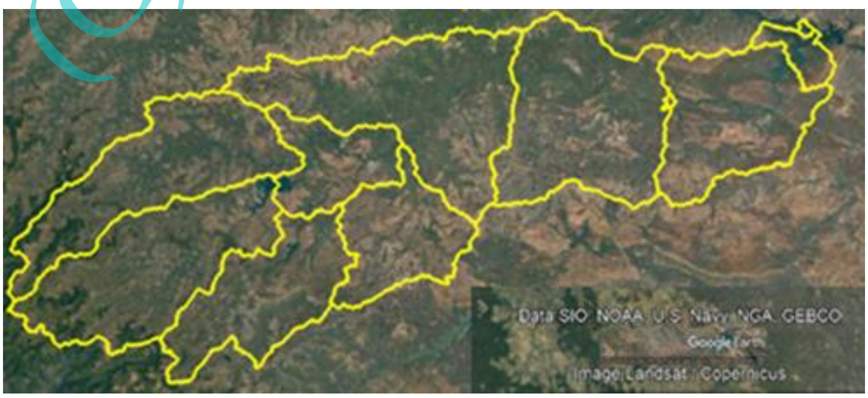


Figure 3.2: Ghataprabha catchment (Source: Google earth image)

Table 3.1 Ghataprabha catchment details covering various administrative boundaries

State	District	Taluk	Area sq.km
Karnataka	Bagalkot	Badami, Bagalkot Bilgi, Jamkhandi, Mudhol	7229.32
	Belagavi	Bailhongal, Belgaum Chikodi, Gokak, Hukeri, Khanapur, Ramdurg, Raybag Saundatti	
	Bijapur	Basavana Bagewadi	
Maharashtra	Kohlapur	Ajra, Chandgad, Gadhinglaj, Gargoti Kagal	1541.92
	Sindhudurg	Sawantawadi	

Topographically, Ghataprabha catchment is undulating with elevations ranging between 484 m to 1050 m. The Ghats show higher stream densities while the plains have sparse streams with interconnected lake systems enabling water storage, groundwater recharge, etc. Figure 3.3, Figure 3.4, and Figure 3.5depicts the topography, slope, and stream network of Ghataprabha catchment.

The major tributaries in this catchment are Hiranyakesi and Markandeya. Dams and reservoirs in this catchment are Hidkal reservoirs, Shirur dam, Rakashop dam, and Jangamhatti dam built on these tributaries which are mainly used for power and irrigation purposes. Some of the evergreen and deciduous species commonly found in the catchment towards western Ghats are the *Eugenia jambolana Lam*(Jambu), *Actinodaphne hookeri Meis* (Haggodimara), *Tectona grandis Linn* (Tega), *Grewia tilaefoliaVahl* (Tadasu) [46], etc.

The catchment receives an annual rainfall of 650 mm to 3000 mm across the catchment with 650 mm in plain lands against 3000 mm in Ghats [47] (Figure 3.6). Southwest monsoons between June to September contribute to 81.34% of rainfall, while the Northeast monsoons between October to December contribute to 18.65% of precipitation. The monthly temperature variations depict that it is as low as 15.34℃ (December) to as high as 34.65℃ (April) across the catchment (Figure 3.7)

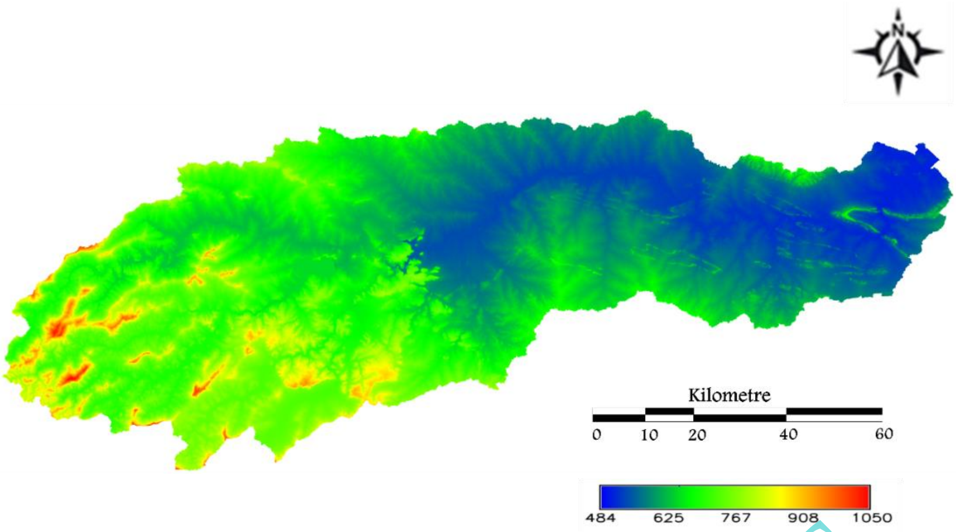


Figure 3.3: Elevation map

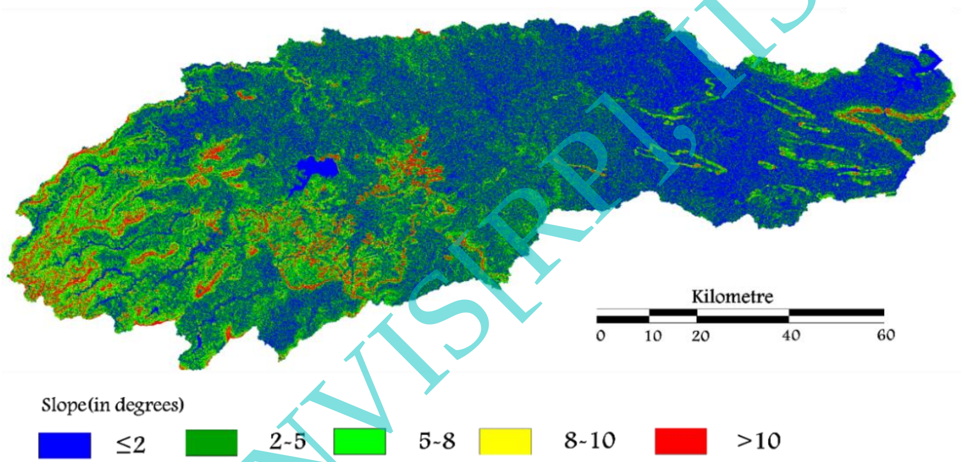


Figure 3.4: Slope map

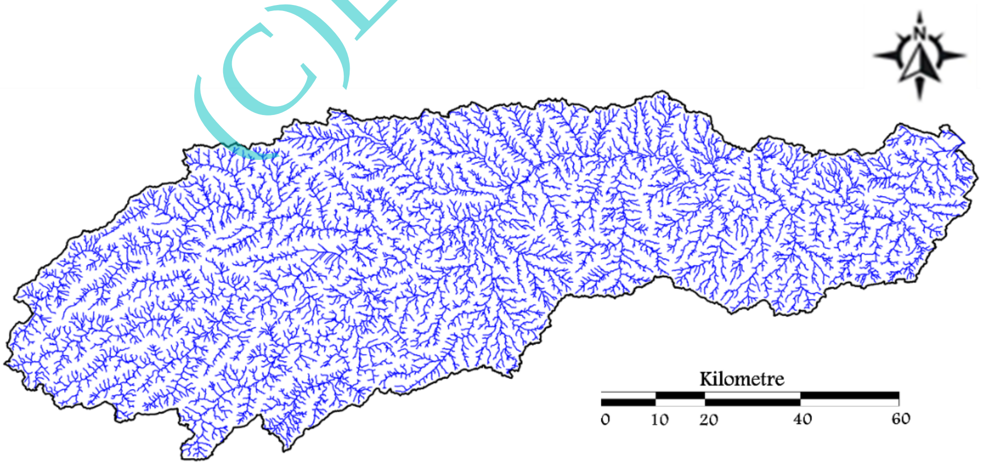


Figure 3.5: Stream network

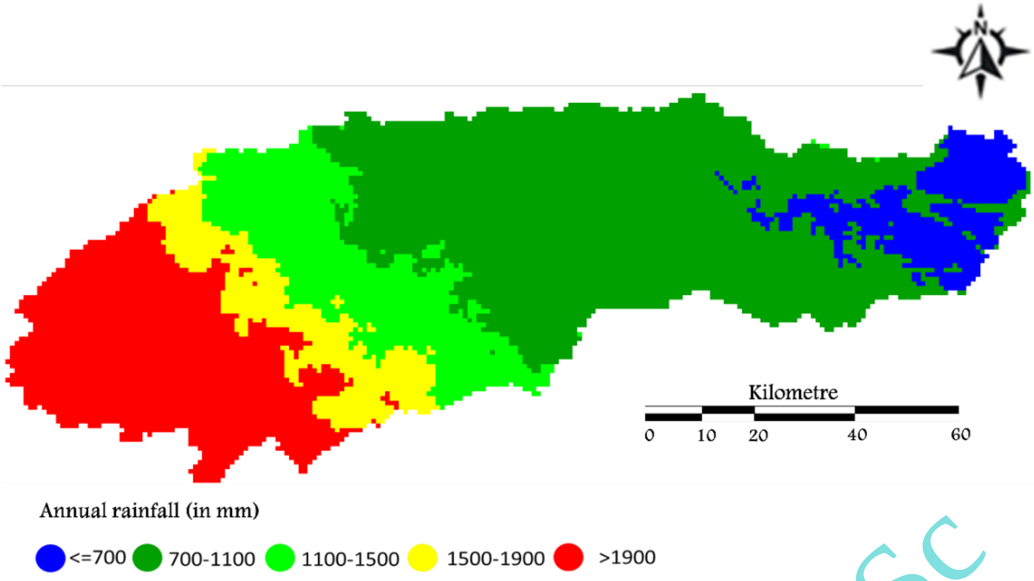


Figure 3.6: Annual rainfall (mm)

An outline of the geology of Ghataprabha basin reveals the well-marked geological groups such as pre-Cambrian, i.e., Archean's, Kaladgis. Followed with Deccan Traps, then the tertiary and quaternary like the laterites, alluvium, and soils (Figure 3.8)

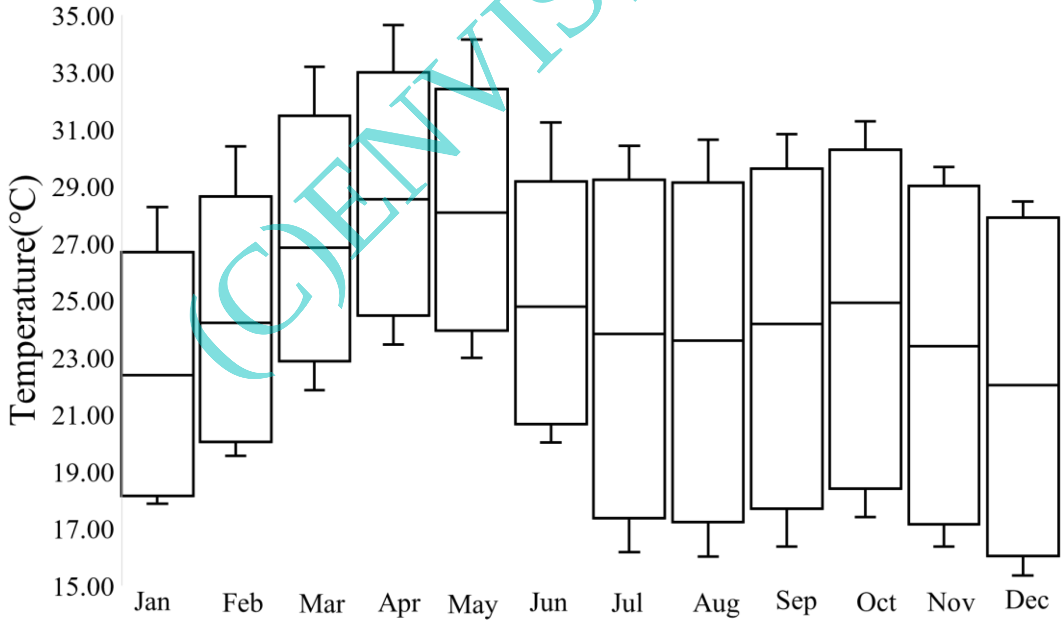


Figure 3.7: Monthly temperature variations

This consist of Gneiss, Granite, Quartzite, Schist, Laterite and Alluvium (Figure 3.9). Major soils in this region are the Laterite, Red, and Black Soils. Laterite soils are found in the hilly tracks of Western Ghats i.e., Kholapur and Sindhudurg districts of Maharashtra. These soils are found in regions with high rainfall with a great extent of phosphorus and potash. Mixed red and black soils are formed from the combination of Deccan traps and laterites. Black soils cover the majority of the catchment. They are called "regur". Deep black soils have a high clay content of about 40% to 60%, highly fertile, and excellent supporting material for the vegetation. On the other side, shallow black soils have low organic content with a low fertility rate. The crops usually grown are maize, groundnut, sunflower, chickpea, etc. Vegetables such as tomatoes, brinjal, potato, etc., are also commonly grown in this region. Cash crops such as cotton and sugarcane are highly supportive crops in this catchment.

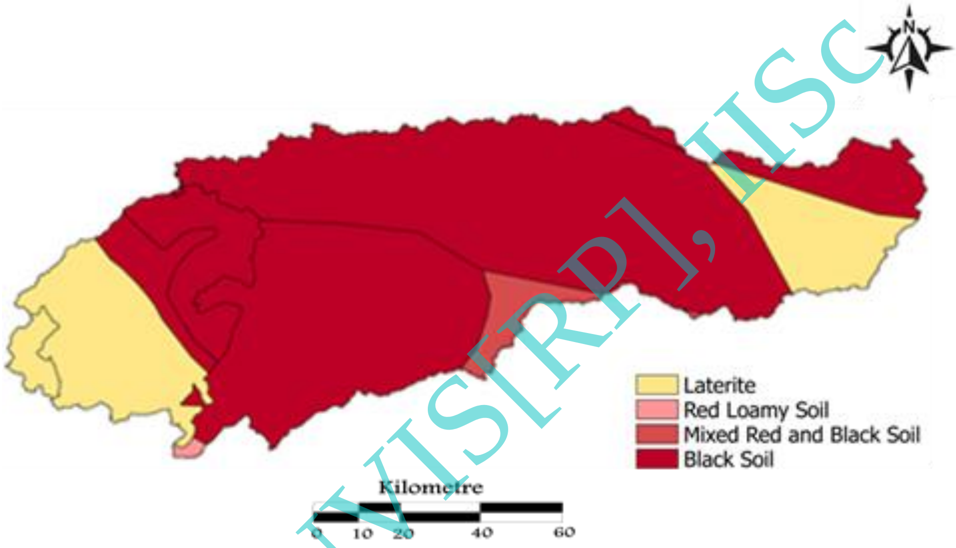


Figure 3.8:Soil map

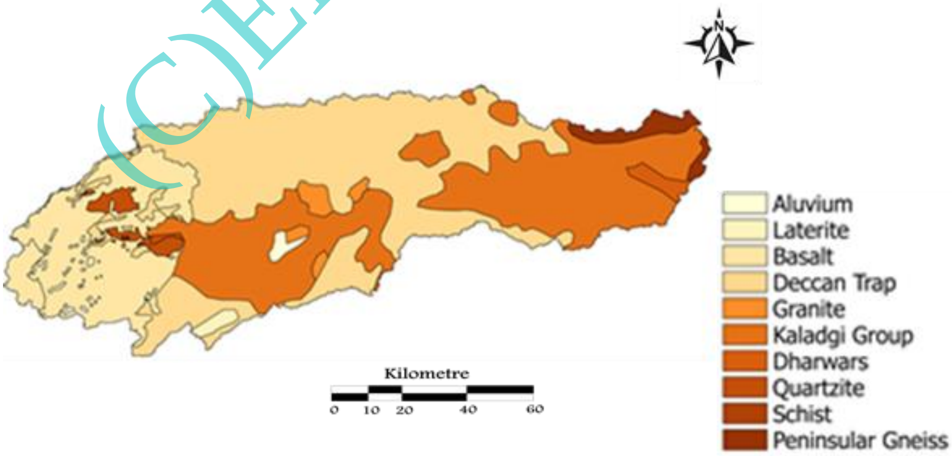


Figure 3.9: Lithology map

Decadal population[48] reveals that there is high dynamics in the Ghataprabha catchment (Figure 3.10). The total population of the Ghataprabha catchment was 2871043 (as per the 2001 census), which is increased to 3277255 in 2011 with a decadal increase of 14.14%. The sub-catchment (KSNU027) comprising of Belgaum taluk is with higher population densities in the region varying from 200 (persons per km^2) to 1000 (persons per km^2). Gokak region (KSNU031) of the catchment has higher population densities, with an increase from 296.25 (persons per km^2) in 1991 to 451.47 (persons per km^2) in 2019. The projected population densities reveal that every sub-basin is prone to have a higher density of more than 300 persons per km^2.

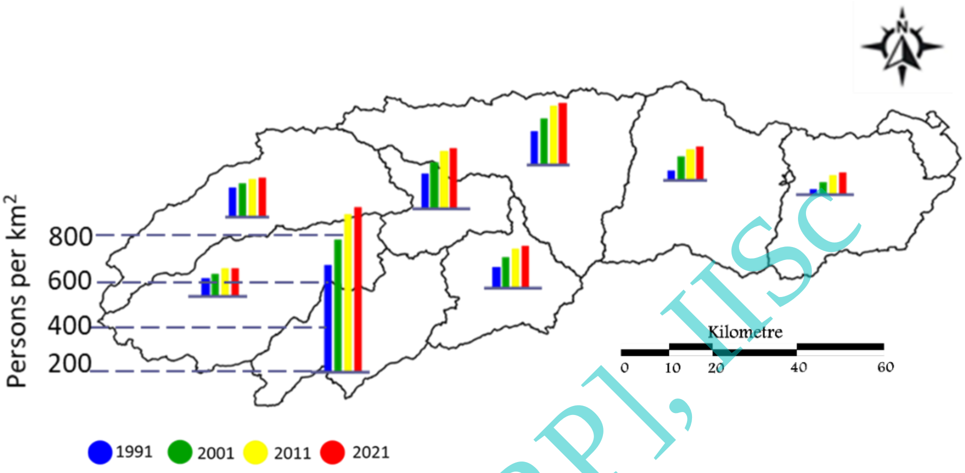


Figure 3.10: Population density

The diversity of species is spread across the Ghats section of the catchment, with protected areas of Bhimgad wildlife sanctuary about 131.67 km^2 and Ghataprabha bird sanctuary approximately 29.79 km^2. Commonly found birds are *Ploceus philippinus (*Baya weaver bird), *Bubulcus ibis (*Cattle Egret), *Phylacrocorox niger*, etc. Trees such as *Acacia Arabica (*Karijali), *Holoptelia integrifolia(*Tapsi) etc. are seen here.[46]

3.2 Malaprabha

Malaprabha river is a tributary of Krishna river which originates at Jamboti village, Khanapur taluk, in Belgaum district (Figure 3.11, Figure 3.12), Karnataka—originating from Sahyadri hills at an altitude of 792.4 m. Malaprabha flows for a distance of 306 km, towards the east, joining Krishna river at Kudalasangam. Extending between 14° 59' 11.83"N to 16° 13' 54.37"N Latitude and 74° 11' 37.86"E to 76° 16' 59.63"E Longitude. Malaprabha catchment covers an area of 12480.85 km^2, accounts for about 5 % of the Krishna basin. It spreads its extent across Karnataka, covering eight districts and 23 taluks, as described in Table 3.2.

Table 3.2

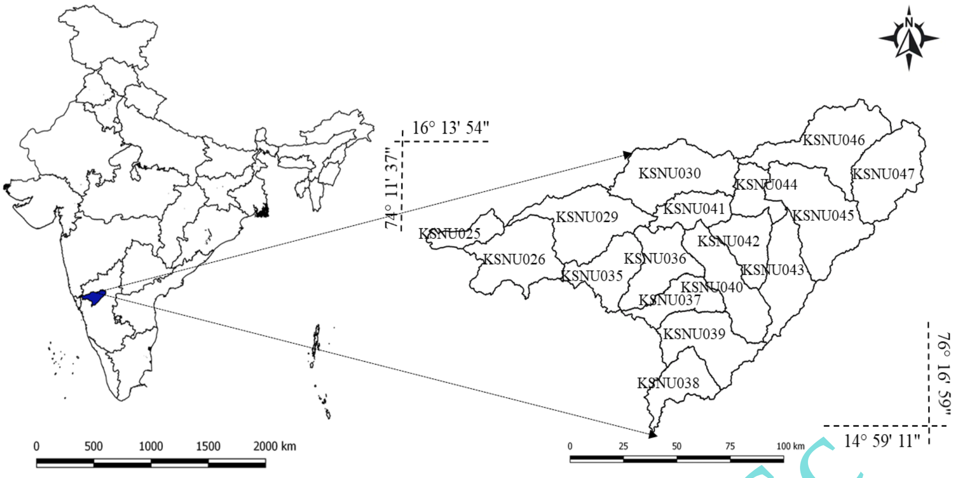


Figure 3.11: Malaprabha catchment, India

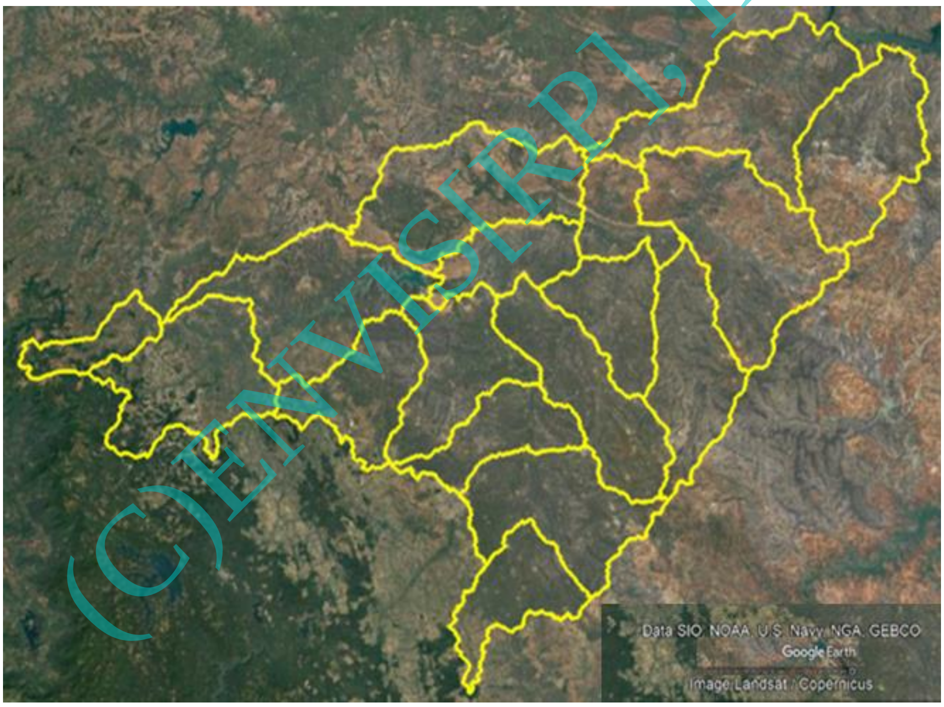


Figure 3.12: Malaprabha and its sub catchment
(Source: Google earth image)

Table 3.2:Malaprabha catchment details covering various administrative boundaries

State	District	Taluk
Karnataka	Bagalkot	Badami, Bagalkot, Hungund
	Belgaum	Bailhongal, Belgaum, Khanapur, Ramdurg, Saundatti
	Bijapur	Muddebihal
	Dharward	Dharward, Hubli, Kalaghatgi, Kundgol, Navalgund
	Gadag	Gadag, Nargund, Ron, Shirahatti
	Haveri	Shiggaon
	Koppal	Kushtagi, Yelbarga
	Raichur	Lingasugur

The entire basin experiences a semi-arid type of agro-climatic zone in hilly regions, northern dry and northern transition zone in Karnataka state. Topographically the terrain varies from 481 to 1036 m (Figure 3.13), highly undulating hilly regions compared to plain regions. Slope plays a vital role in the capability of land assessment and land irrigability. The majority of the catchment is with a gentle slope (Figure 3.14). The sub-catchments (KSNU025, KSNU026) experiences a steep slope of about 15% due to Ghats. The major tributaries are Bennihalla, Hirehalla, Tuparihalla, Alurhalla, Sasivehalla, Saraswathihalla, and others. Factors such as slope, geological features, topography play an important role in determining the stream network Figure 3.15. The dendritic pattern is seen in the central and eastern parts of the catchment, where more flat lands cover Badami, Bailhongal, etc. Parallel and sub-parallel drainage network is seen in undulating terrains of Khanapur and radial patterns in basaltic plateaus. Higher drainage density is seen at Ghats over plain lands. The catchment receives an annual rainfall of 650 mm to 3000 mm across the catchment with 650 mm in plain lands against 3000 mm in Ghats [47](Figure 3.16). Southwest monsoons between June to September contribute to 70.23% of rainfall, while the Northeast monsoons between October to December contribute to 29.77% of rainfall. The monthly temperature variations depict that it is as low as 15.38°C (December) to as high as 36.45°C (May) across the catchment Figure 3.17.

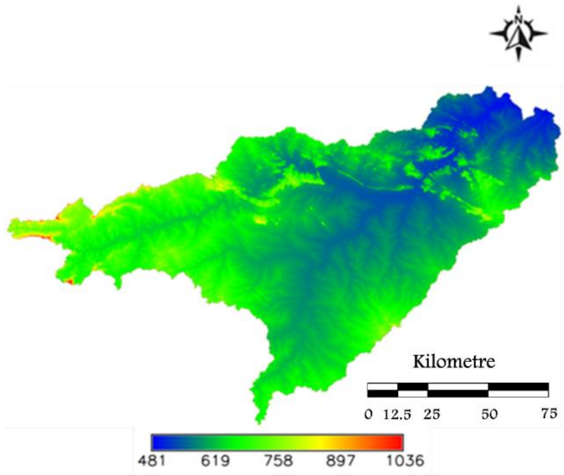


Figure 3.13: Elevation map

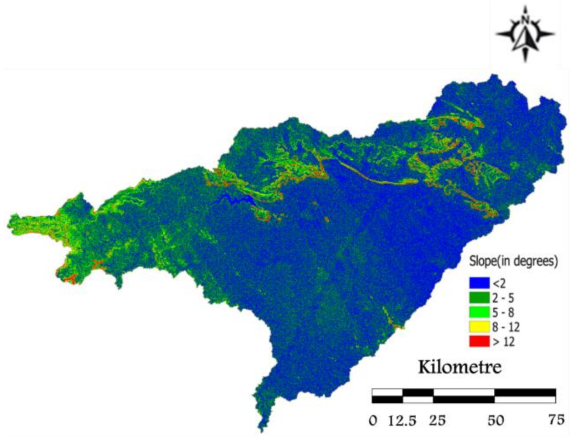


Figure 3.14: Slope map

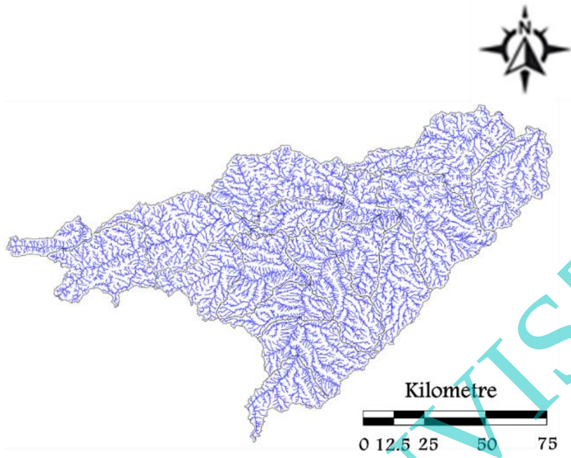


Figure 3.15: Stream network

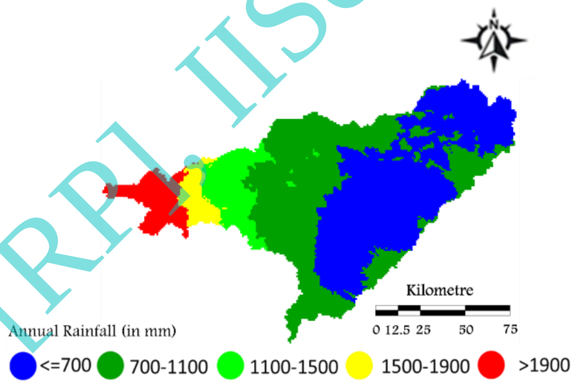


Figure 3.16: Annual rainfall

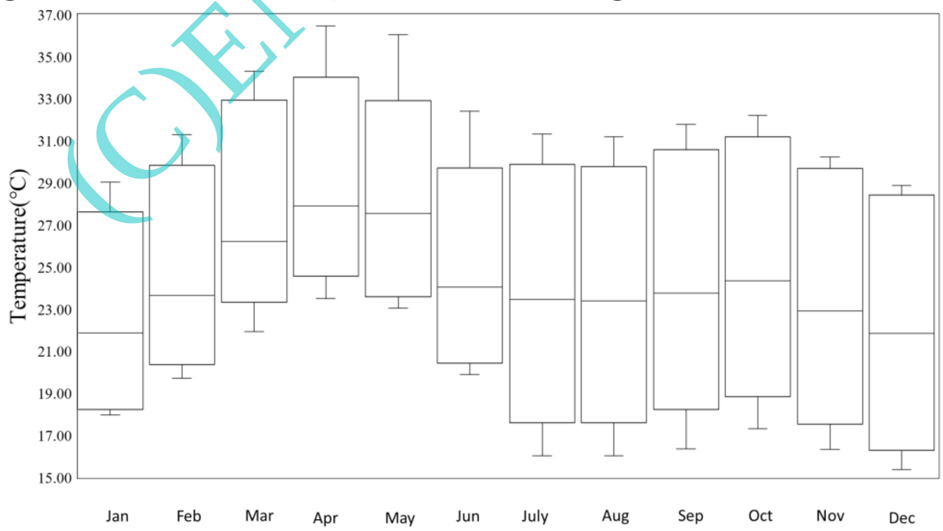


Figure 3.17: Monthly temperature variations

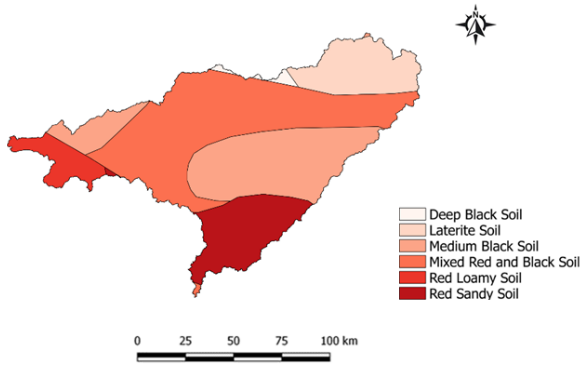


Figure 3.18: Soil map

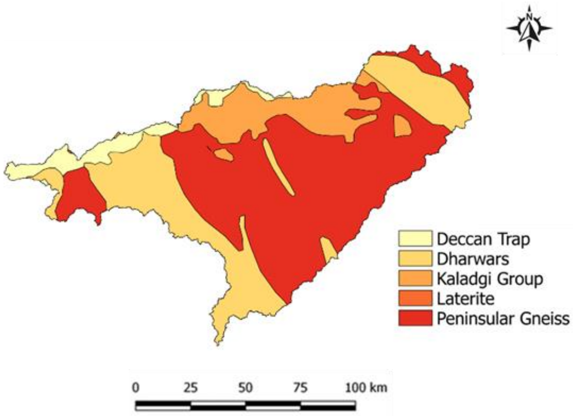


Figure 3.19: Lithology map

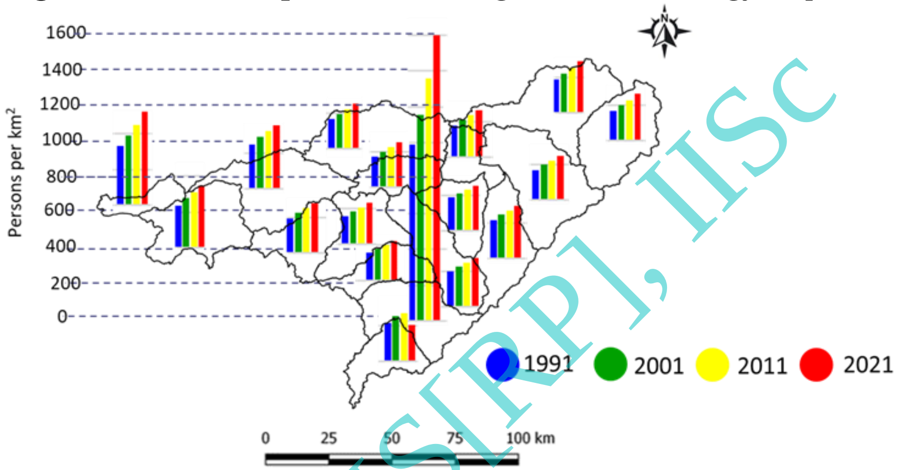


Figure 3.20: Population Density

Soil (Figure 3.18) constitutes the most critical resource for agriculture. The Malaprabha basin has varied soil resources from different parent materials such as granite, gneiss, deccan trap, schists, and limestone sedimentary formations (Figure 3.19). Soils [49] majorly present are the varieties of black soil varying from shallow, medium, and deep black soils (Figure 3.18). Red gravelly and non-gravelly clay soils and loamy soils are seen in this region. The principal crops are groundnut, jowar, maize, paddy, bajra, etc. Pulses such as soybean, green gram, horse gram are commonly sown in this region, and cash crops such as cotton, sugarcane, and tobacco are also grown in this region.

An undulating plain is seen in the eastern plateaus with hills of lithology dharwars and kaladgi series [50]. The fertile valleys of Malaprabha and the geomorphic features have significantly influenced agricultural activities. The total population of the Malaprabha catchment was 3588186 (as per 2001 census data), which is increased to 4056204 (in 2011) with 13.04% decadal growth. The sub-catchment (KSNU039) comprising of Hubli is with increasing population from 818999 (1991) to 1126290 (2011). The population densities from 1991 to the predicted densities in 2021 are shown in Figure 3.20, wherein the sub-catchment (KSNU039) has a higher population than other sub-catchments. The population density varies from 989.44 to 1601.52 persons per km^2. Due to rapid urbanization the densities show high dynamics.

3.3 Mahadayi (Mandovi)

Mahadayi is an interstate river that originates at Jamboti village, Khanpur taluk, in Belgaum district, which flows down the entire width and breadth of Goa joining at Arabian Sea (Figure 3.21, Figure 3.22). Originating in the Western Ghats, Mahadayi flows for a distance of 87 km, towards the west. Mahadayi spreads over an area of 2007.13 km^2 and extends between 15°14’12” N to 15°41’59” N Latitude and 73°45’25” E to 74°26’37” E Longitude. The catchment spreads across three states, namely Karnataka, Goa, and Maharashtra. This river is the lifeline for Goa, as most of the watershed falls in Goa; at the same time, it serves the purpose of agriculture and horticulture activities followed by human needs. The catchment extends across Coastal plains, the Midland region, and the Western Ghats. The river is known as Mahadayi in Karnataka and as Mandovi in Goa. The main tributaries of this river are Kotrachi nadi, Surla nadi, Ragada nadi. It is divided into five watersheds: Mhadei, Khandepar, Valvanti, Mapusa, Sinquerim, and the lower Mandovi watershed. Spreads across five districts and nine taluks as described in Table 3.3.

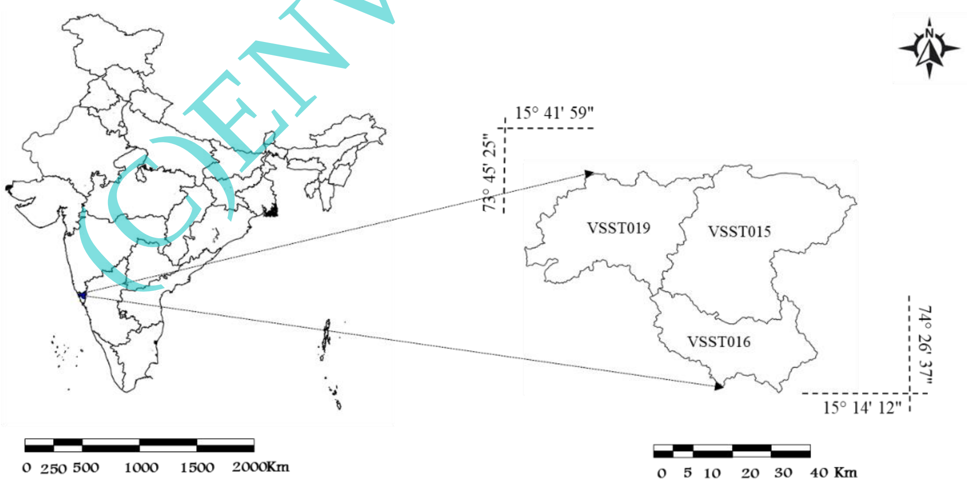


Figure 3.21: Mahadayi/Mandovi catchment

Figure 3.22: Mahadayi/Mandovi (Source Google earth image)

Table 3.3: Mahadayi catchment details covering various administrative boundaries

State	District	Taluk	Area sq.km
Karnataka	Belgaum	Khanapur	391.4
	Uttar Kannada	Joida	
Goa	North Goa	Bicholim, Bardez, Sattari Tiswadi, Ponda	1545.5
	South Goa	Sanguem	
Maharashtra	Sindhudurg	Sawantawadi	70.25

Topographically (Figure 3.23), the Mahadayi catchment is undulating terrain between 0 m and 1024 m. Doodhsagar falls, Vajra poha falls etc., are found in this catchment due to high variations in the slopes. Braganja Ghats have higher slopes. The Ghats show higher stream densities while the plains have sparse streams with interconnected lake systems enabling water storage, ground water recharge, etc. Figure 3.23, Figure 3.24, and Figure 3.25 depict the topography, slope, and stream network of the Mahadayi river.

The catchment receives an annual rainfall Figure 3.26) of about 3200mm across the catchment. Southwest monsoons between June and September contribute to 90.15% of rainfall, while the Northeast monsoons between October and December contribute to 9.85% of rainfall [47]. The monthly temperature (Figure 3.27) varies between 17.84℃ (December) and 32.51℃ (May) across the catchment. Geologically, rock types consist of Gneiss, Granite, Schist, Laterite, etc. (Figure 3.28) [50]. Iron, bauxite, limestone, quartz, etc., are the commonly found ores in this catchment. Major soils[49] are Rhodustalfs, Chromusterts, Palehumults [51], etc. The major crops in this region are paddy, sugarcane, banana, areca nut, coconut, cashew nut, mango, etc.

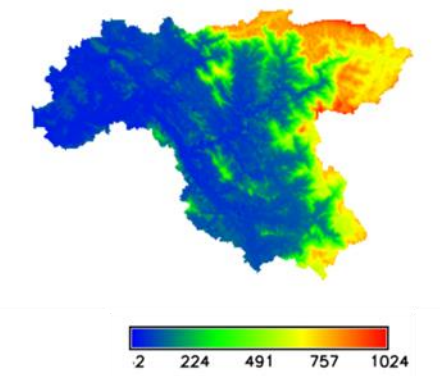


Figure 3.23: Elevation map

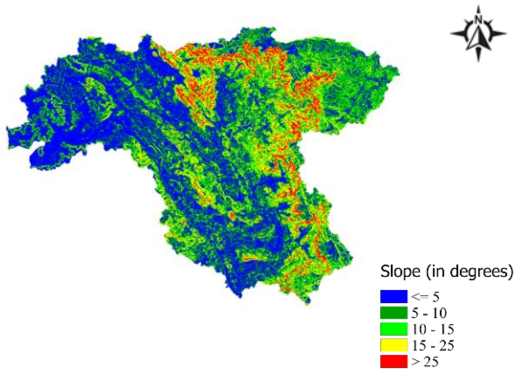


Figure 3.24: Slope map

Figure 3.25: Stream network

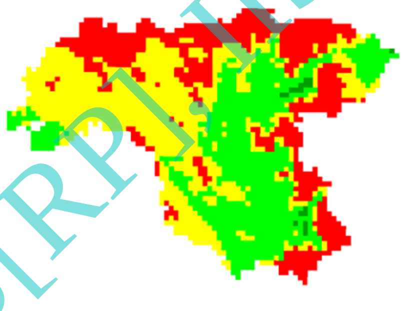
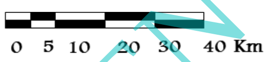
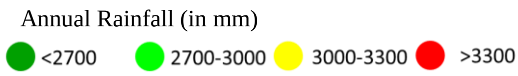


Figure 3.26: Annual rainfall





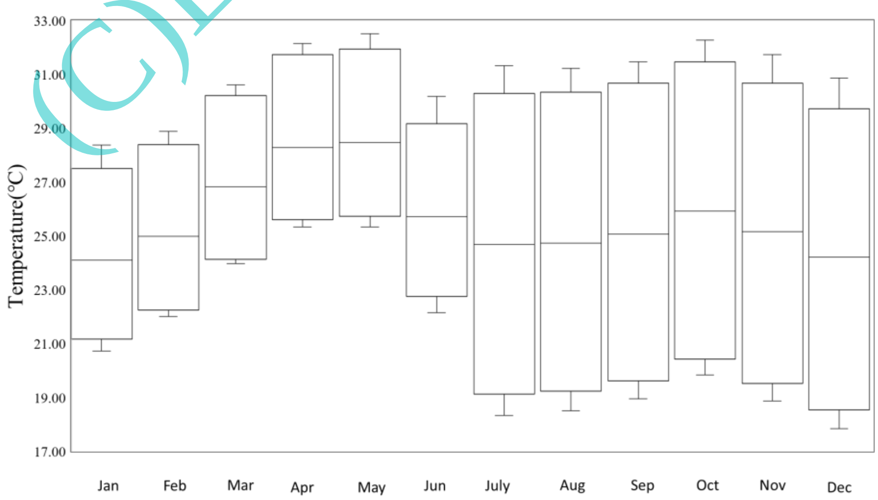
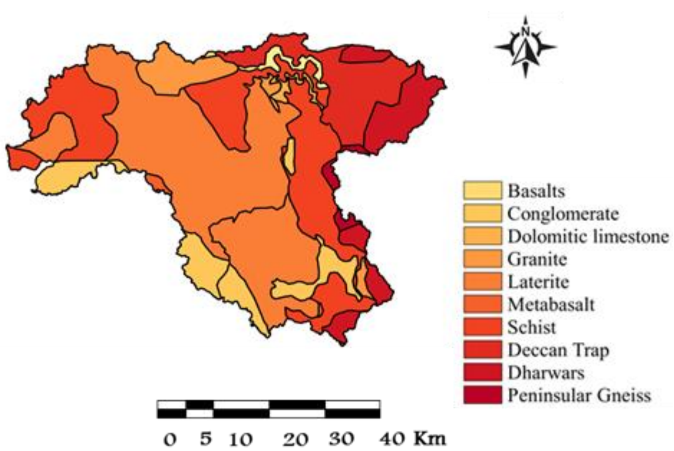


Figure 3.27: Monthly temperature variations



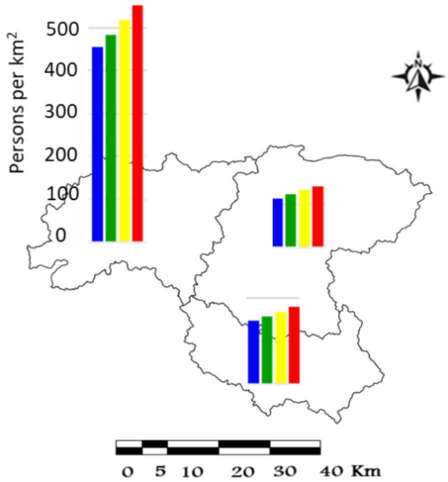


Figure 3.28: Lithology map Figure 3.29: Population density

Population dynamics (Figure 3.29) - Total population in the Mahadayi catchment as per 2001 census data was 503532, which was increased to 539285 in 2011 with a decadal [48] growth rate of 7.1%. The sub-basin (VSS019), comprising the North Goa district, has turned densely populated over time from 1991 to 2011. Major communities in this catchment are Kumri Marati, Goudas, Konkanis, Havyaka Brahmin, Christians, etc.

High diversity of flora and fauna is present in this catchment. Forest types such as evergreen, semi-evergreen, moist deciduous, scrubs and thorns, etc., are spread with a wide variety of species such as *Acacia sp.*, *Careya arborea*, *Ficus religiosa*, *Mallotus philippensis*, *Syzygium sp*, etc. [51]. Mammals such as black panthers, leopard, lion tailed macaque etc. are commonly seen in this region. Vipers, rat snake, russel vipers, monitor lizards, etc. are also seen in this region.

Chapter 4 : Materials and methods

4.1 Delineation of catchment

Catchment boundaries are delineated based on the catchment properties, such as considering the ridge and valleys, stream network, contours, etc. Initially, the study area's topographic maps (Figure 4.1) were downloaded from the Survey of India (http://surveyofindia.gov.in). The topographic sheets were georeferenced, and the catchment delineation was carried out based on the catchment properties. The digitization of drains and streams was carried out to see the accuracy of the data, compared with CGWB (Figure 4.2 & Figure 4.3) (Central Ground Water Body) boundaries.

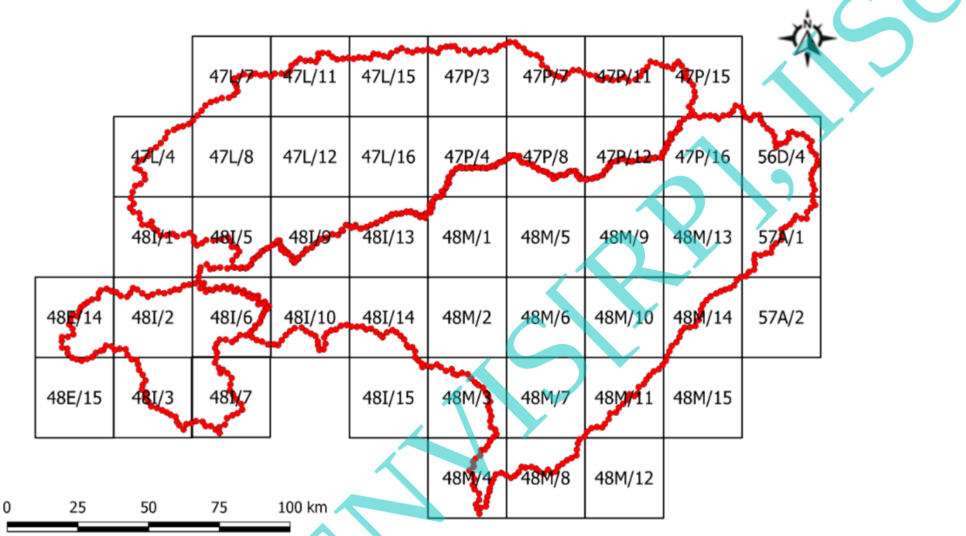


Figure 4.1: The Survey of India topographic map no's

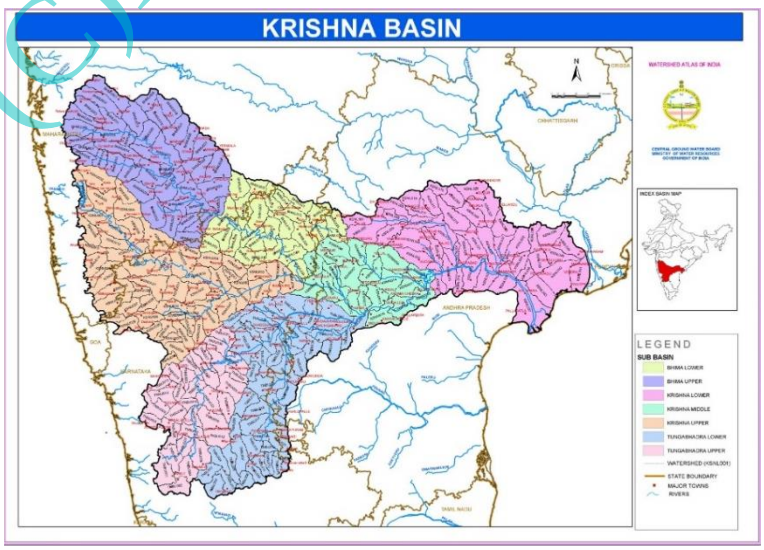


Figure 4.2: Krishna basin

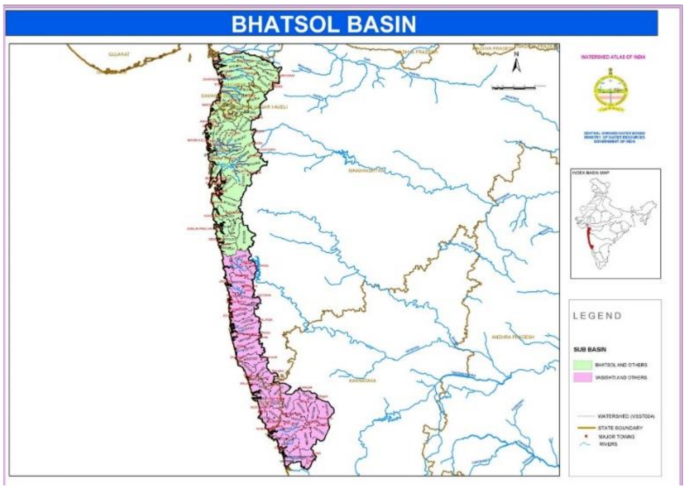


Figure 4.3: Bhatsol basin

The catchment boundaries for the study area of Ghataprabha, Malaprabha, and Mahadayi were delineated using the hydrological modeling tool (SWAT), as explained below. Catchment delineation using SWAT (Soil Water Assessment Tool)

The process was carried out in QSWAT 1.7 version using QGIS 2.6 Version (32 bit) as follows:

i. **Data acquisition**: SRTM (Shuttle Radar Topography Mission), DEM (Digital elevation model) was downloaded from USGS Earth explorer [52] (Figure 4.4). The resolution of the data is 30 m, with each pixel representing the elevation of the area above the mean sea level (MSL). The SRTM data downloaded is merged (Figure 4.5) and cropped for the area of interest (AOI) with a buffer of 5 km. The high-resolution data was used for the extraction of boundaries.

ii. **Data preprocessing and processing**: The clipped AOI for the regions of Ghataprabha, Malaprabha, Mandovi river basins are projected to WGS84 UTM 43N. The geo-referenced topographic sheets are overlaid to determine the flow direction and to identify the catchment drains of the study region. The outlets are determined. The overall process of SWAT is explained as below in the flowchart.

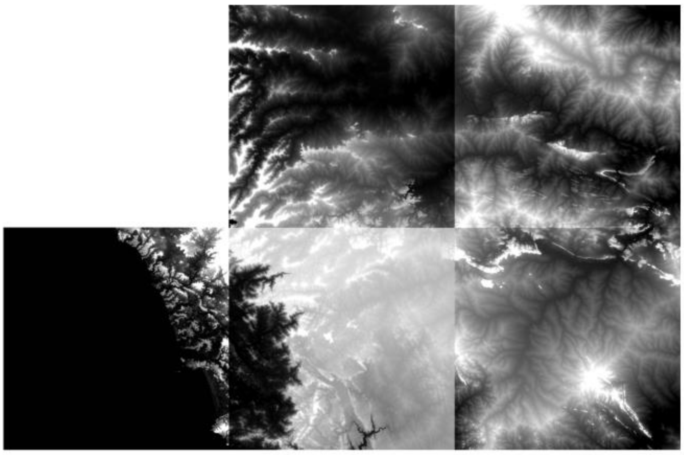


Figure 4.4: SRTM Data from USGS Earth explorer

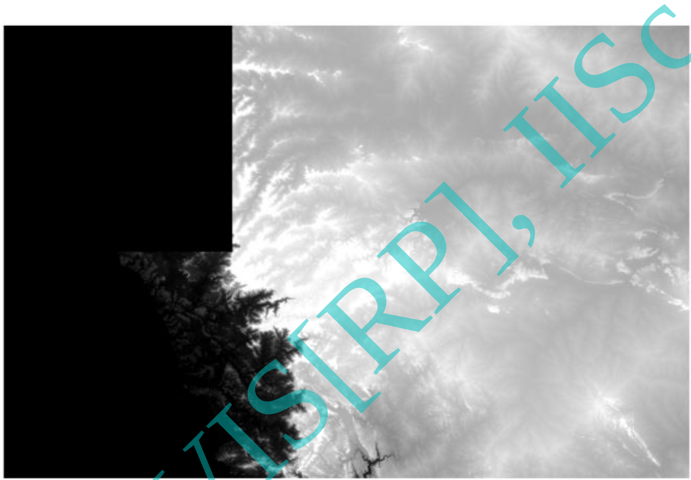


Figure 4.5: SRTM Merged data

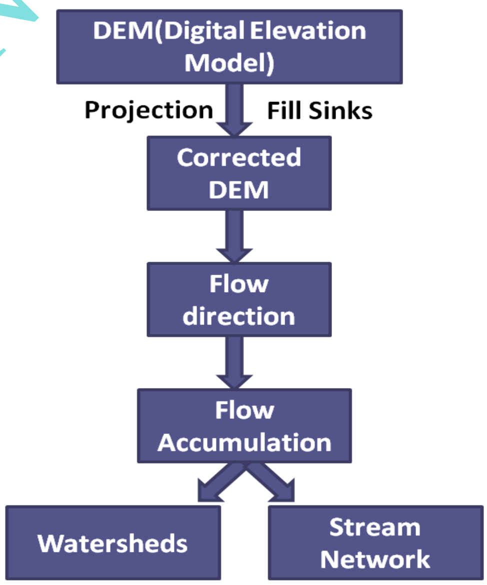


Figure 4.6: Flow chart of SWAT model

The extracted boundaries were overlaid on Survey of India topographic sheets to check the correction and variations. One typical example for sub-catchment KSNU043 is given in Table 4.1.

Table 4.1: Comparison of digitized area with the reference data

KSNU043 maps	Area (km^2)
Topographic sheets	756.63
SWAT(Soil water assessment model)	752.84
CGWB	756

The results revealed that the boundaries delineated using topographic sheets were in good relation with extracted boundaries from SWAT varying up to 0.5 %. In contrast, the topographic with CGWB boundaries varied up to 4%. SWAT studies for the extraction of boundaries proved beneficial over other data because of its explicit usage of high-resolution data in the generation of boundaries.

The overall method could be analyzed as shown in figure 4.7 below:

1. Land use analysis
2. Hydrological balance
3. Evaluating the hydrological status

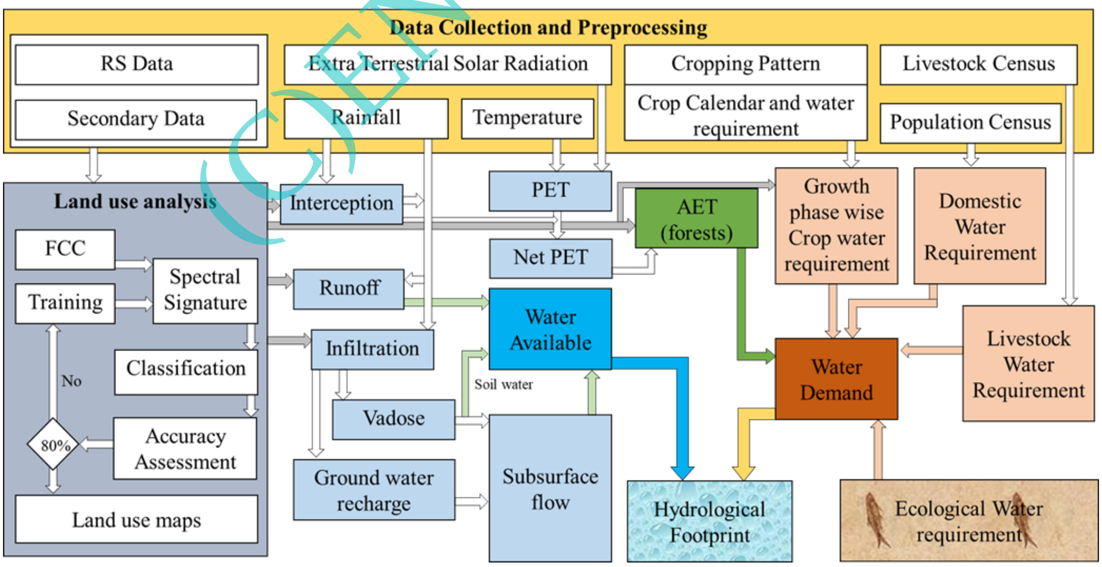


Figure 4.7: Method of land use dynamics and ecohydrological footprint

4.2 Land use assessment

Land use analysis involves:

i. **Remote sensing satellite data acquisition**: Satellite launched by the joint mission of NASA and USGS, created a revolution in the field of remote sciences since 23rd July 1972. With seven successful missions over more than 40 years, Landsat has documented and continues to document improvements made in spectral, spatial, radiometric, and geometric performance. The products used for the current study are the Landsat-1 and Landsat-8 to determine the long-term temporal change for the study area catchments. Landsat 1 had MSS (Multi-Spectral Scanner), which consisted of 4 bands as described below (Table 4.2). The scene size was approximately 170 km (NS) by 185 km(EW) with the original pixel size was about 69m by 57m which was resampled to 60* m.

Table 4.2: Landsat 1 bands

Landsat-1 (Multi-Spectral Scanner)		
Landsat bands	Wavelength(micrometres)	Resolution
Band-4(Green)	0.5-0.6	60*
Band-5(Red)	0.6-0.7	60*
Band-6(Near Infrared-NIR)	0.7-0.8	60*
Band-7(Near Infrared-NIR)	0.8-1.1	60*

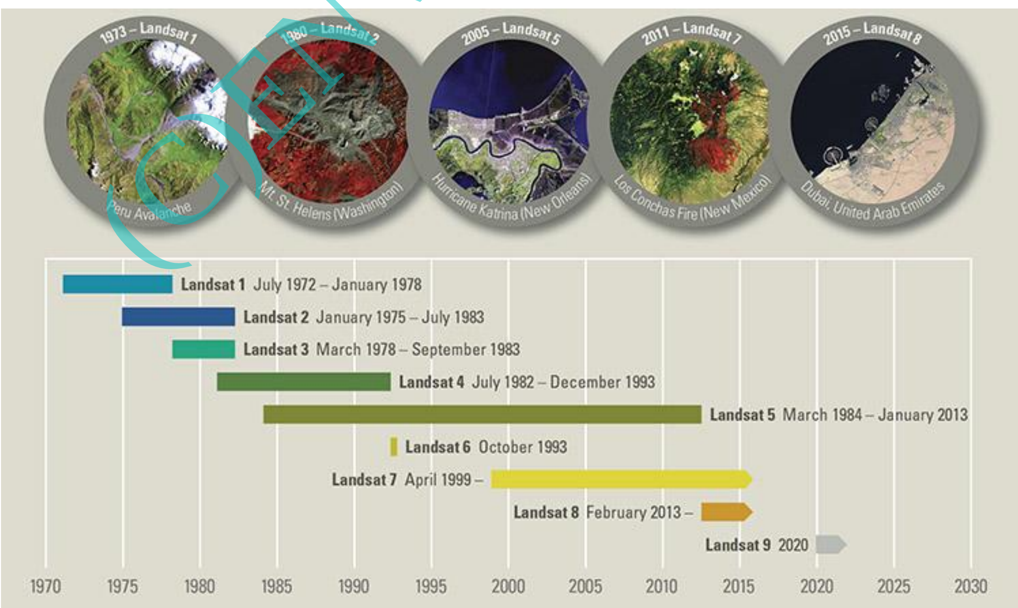


Figure 4.8: Landsat missions

Landsat-8 satellite data was used for the assessment of the recent land-use trends. It has Operational Land Imager and Thermal Infrared Sensors i.e., OLI and TIRS consisting of 11 bands (Table 4.3) based on a push broom mechanism. The approximate scene size is 170 km (NS) by 183 km (EW). Band 1 is useful for coastal studies and aerosol studies and Band 9 for cirrus cloud detection. Thermal bands are useful in determining the land surface temperatures which are collected at 100 meters.

Table 4.3: Landsat 8 bands

Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensors (TIRS)		
Landsat bands	Wavelength(micrometres)	Resolution
Band-1(Ultra blue –coastal/aerosol)	0.435-0.451	30
Band-2(Blue)	0.452-0.512	30
Band-3(Green)	0.533-0.590	30
Band-4(Red)	0.636-0.673	30
Band-5(Near Infrared-NIR)	0.851-0.879	30
Band-6(Shortwave Infrared-SWIR 1)	1.566-1.651	30
Band-7(Shortwave Infrared-SWIR 2)	2.107-2.294	30
Band-8(Panchromatic)	0.503-0.676	15
Band-9(Cirrus)	1.363-1.384	30
Band-10(Thermal Infrared-TIRS1)	10.60-11.19	100*(30)
Band-11(Thermal Infrared-TIRS2)	11.50-12.51	100*(30)

Source: USGS https://landsat.usgs.gov/what-are-band-designations-landsat-satellites

Land uses in the catchments of Ghataprabha, Malaprabha (i.e., Upper Krishna basin), Mandovi have been determined using Landsat satellite data for the temporal analysis. Survey of India toposheets were used for generating the base layers of the catchment, stream networks, etc.

ii. **Pre-processing**: Remote sensing data obtained from USGS earth explorer were initially georeferenced and rectified and cropped for the area of interest for the study catchments. Geo-referencing of remote sensing data was considered based on the prominent points such as road intersections, buildings, etc., from Google earth pro (http://www.google.com), and from the Survey of India topographic maps.

iii. **Generation of False Color Composite**: False color composite represents the data in false colors, which aids to differentiate heterogenous features in landscapes. This false color composite is generated from the combination of green, red, and near-infrared spectral bands.

iv. **Training sets**: Signatures or the training polygons are considered for the classification of the satellite data into various land use categories based on spectral reflectance characteristics (Figure 4.9). Based on the site knowledge, topographic maps from

Survey of India, Virtual Globe datasets, namely Google earth, Bhuvan (http://bhuvan.nrsc.gov.in), etc., were considered for the creation of training sites and signatures. Based on the unique properties of spectral reflectance of various landscape elements, which helps in determining the training sets. These data sets were spread across the study area covering at least 15% of the total area.

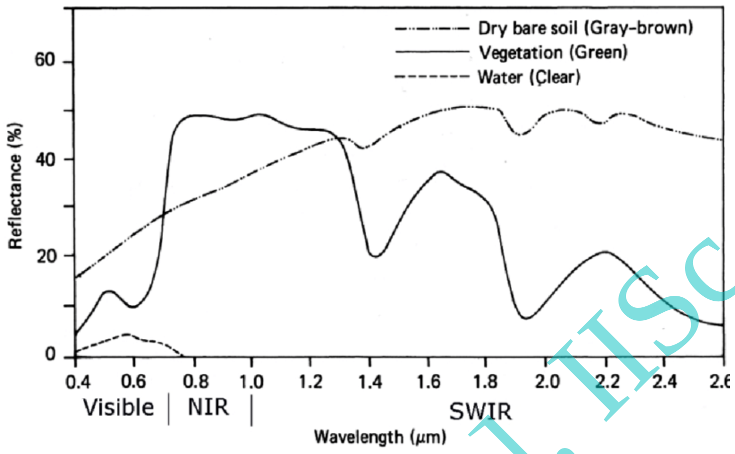


Figure 4.9: Spectral reflectance curve

v. **Classification**: Land use analysis was carried out using supervised classification. Gaussian maximum likelihood algorithm was used for the classification of the dataset. Based on the mean and variance of digital numbers under each training dataset, the unknown pixels are classified. Statistical assessment based on spectral classification and computation of kappa statistics and overall accuracies were established. Of the overall signatures, 65% of the datasets were used for the classification, while the 35% of the pure signatures were used for assessing the classification accuracy. This analysis was computed using an open-source software GRASS –Geographic Resource Analysis Support System (Figure 4.10).

Figure 4.10: GRASS

Land use categories considered in this study are as follows: (i) waterbodies, (ii) built up, (iii) evergreen forests, (iv) deciduous forests, (v) scrublands and grasslands, (vi) agricultural lands, (vii) horticulture, (viii) open spaces and (ix) plantations

vi. **Accuracy assessment**: To assess the correctness of the remotely classified data, the reference data such as google earth, Survey of India toposheets, Bhuvan NRSC etc were considered. Kappa as a measure of agreement was determined between the reference and the classified map.

4.3 Hydro-meteorological assessment:

This involved assessing long-term rainfall data to determine the rainfall trend and number of rainy days over decades. Parameters such as rainfall, temperature(minimum, maximum, and average), extra terrestrial solar radiation, etc., across the catchments were analyzed to understand the hydrological status.

4.3.1 Rainfall

The gridded dataset of the study area for the period between 1901-2018 was considered for the analysis of rainfall. The rainfall datasets were obtained from

i. Terrestrial Hydrology Research Group, Princeton University (Resolution: 0.5 degree gridded dataset).
ii. Worldclim Version 2 from the US government. (Resolution: 1 km^2)

Missing and erroneous rainfall data were computed based on the neighboring datasets through linear regression (Arithmetic average method). Long-term daily rainfall data, which is used to compute the monthly and annual rainfall, were used to derive the rainfall maps throughout the catchment by the process of interpolation to determine the isohyets. This data was used for the determination of gross rainfall volume (in the basin) as per equation 4.1. Net rainfall volume was quantified as the gross rainfall volume subtracted from the interception losses (equation 4.2).

$$RG = A * P \qquad \textbf{(4.1)}$$

Where RG: Gross rainfall (volume in m^3)
A: Catchment area (ha)
P: Precipitation (mm)

$$RN = RG - In \qquad \textbf{(4.2)}$$

Where RN: Net rainfall (Volume in m^3),
In: Interception volume (m^3)

4.3.2 Interception

During rainy days, a portion of precipitation is intercepted before it reaches the ground by leaves, branches, etc., which is determined as interception losses. Drip off from the leaves, plants, trees, etc., join the ground surface as overland flows termed as through fall. If water flows through the stem to reach the ground surface, it is termed stem flow, a subset of interception flow. These interception losses usually account for about 15-30% based on literature studies([10], [41], [44]). Leaf area index is the essential factor that influences the interception rates to a greater extent, as shown in the table below, which varies monthly based on the land use type. The canopy interception in a catchment is mainly dependant on the size and the spread of vegetation within a catchment.

Table 4.4:Interception loss[44]

Vegetation types	Period	Interception
Evergreen/semi evergreen forests	June-October	I=5.5+0.30 (P)
Moist deciduous forests	June-October	I=5.0+0.30 (P)
Plantations	June-October	I=5.0+0.20 (P)
Agricultural crops (paddy)	July-August September	I=1.8+0.10 (P) I=2.0+0.18 (P)
Grasslands and scrubs	June-September October	I=3.5+0.18 (P) I=2.5+0.10 (P)

4.3.3 Runoff

Precipitation or the net rainfall would contribute to either runoff or infiltration. Runoff could be either surface runoff or sub-surface runoff, depending on the topological factors of the watershed. Surface or overland flow was estimated based on the rational formula as,

$$Q = \sum (Ci \times PR \times Ai)/1000 \qquad \textbf{(4.3)}$$

Where, Q: Runoff in cubic meters per month;

C: catchment/ Runoff coefficient depends on land uses;

PR: Net rainfall in mm; i: Land use type;

Ai= Area of Landscape i, as square meters.

Figure 4.11 illustrates that the runoff coefficient varies depending on land uses, with a higher catchment coefficient for urbanized regions over watersheds with vegetation cover. Urbanized areas are paved surfaces that allow only a fraction of water to infiltrate with a major contribution to runoff.

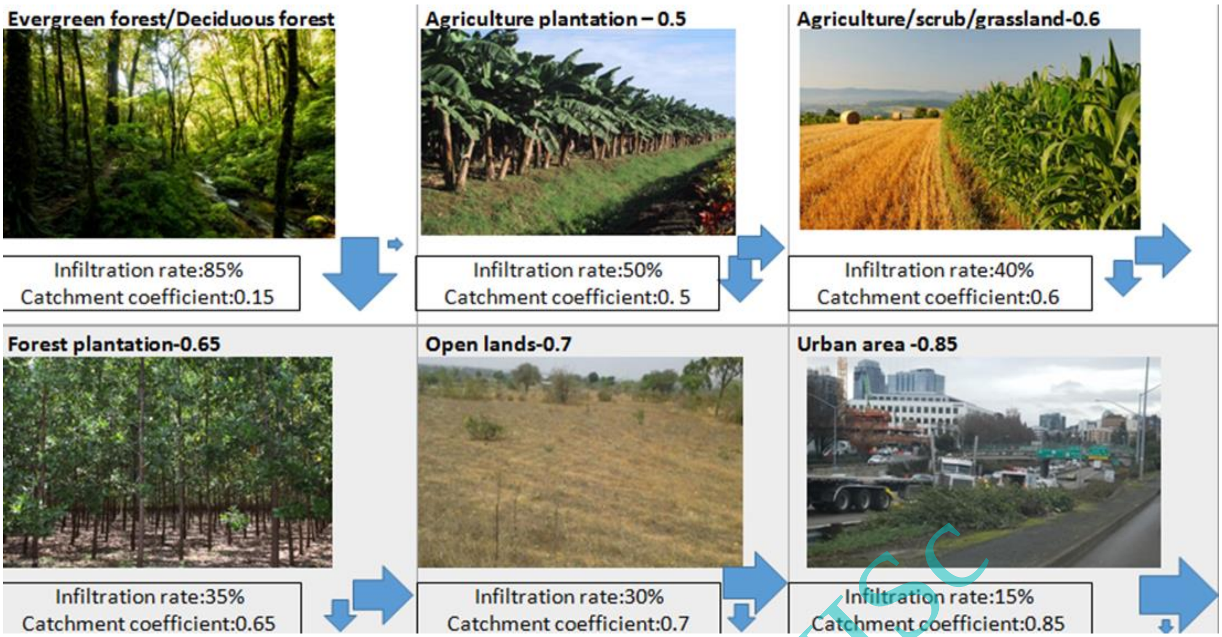


Figure 4.11: Catchment coefficients with infiltration rates

4.3.4 Infiltration

Infiltration is the process of flow of water into the ground, which mainly depends on the soil characteristics depending on the texture, porosity, hydraulic conductivity, etc. The water percolated reaches the root zone or the vadose zone and retains water to its field capacity depending on the soil parameters in the watershed area and further recharges the ground water aquifers and the rest flows as laterally as stream flow. Equation 4.4 determines infiltration,

$$\text{Inf} = \text{RN} - \text{Q} \qquad \textbf{(4.4)}$$

Where, RN: Net rainfall yield volume (cubic meters); Q: Runoff in cubic meters per month.

4.3.5 Ground water recharge

The water percolated below the soil stratum after it gets saturated helps in recharging the aquifers after satisfying the water available capacity and pipe flow. Determination of ground water recharge is carried out by Krishna Rao equation (**Error! Reference source not found.**) b ased on soil parameters, lithology, etc., to estimate the ground water recharge .

$$\text{GWR} = \text{RC} \times (\text{PR} - \text{C}) \times \text{A} \qquad \textbf{(4.5)}$$

Where GWR: Ground water recharge; R_C: Ground water recharge coefficient; C: Rainfall coefficient; A: Area of the catchment.

The recharge coefficient (Table 4.5) and the constant vary depending on land use with the annual rainfall.

Table 4.5: Ground water recharge coefficients

Annual rainfall	Rc	C
400 to 600 mm	0.2	400
600 to 1000 mm	0.25	400
>2000 mm	0.35	600

4.3.6 Sub Surface Flow

The component of infiltered water after saturating the aquifer flows laterally contributing to pipe flows and base flows. These flows have drainage capacities slower than superficial flows.

i. **Pipe flow**: Once the soil gets saturated in the vadose zone during monsoons, in the post monsoons, these waters flow as pipe flow based on the characteristics of soil and the corresponding pipe flow coefficient, given by equation as follows

$$PF = (Inf - GWR) \times KP \qquad \textbf{(4.6)}$$

Where, PF: Pipe flow; Inf: Infiltration volume; K_P: Pipe flow coefficient (Table 2.2)

ii. **Ground water discharge** (base flows) is determined based on the properties of aquifers under each land use. This is estimated by multiplying the specific yield with the recharged water. Specific yield is the amount of water yielded from the water-bearing material once it gets saturated. These flows appear post-monsoon after the pipe flow recedes. This generally contributes to the rivers in the dry season. The ground water discharge is estimated as follows

$$GWD = GWR \times YS \qquad \textbf{(4.7)}$$

Where GWD: Ground water discharge; GWR: Ground water recharge;

YS: Specific yield

4.4 Green water and blue water demands

4.4.1 Green water requirement: Green water needs comprises of evapotranspiration requirements of forests. Evaporation is a hydrological cycle process, where the liquid water transforms into a gaseous state and diffuses into the atmosphere from the available energy from the sun or atmosphere. During monsoons, evaporation may be a minor component as there is little available energy to drive this process and vice versa. In non-monsoons, though the available energy is plenty, the availability of water is less. The evaporation occurs as actual evaporation from the soil matrix or through the stomata of the leaves as transpiration. The combination of these two is often referred to as evapotranspiration. Some of the essential factors that affect evapotranspiration are as follows, described in Figure 4.12.

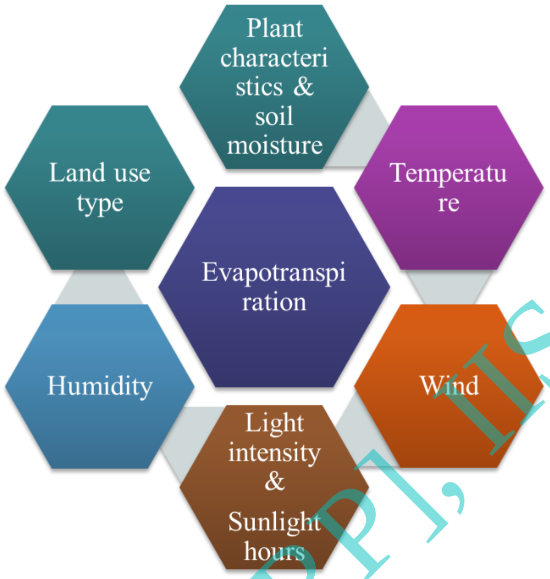


Figure 4.12: Factors affecting evapotranspiration

Potential evapotranspiration (PET) is defined as the sufficient quantity of available moisture to meet vegetation requirements completely. It no longer critically depends on soil and plant factors but essentially depends on the climatic factors. PET is determined using Hargreaves method, an empirical-based radiation equation, which performs well at humid climates, given by the equation 4.8:

$$\mathbf{PET} = \mathbf{0.0023} \times \left(\frac{\mathbf{RA}}{\boldsymbol{\lambda}}\right) \times \sqrt{\mathbf{Tmax} - \mathbf{Tmin}} \times \left(\frac{\mathbf{Tmax+Tmin}}{\mathbf{2}} + \mathbf{17.8}\right) \quad (4.8)$$

$$\mathbf{AET} = \mathbf{PET} \times \mathbf{KC} \quad (4.9)$$

Where, R_A: Extra-terrestrial radiation (MJ/m^2 /day); Tmax: Maximum temperature; Tmin: Minimum temperature; λ: latent heat of vaporization of water (2.501 MJ/kg), KC: Evapotranspiration coefficient

Actual evapotranspiration (AET) is the actual evaporation occurring in a specific situation, depending on the region's atmospheric conditions and water availability. It mainly depends on meteorological factors, soil, and plant factors. AET is computed as per equation 4.9 using potential evapotranspiration and evapotranspiration coefficient (K_C).

Table 4.6: Evapotranspiration coefficients

Land use	KC
Built-up	0.15
Water	1.05
Open space	0.3
Evergreen forest	0.95
Scrub and grassland	0.8
Forest Plantation	0.85
Agriculture Plantation	0.8
Deciduous forest	0.85

4.4.2 Blue water requirements

This constitutes the requirements for society, i.e., domestic, livestock, and agricultural needs.

4.4.2.1 Agriculture water requirements

Agriculture or crop water requirement is defined as the wholesome water required for the crops, which involves planting to harvest stage in a particular soil regime when sufficient soil water is maintained by rainfall and irrigation so that it does not affect the growth and yield crop. The water requirement for various crops was estimated considering the growth phases and cropping pattern ([53], [54]) in the catchment. This data was compiled based on telephonic surveys and publications such as District at a glance, Department of agriculture, etc. Land use information was used in order to estimate the cropping area of various crops grown in the catchment for determination of the volume of water required month-wise collated for the sub-catchments.

Table 4.7: Crop water requirement

Crops	Crop type	Delta (Water requirement mm)
Paddy	Kharif crop	900-2500
Jowar	Kharif/Rabi crop	200-300
Bajra	Kharif crop	300-400
Maize	Kharif/Rabi crop	400-600
Ragi	Kharif/Rabi crop	250-300
Wheat	Rabi crop	400-450

Other Cereals and millets	Kharif crop	400-450
Pulses	Kharif crop	250-300
Fruits & vegetables	Kharif/Rabi crop	2000-3000
Oil seeds	Kharif/Rabi crop	400-500
Cotton	Kharif crop	600-700
Coconut	Perennial crop	1500-2000
Arecanut	Perennial crop	1800-2200
Sugarcane	Perennial crop	1400-3000
Tobacco	Perennial crop	400-500
Source: http://vikaspedia.in/agriculture/crop-production/package-of-practices/plantation-crops/arecanut-micro-irrigation water areca pg:14		

Figure 4.13: Blue water requirements

4.4.2.2 Livestock water requirements

Initially, the livestock census data was collated from the publication 'District at a glance' (https://karnataka.nic.in) for various taluks, which were further interpolated sub-basin wise to determine the livestock population. The water requirements for various livestock were determined based on the telephonic interviews with a structured questionnaire to estimate the demands based on the different seasons. This data (Table 4.8) was further enhanced by consulting the veterinary doctors in these regions.

Table 4.8: Livestock water requirements

Water requirement in liters per animal								
Season/Animal	Cattle	Buffalo	Sheep	Goat	Pigs	Rabbits	Dogs	Poultry
Monsoon	20-25	25-30	4-6	4-6	6-8	0.3-0.35	2-6	0.2-0.25
Summer	30-35	35-40	6-8	6-8	9-12	0.5-0.6	6-8	0.3-0.35
Winter	25-30	30-35	6-8	6-8	8-10	0.4-0.45	2-6	0.25-0.3

4.4.2.3 Domestic water requirements

Population dynamics is analyzed to determine and understand the water requirements in the catchments and predict the population demands in the future. Population census data for taluks during the periods 2001 and 2011 were collected, which were interpolated at the sub-basin level. Based on the population rate from the earlier decades, the population for the recent year 2019 was predicted based on the geometric increase method as explained in the equation below.

$$\boldsymbol{r} = \left\{\frac{\left(\frac{P2011}{P2001}\right)-1}{n}\right\} \quad \textbf{(4.10)}$$

$$\mathbf{P_{2018}=P_{2011}(1+nr)} \qquad \textbf{(4.11)}$$

Where P_{2001} and P_{2011} are population for the year 2001 and 2011 respectively; n is the number of decades which is equal to 0.7 for determination of population for the year 2018; r is the rate of change.

Season/Animal	Cattle
Monsoon	85
Summer	135
Winter	100

Domestic water requirement is determined as a function of water requirement for a person per day, which includes bathing, washing, drinking, and other basic needs, varying seasonally.

4.5 Hydrological status

The hydrological footprint in the basins were analyzed monthly. The total available blue water resources consisting of rainfall, overland flows, pipe flow, base flows, soil water, etc., were considered as the input to the system. Water demands in the catchment were determined based on domestic, livestock, and agriculture water requirements i.e., the blue water needs and similarly green water needs for forests were determined. The eco-hydrological footprint of the basins was carried out to determine the hydrological status to determine whether it is a sufficient hydrological condition, i.e. the supplies are sufficient to meet the demands or the deficit condition if demands cross the availability of blue water resources. The hydrological footprint is computed in the study basins by considering the water supply and demand,

Chapter 5 : Results and discussions

5.1 Long term spatiotemporal assessment of rainfall: Long-term rainfall analysis, such as rainfall and rainy days' trend, across the catchments of Ghataprabha, Malaprabha, and Mahadayi were carried out using 0.5-degree gridded data at daily time steps between 1901 to 2018 obtained from the Princeton University hydrology database. The analysis revealed that (Figure 5.5, Figure 5.9, Figure 5.13, Figure 5.21, Figure 5.37) the Western Ghats are experiencing a decline in rainfall ranging from 90 mm to 230 mm in the last century. Especially the regions of Bicholim, Sattari, Supa, Khanapur have experienced these changes in rainfall in the last century. The intensity of rainfall as per IMD classification is listed in Table 5.1 and weekly/seasonal rainfall distribution at the regional scale in Table 5.2

Table 5.1: Intensity of rainfall (Source: IMD, Pune)

Condition	Rainfall amount (in mm)
No rain	0.0
Very light rain	0.1-2.4
Light rain	2.5-7.5
Moderate rain	7.6-35.5
Rather heavy	35.6-64.4
Heavy rain	64.5-124.4
Very heavy rain	124.5-244.4
Extremely heavy rain	>244.5

.Table 5.2: Weekly/Seasonal rainfall distribution at the region scale

IMD Classification	Condition
Severe Drought	X < -60%
Drought	-60% < X < -20%
Normal rainfall	-20% < X < +20%
Excess Rainfall	X > 20%
X: Percentage departure of realized rainfall from normal rainfall	

As per IMD, rainy days are termed when rainfall intensity is greater than 2.5 mm/day. Long-term analysis of rainy days shows a similar picture as rainfall at the Ghats, i.e., rainy days show a declining trend over time. Although the regions of Bagalkot, Muddenihala, Kalghatgi (Agro-climatic zone: Northern dry zone) have experienced an increase in rainfall over the last century with no change in the rainy days. The landscapes mainly influence the rainfall changes, and changes in these landscapes are explained in detail in sections 5.2, 5.5, and 5.8 for Ghataprabha, Malaprabha, and Mandovi, respectively.

This section helps in determining the rainfall trend and number of rainy days in detail, as below.

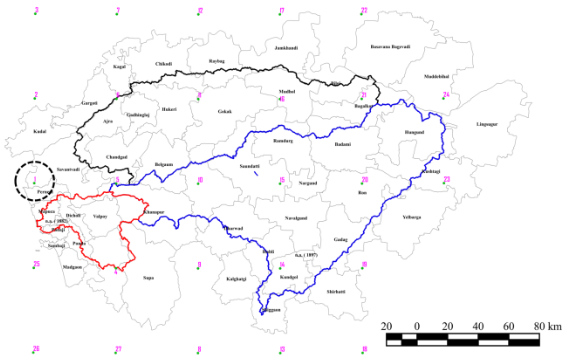


Figure 5.1: Location of gauged Id-1

Id-1

Coordinates: (73.75°E,15.75°N)
State: Goa, Maharashtra.
District: North Goa, Sindhudurg.
Taluks: Bicholim, Bardez, Pernem, Ponda, Sattari, Tiswadi, Sawantwadi.
The average annual rainfall at this grid is about 2634 mm with a COV of 0.18. The lowest rainfall was observed in the year 1905. Trend analysis showed an increasing rainfall with time, i.e., about 473 mm in 118 years, whereas the number of rainy days almost remained the same

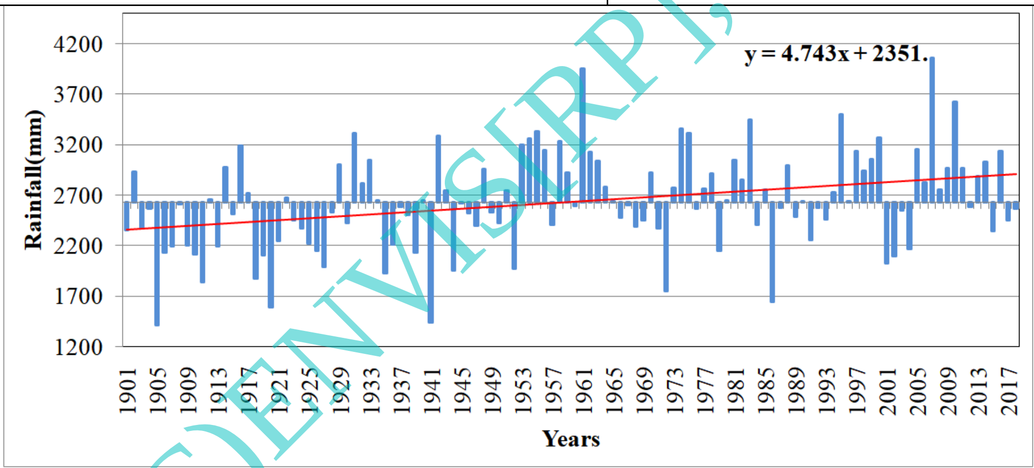


Figure 5.2: Rainfall trend analysis (Id-1)

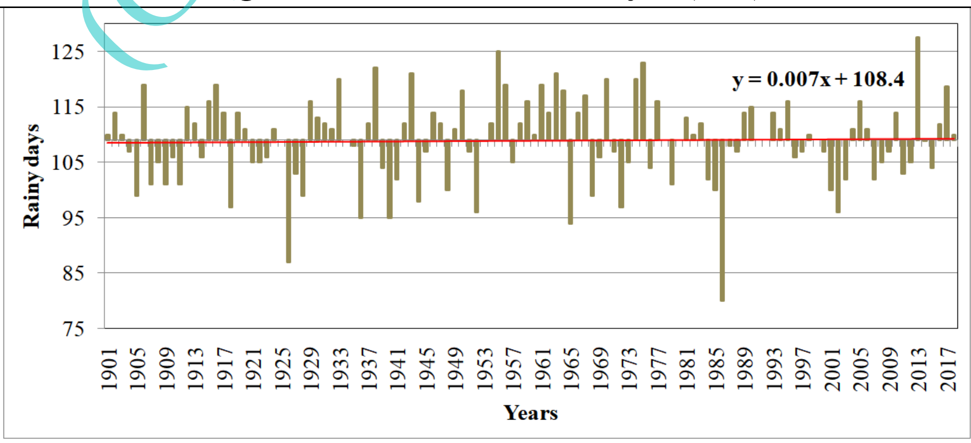


Figure 5.3: Rainy Days Trend Analysis (Id-1)

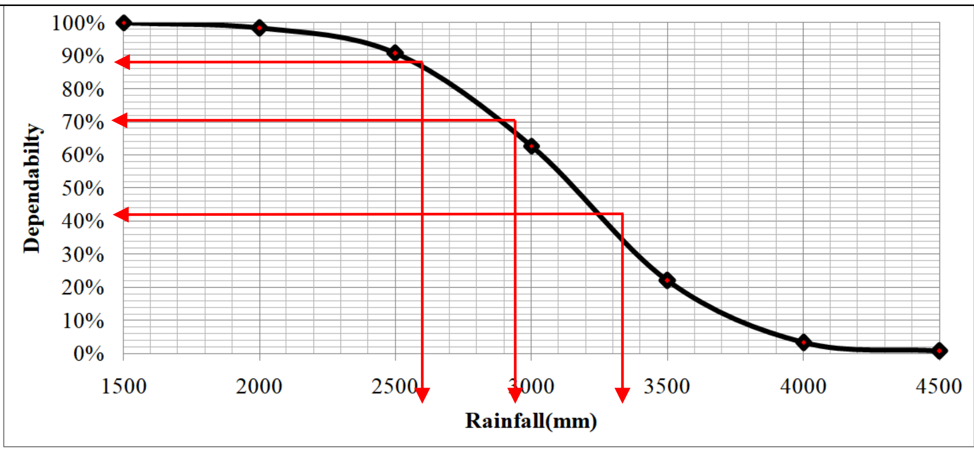


Figure 5.4: Dependability (Id-1)

Dependability (%)	50	75	90
Rainfall(mm)	3860	2800	2165

Table 5.3: Rainfall characteristics (Id-1)

Average (mm)	2634		Median (mm)	2608
Minimum (mm)	1414		Maximum (mm)	4059
Standard Deviation (mm)	482.05		Coefficient of Variation	0.18
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<1500	2	0.017	100%	59
1500-2000	9	0.076	98%	13
2000-2500	33	0.280	91%	4
2500-3000	48	0.407	63%	2
3000-3500	22	0.186	22%	5
3500-4000	3	0.025	3%	39
> 4000	1	0.008	1%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 1054 mm	0%	-
Drought	-60% Avg < -20% Avg	1054 mm to 2108 mm	11.9%	8
Normal rainfall	±20%Avg	2108 mm to 3162 mm	75.4%	1
Excess Rainfall	> 20% Avg	> 3162 mm	12.7%	8

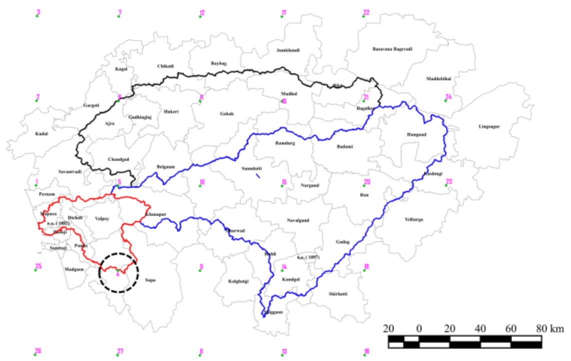


Figure 5.5: Location of Gauged Id-4

Id-4

Coordinates: (74.25°E, 15.25°N)
State: Goa, Karnataka.
District: North Goa, South goa, Uttara Kannada, Belgaum.
Taluks: Bicholim, Ponda, Sattari, Sanguem, Khanapur, Supa.
The average annual rainfall at this grid is about 2478 mm, with a COV of 0.18. The lowest rainfall was observed in the year 1905. Trend analysis showed decreasing rainfall with time, i.e., about 230 mm in 118 years, whereas rainy days remained the same.

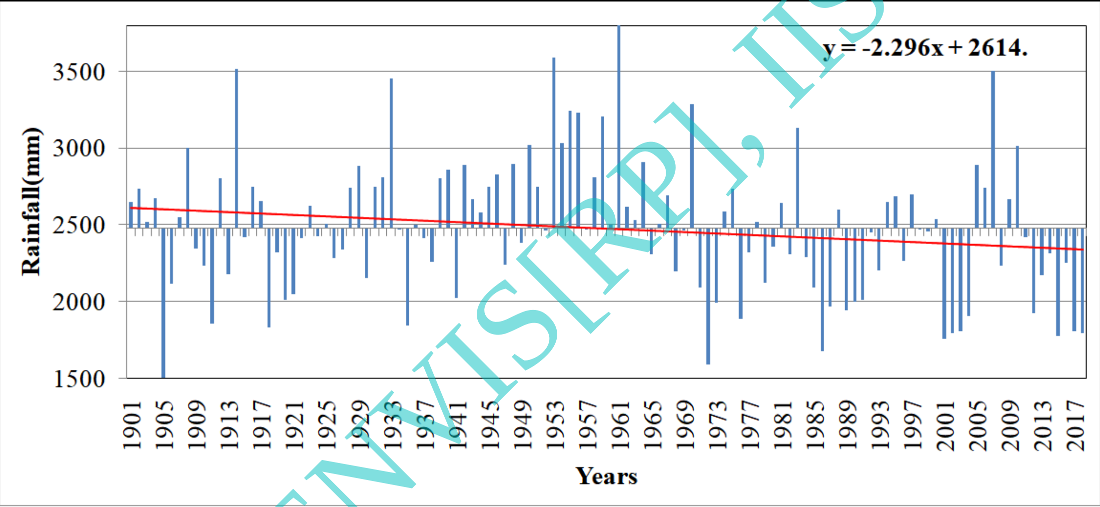


Figure 5.6: Rainfall Trend Analysis (Id-4)

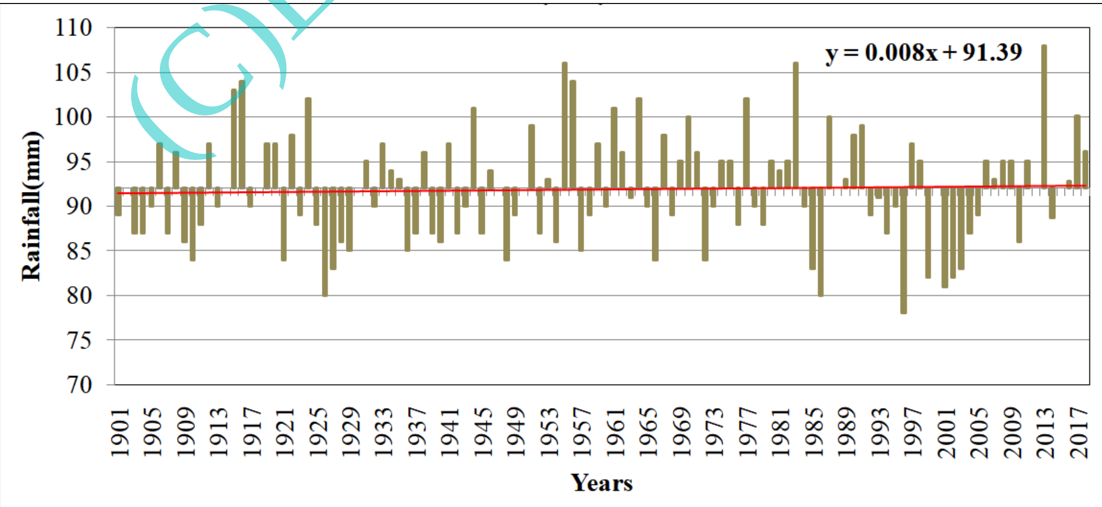


Figure 5.7: Rainy Days Trend Analysis (Id-4)

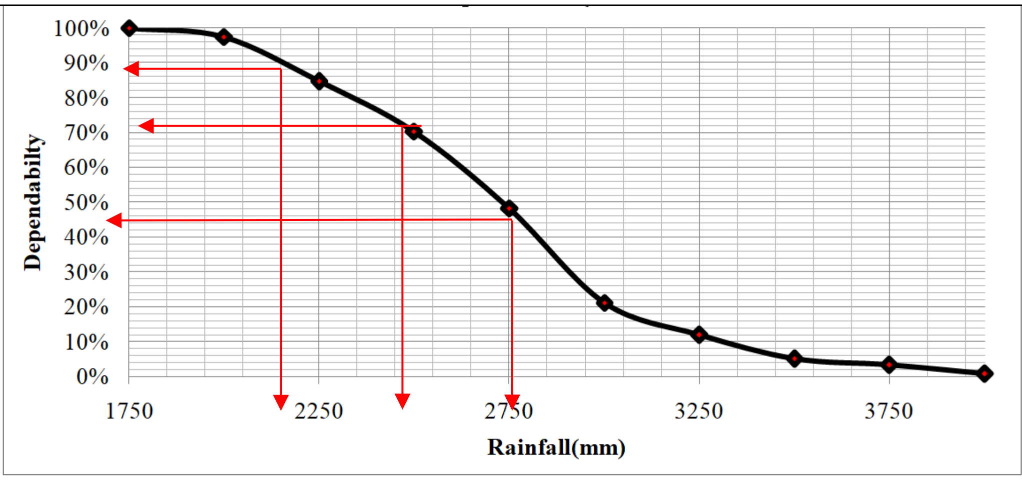


Figure 5.8: Dependability (Id-4)

Dependability	50	75	90
Rainfall(mm)	2692	2300	2063

Table 5.4: Rainfall characteristics (Id -4)

Average (mm)	2478	Median (mm)		2470
Minimum (mm)	1503	Maximum (mm)		3799
Standard Deviation (mm)	447.37	Coefficient of Variation		0.18
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<1750	3	0.025	100%	39
1750-2000	15	0.127	97%	8
2000-2250	17	0.144	85%	7
2250-2500	26	0.220	70%	5
2500-2750	32	0.271	48%	4
2750-3000	11	0.093	21%	11
3000-3250	8	0.068	12%	15
3250-3500	2	0.017	5%	59
3500-3750	3	0.025	3%	39
>3750	1	0.008	1%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 991 mm	-	-
Drought	-60% Avg < -20% Avg	991 mm to 1982 mm	14.4%	7
Normal rainfall	±20%Avg	1982 mm to 2974 mm	73.7%	1
Excess Rainfall	> 20% Avg	> 2974 mm	11.9%	8

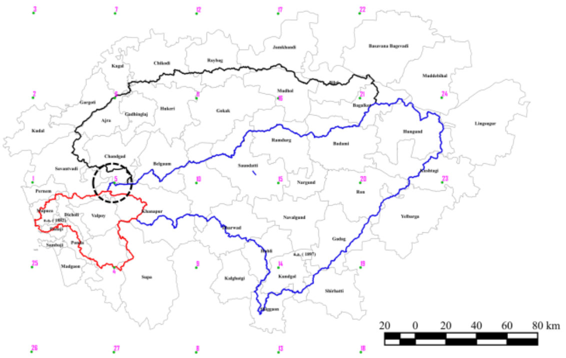


Figure 5.9: Location of Gauged Id-5

Id 5

Coordinates: (74.25°E, 15.75°N)

State: Goa, Karnataka, Maharashtra.

District: Belgaum, Kolhapur, North Goa, Sindhudurg, Uttara Kannada.

Taluks: Belgaum, Khanapur, Gandhinglaj, Chandagad, Supa, Bicholim, Sattari, Sawantwadi.

The average annual rainfall at this grid is about 1806 mm, with a COV of 0.2. The lowest rainfall was observed in the year 1905. Trend analysis showed decreasing rainfall with time, i.e., about 37 mm in 100 years, whereas the number of rainy days increased to just above one day since 1900.

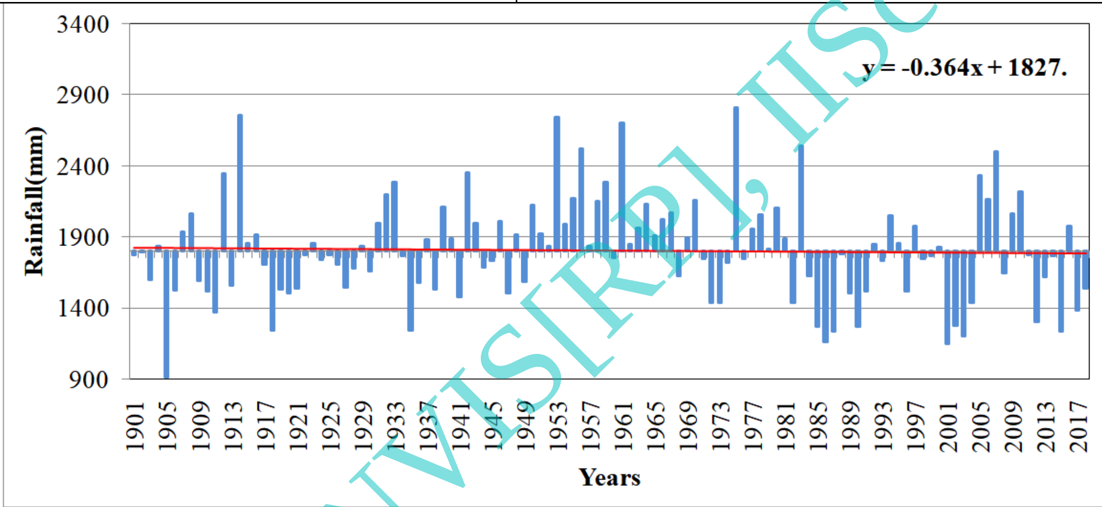


Figure 5.10: Rainfall Trend Analysis (Id-5)

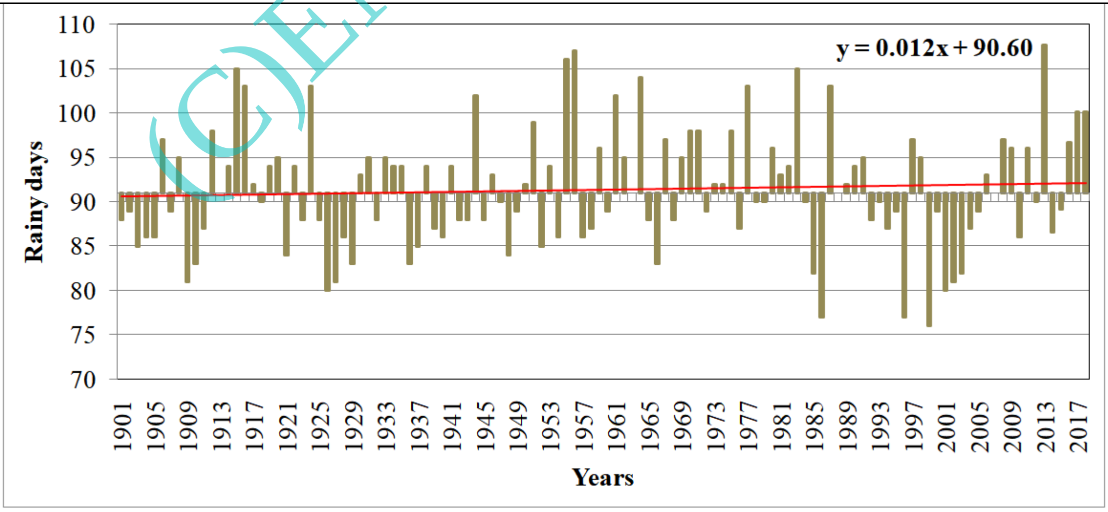


Figure 5.11: Rainy Days Trend Analysis (Id-5)

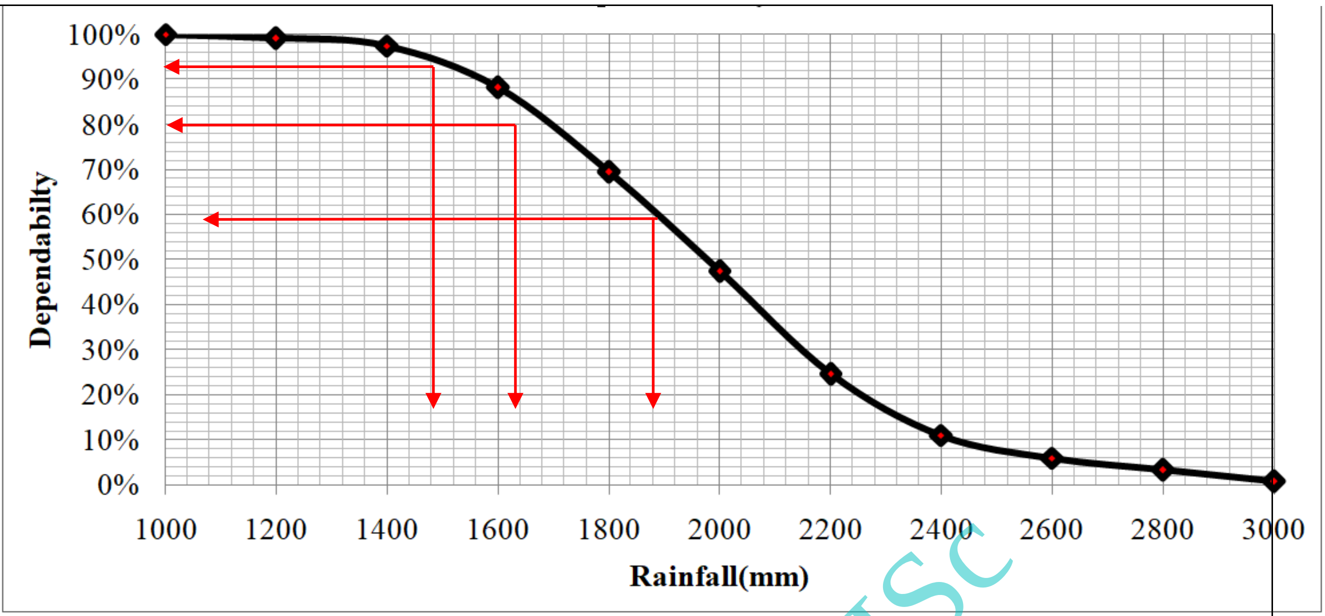


Figure 5.12: Dependability (Id-5)

Dependability	50	75	90
Rainfall(mm)	1946	1584	1368

Table 5.5: Rainfall characteristics (Id-5)

Average (mm)	1806	Median (mm)		1779
Minimum (mm)	916	Maximum (mm)		2812
Standard Deviation (mm)	360.87	Coefficient of Variation		0.2
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<1000	1	0.008	100%	118
1000-1200	2	0.017	99%	59
1200-1400	11	0.093	97%	11
1400-1600	22	0.186	88%	5
1600-1800	26	0.220	69%	5
1800-2000	27	0.229	47%	4
2000-2200	16	0.136	25%	7
2200-2400	6	0.051	11%	20
2400-2600	3	0.025	6%	39
2600-2800	3	0.025	3%	39
>2800	1	0.008	1%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 722 mm	-	-
Drought	-60% Avg < -20% Avg	722 mm to 1444 mm	15.3%	7
Normal rainfall	±20%Avg	1444 mm to 2166 mm	72.0%	1
Excess Rainfall	> 20% Avg	> 2166 mm	12.7%	8

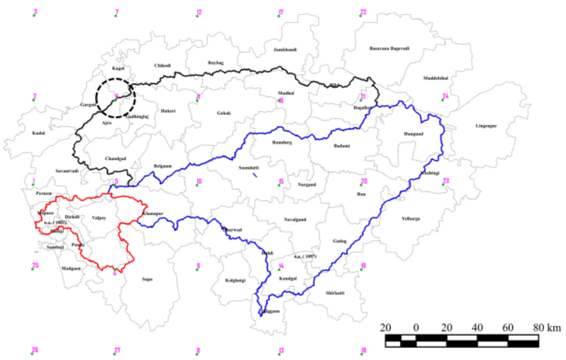


Figure 5.13: Location of Gauged Id-6

Id 6

Coordinates: (74.25°E, 16.25°N)

State: Karnataka, Maharashtra.

District: Belgaum, Sindhudurg, Kolhapur.

Taluks: Belgaum, Chikkodi, Hukkeri, Ajra, Chandgad, Gadhinglaj, Bhudargad, Kagal, Radhanangiri, Sawantwadi.

The average annual rainfall at this grid is about 1350 mm, with a COV of 0.21. The lowest rainfall was observed in 1905, whereas the highest was noticed in 1913. Trend analysis showed an increase in rainfall with time, i.e., about 90 mm in 100 years, whereas the number of rainy days increased slightly within this period

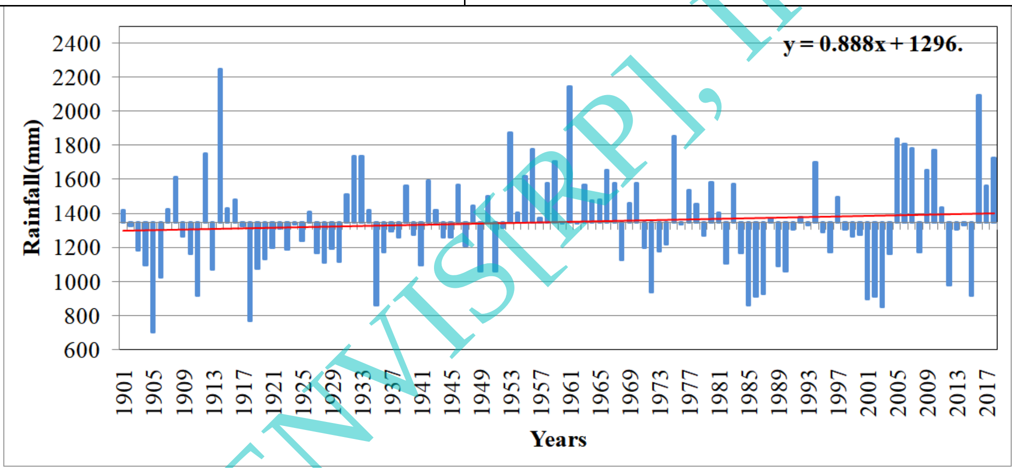


Figure 5.14: Rainfall Trend Analysis (Id-6)

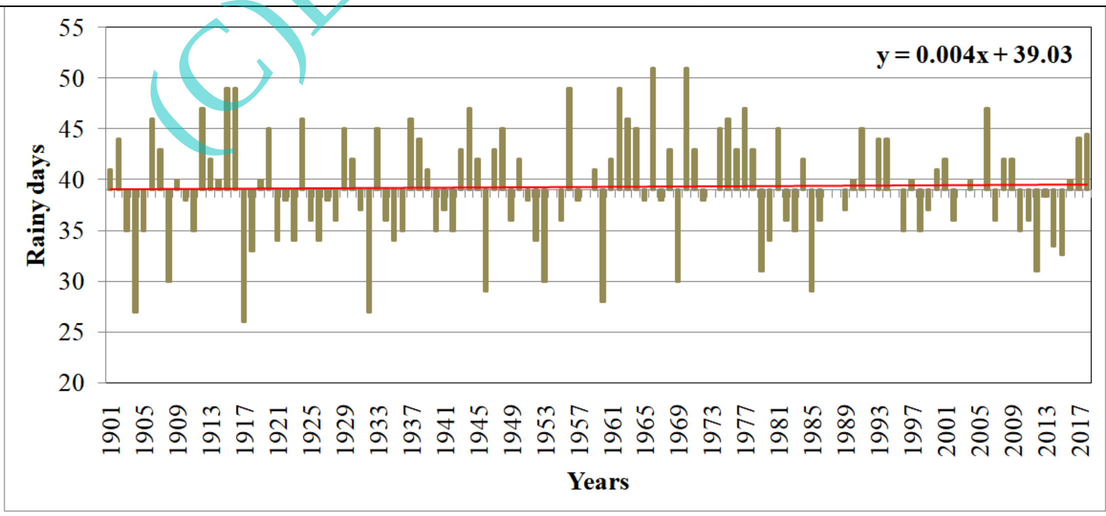


Figure 5.15: Rainy Days Trend Analysis (Id-6)

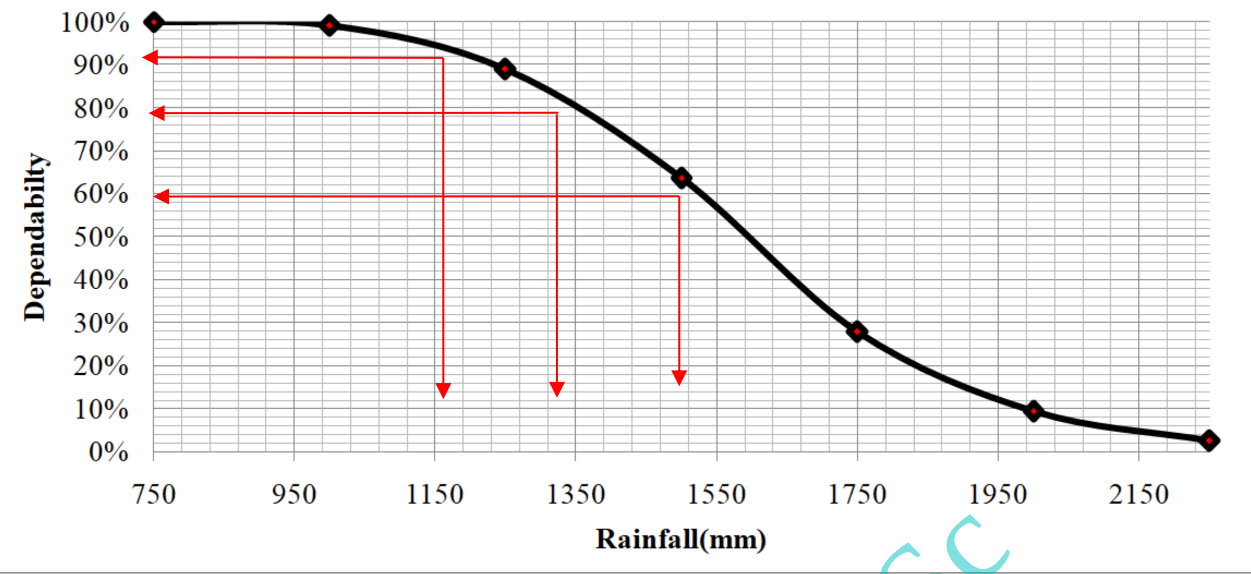


Figure 5.16: Dependability (Id-6)

Dependability	50	75	90
Rainfall(mm)	1613	1264	1054

Table 5.6: Rainfall characteristics (Id-6)

Average (mm)	1350	Median (mm)	1328	
Minimum (mm)	705	Maximum (mm)	2250	
Standard Deviation (mm)	289.70	Coefficient of Variation	0.21	
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<500	0	0.000	100%	-
1000-500	13	0.110	100%	9
1000-1500	72	0.610	89%	2
1500-2000	30	0.254	28%	4
>2000	3	0.025	3%	39
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 540 mm	-	-
Drought	-60% Avg < -20% Avg	540 mm to 1080 mm	16.1%	6
Normal rainfall	±20%Avg	1080 mm to 1620 mm	68.6%	2
Excess Rainfall	> 20% Avg	> 1620 mm	15.3%	7

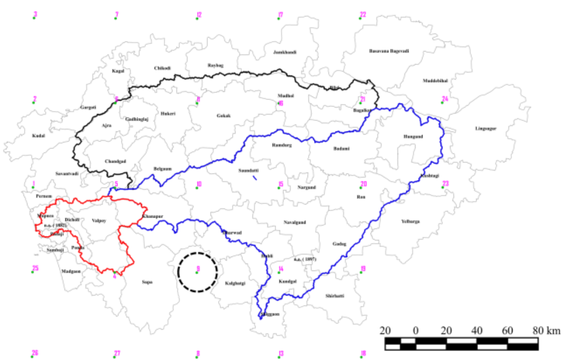


Figure 5.17: Location of Gauged Id-9

Id 9

Coordinates: (74.75ºE, 15.25ºN)

State: Karnataka

District: Belgaum, Dharwad

Taluks: Bailhongal, Khanapur, Dharward, Hubli

The average annual rainfall at this grid is about 1385 mm, with a COV of 0.21. The lowest rainfall was observed in the year 1905. Trend analysis showed a decrease in rainfall with time, i.e., about 207 mm in 100 years, whereas the number of rainy days remained the same in this period.

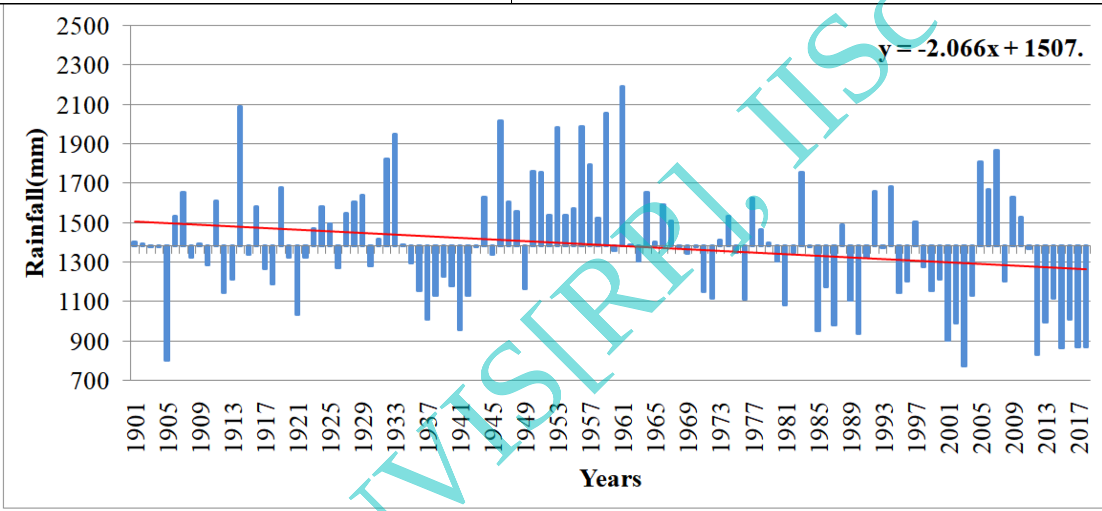


Figure 5.18: Rainfall Trend Analysis (Id-9)

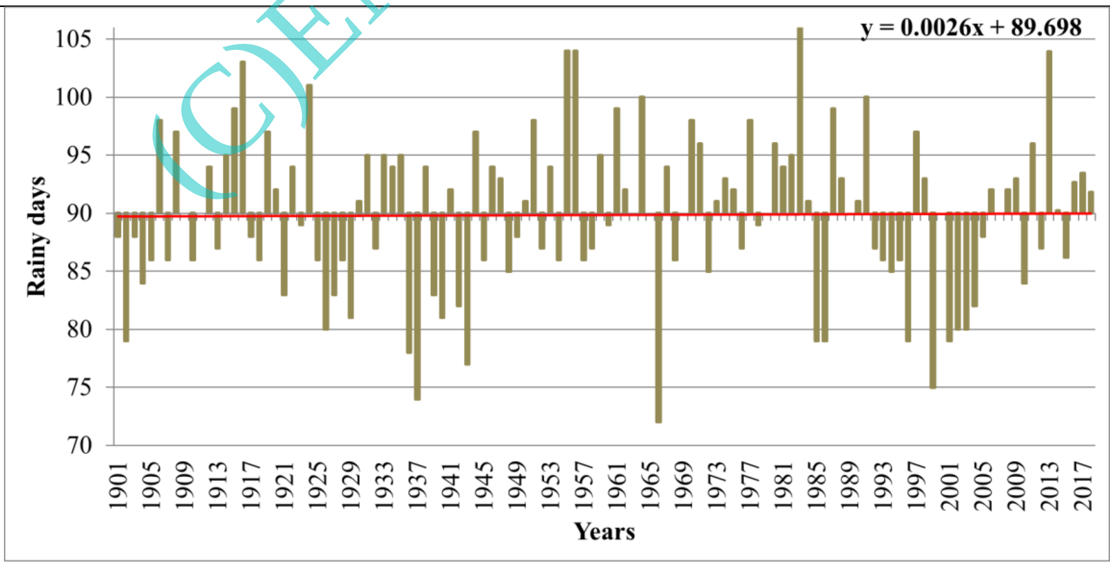


Figure 5.19: Rainy Days Trend Analysis (Id-9)

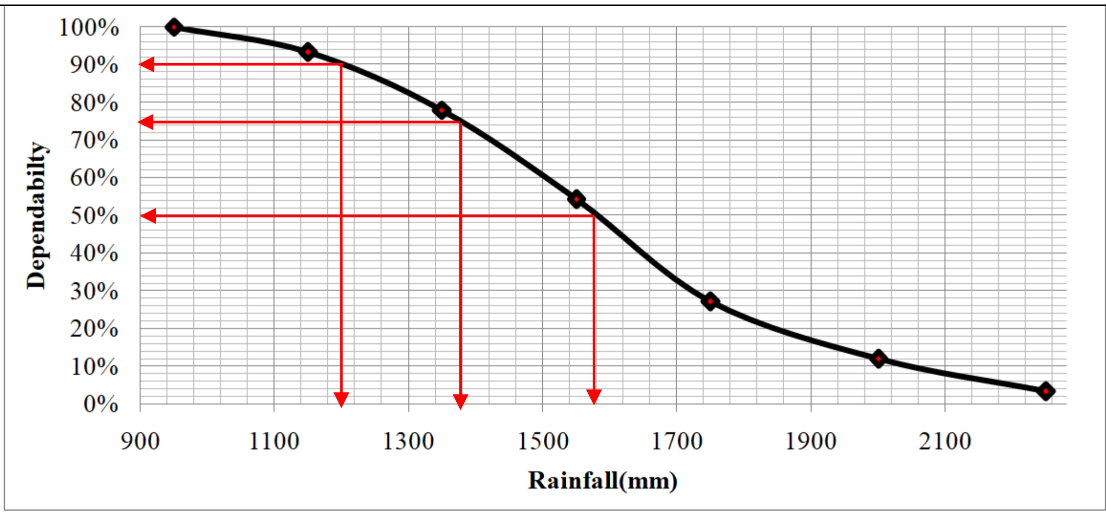


Figure 5.20: Dependability (Id-9)

Dependability (%)	50	75	90
Rainfall(mm)	1570	1300	1138

Table 5.7: Rainfall characteristics (Id-9)

Average (mm)	1385	Median (mm)	1379
Minimum (mm)	773	Maximum (mm)	2193
Standard Deviation (mm)	296.24	Coefficient of Variation	0.21

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<950	8	0.068	100%	15
950-1150	18	0.153	93%	7
1150-1350	28	0.237	78%	4
1350-1550	32	0.271	54%	4
1550-1750	18	0.153	27%	7
1750-2000	10	0.085	12%	12
>2000	4	0.034	3%	30
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 554 mm	-	-
Drought	-60% Avg < -20% Avg	554 mm to 1108 mm	15.3%	6.6
Normal rainfall	±20%Avg	1108 mm to 1662 mm	70.3%	1.4
Excess Rainfall	> 20% Avg	> 1662 mm	14.4%	6.9

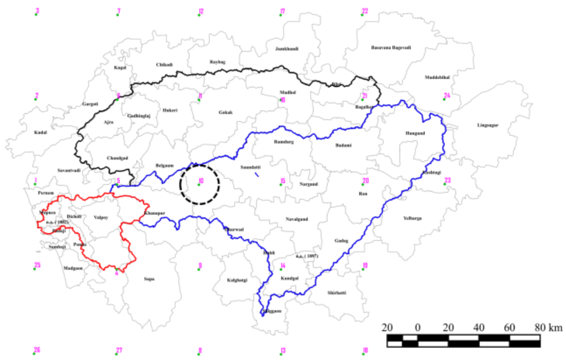


Figure 5.21: Location of Gauged Id-10

Id 10

Coordinates: (74.75°E, 15.75°N)

State: Karnataka.

District: Belgaum, Dharward.

Taluks: Bailhongal, Gokak, Hukkeri Belgavi, Khanapur, Savadatti, Dharward.

The average annual rainfall at this grid is about 1074 mm, with a COV of 0.24. The lowest rainfall was observed in the year 2001. Trend analysis showed decreasing rainfall with time, i.e., about 300 mm in 100 years, whereas rainy days decreased by over 2 days.

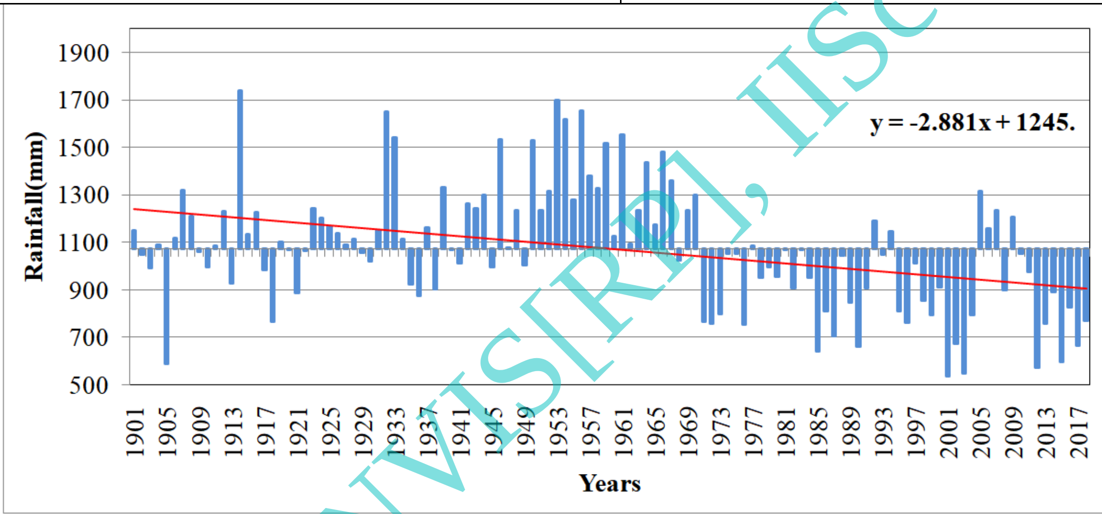


Figure 5.22: Rainfall Trend Analysis (Id-10)

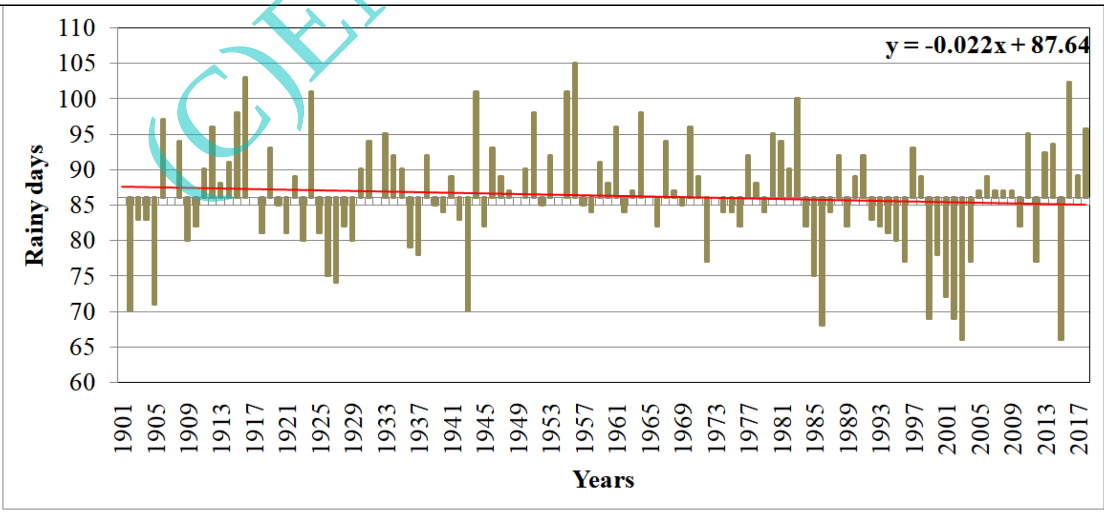


Figure 5.23:Rainy Days Trend Analysis (Id-10)

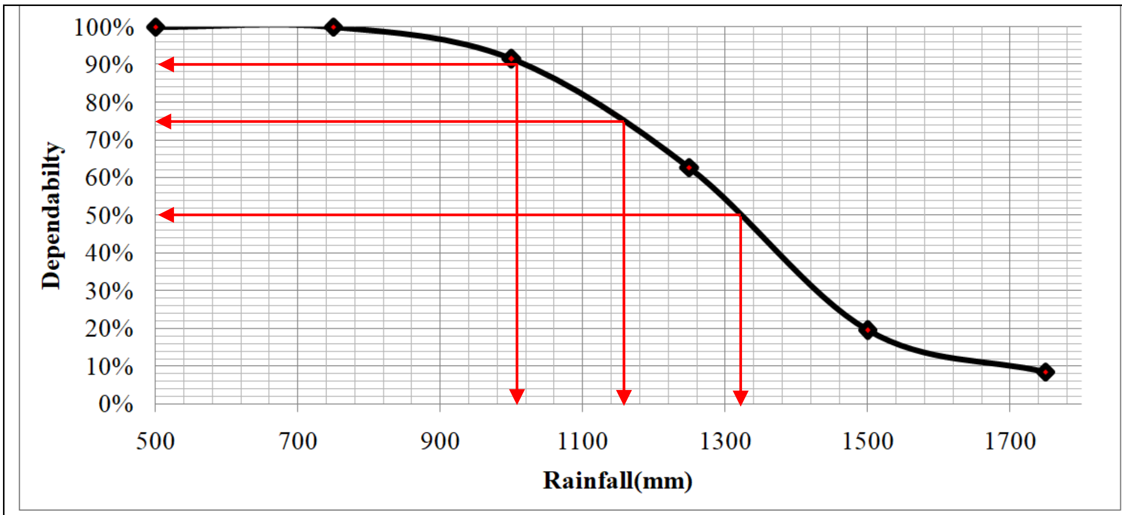


Figure 5.24: Dependability (Id-10)

Dependability (%)	50	75	90
Rainfall(mm)	1295	1065	927

Table 5.8:Rainfall characteristics (Id-10)

Average (mm)	1074	Median (mm)	1073
Minimum (mm)	540	Maximum (mm)	1741
Standard Deviation (mm)	259.54	Coefficient of Variation	0.24

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<750	10	0.085	100%	12
750-1000	34	0.288	92%	3
1000-1250	51	0.432	63%	2
1250-1500	13	0.110	19%	9
>1500	10	0.085	8%	12
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 430 mm	-	-
Drought	-60% Avg < -20% Avg	430 mm to 860 mm	21.2%	5
Normal rainfall	±20%Avg	860 mm to 1290 mm	61.0%	2
Excess Rainfall	> 20% Avg	> 1290 mm	17.8%	6

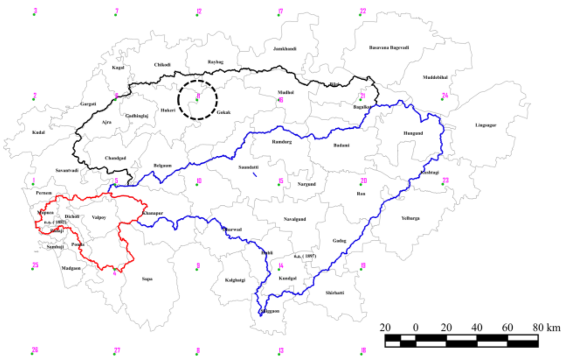


Figure 5.25: Location of Gauged Id

Id 11

Coordinates: (74.75°E, 16.25°N)
State: Karnataka
District: Belgaum, Bagalkot
Taluks: Jamkhandi, Mudhol, Bailhongal, Belgaum, Chikkodi, Gokak, Hukkeri,Raibag, Savadatti

The average annual rainfall at this grid is about 1023 mm, with a COV of 0.22. The lowest rainfall was observed in the year 1905. Trend analysis showed decreasing rainfall with time, i.e., about 120 mm in 100 years, whereas the number of rainy days increased about a day and a half within this period

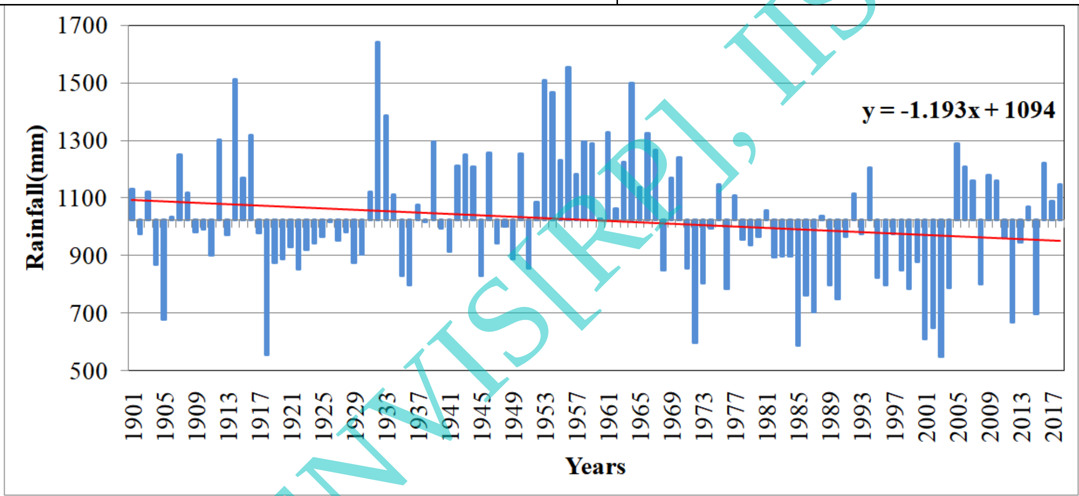


Figure 5.26: Rainfall Trend Analysis (Id-11)

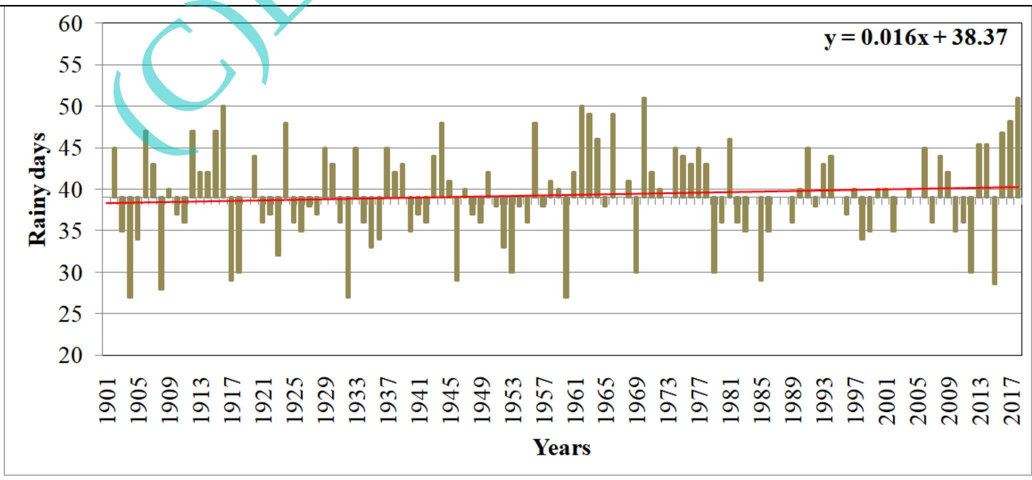


Figure 5.27: Rainy Days Trend Analysis (Id-11)

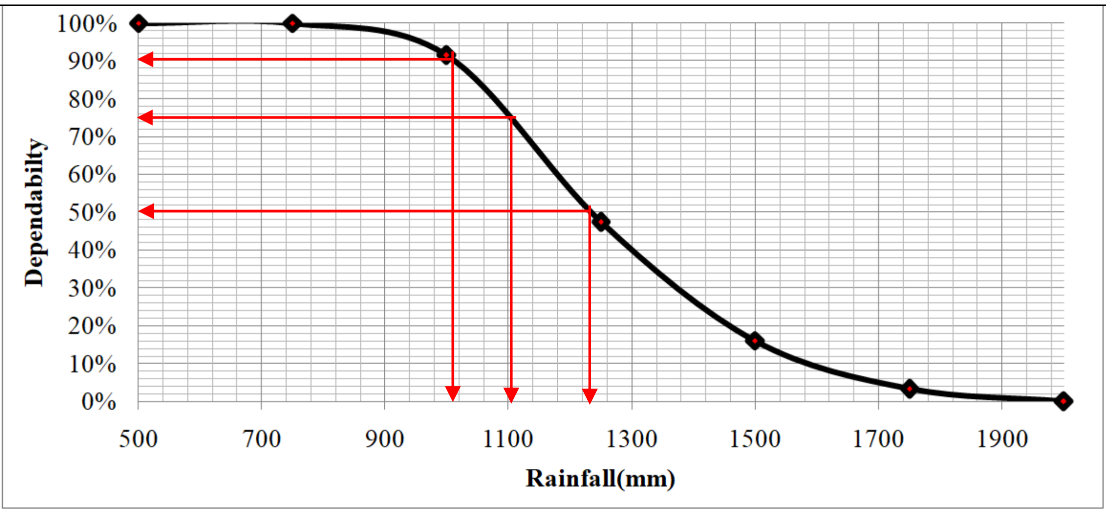


Figure 5.28:Dependability (Id-11)

Dependability (%)	50	75	90
Rainfall(mm)	1241	1030	904

Table 5.9: Rainfall characteristics (Id-11)

Average (mm)	1023	Median (mm)	988
Minimum (mm)	550	Maximum (mm)	1640
Standard Deviation (mm)	223.38	Coefficient of Variation	0.22

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<750	10	0.085	100%	12
750-1000	52	0.441	92%	2
1000-1250	37	0.314	47%	3
1250-1500	15	0.127	16%	8
1500-1750	4	0.034	3%	30
>1750	0	0.000	0%	-

IMD based Classification

IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 409 mm	-	-
Drought	-60% Avg < -20% Avg	409 mm to 818 mm	16.9%	6
Normal rainfall	±20%Avg	818 mm to 1227 mm	64.4%	2
Excess Rainfall	> 20% Avg	> 1227 mm	18.6%	5

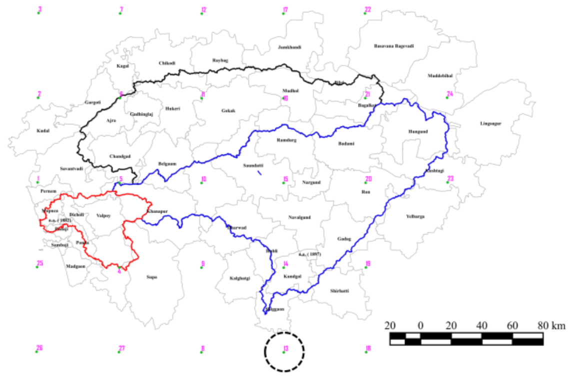


Figure 5.29: Location of Gauged Id -13

Id 13

Coordinates: (75.25°E, 14.75°N)

State: Karnataka

District: Haveri

Taluks: Shiggaon

The average annual rainfall at this grid is about 1094 mm, with a COV of 0.2. The lowest rainfall was observed in the year 2017. Trend analysis showed decreasing rainfall with time, i.e., about 120 mm in 100 years, whereas the number of rainy days remained the same within this period

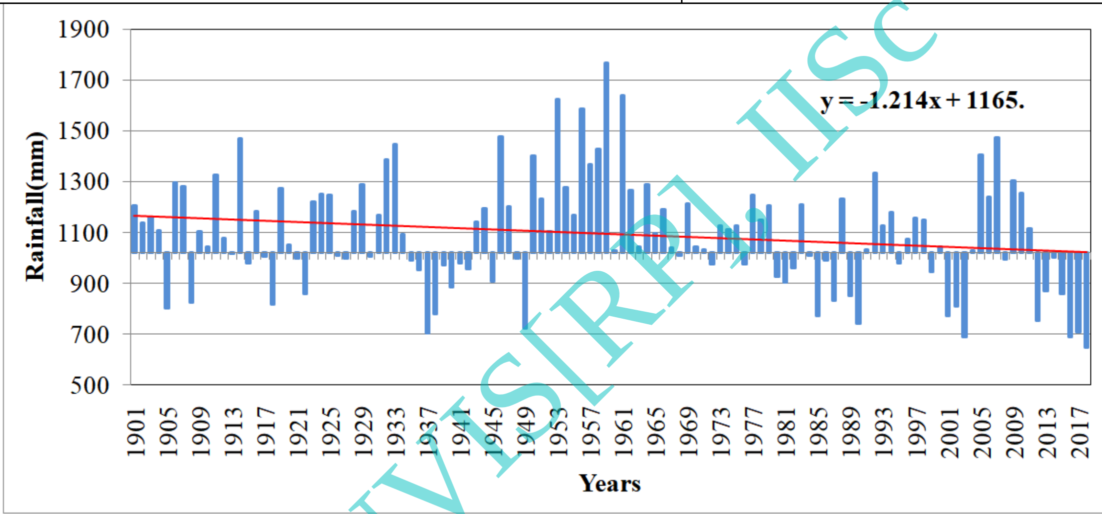


Figure 5.30: Rainfall Trend Analysis (Id-13)

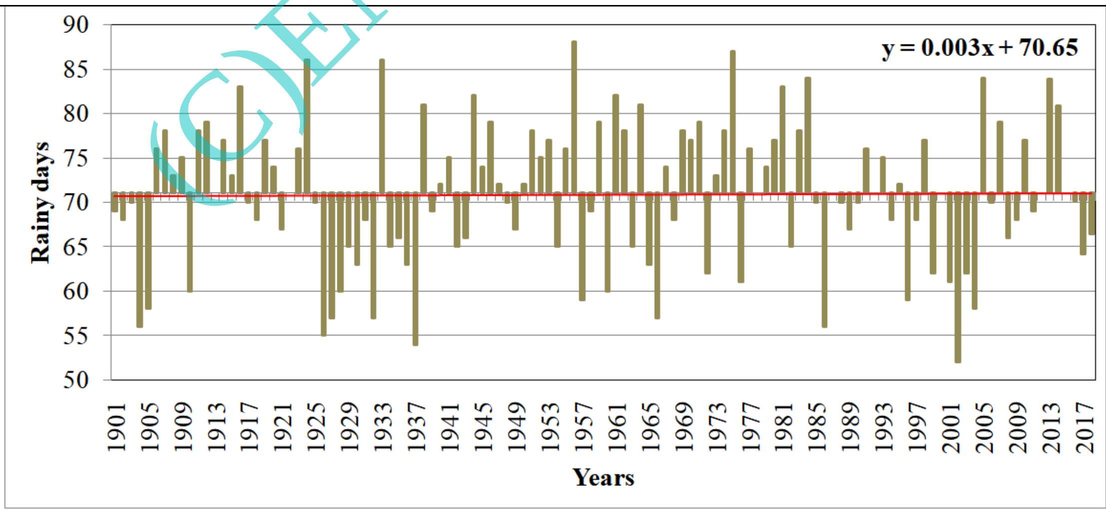


Figure 5.31: Rainy Days Trend Analysis (Id-13)

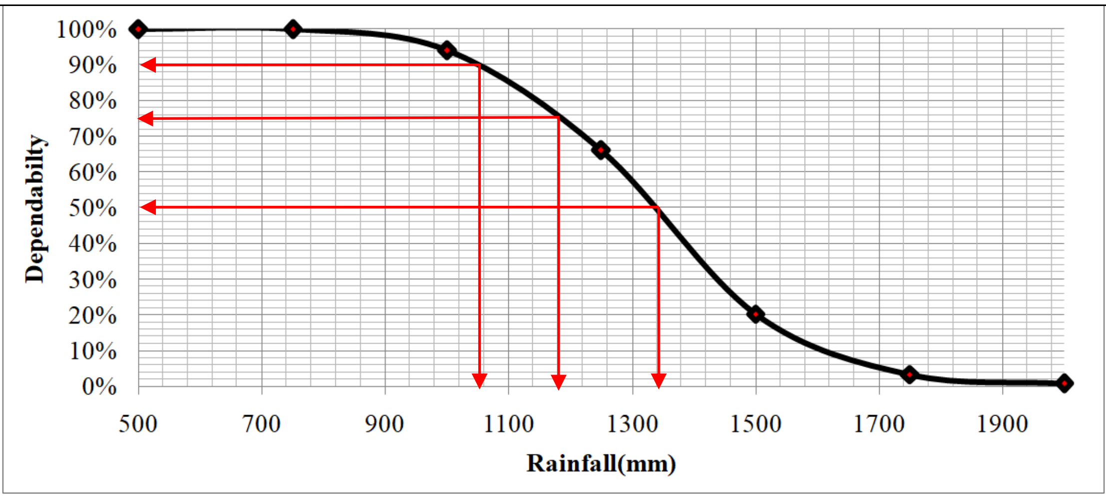


Figure 5.32: Dependability (Id-13)

Dependability (%)	50	75	90
Rainfall (mm)	1312	1078	938

Table 5.10: Rainfall characteristics (Id-13)

Average (mm)	1094	Median (mm)	1084
Minimum (mm)	649	Maximum (mm)	1768
Standard Deviation (mm)	218.01	Coefficient of Variation	0.2

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<750	7	0.059	100%	7
750-1000	33	0.280	94%	33
1000-1250	54	0.458	66%	54
1250-1500	20	0.169	20%	20
1500-1750	3	0.025	3%	3
>1750	1	0.008	1%	1
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 437 mm	-	-
Drought	-60% Avg < -20% Avg	437 mm to 874 mm	16.9%	6
Normal rainfall	±20%Avg	874 mm to 1312 mm	70.3%	1
Excess Rainfall	> 20% Avg	> 1312 mm	12.7%	8

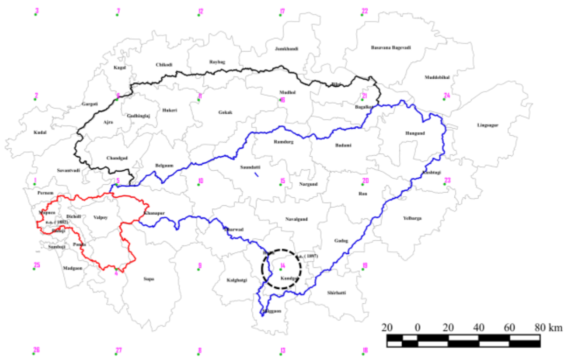


Figure 5.33: Location of Gauged Id-14

Id 14

Coordinates: (75.25ºE, 15.25ºN)

State: Karnataka

District: Dharwad, Gadag, Haveri

Taluks: Dharwad, Hubli, Kalaghatagi, Kundgol, Navalgund, Gadag, Shirahatti Shiggaon

The average annual rainfall at this grid is about 840 mm, with a COV of 0.23. The lowest rainfall was observed in the year 1905 and highest in 1946. Trend analysis showed decreasing rainfall with time, i.e., about 126 mm in 100 years, with a decrease in rainy days, about three days.

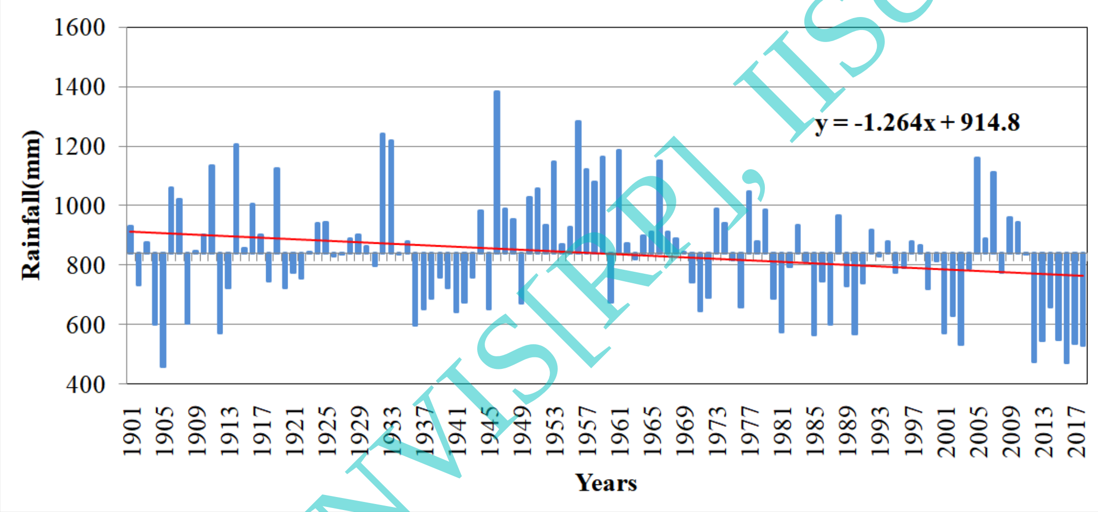


Figure 5.34: Rainfall Trend Analysis (Id-14)

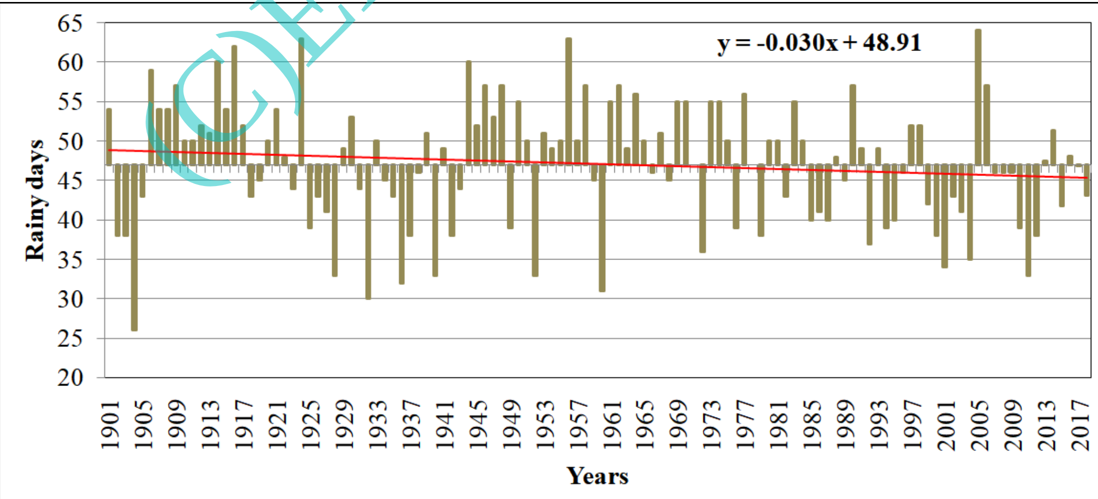


Figure 5.35: Rainy Days Trend Analysis (Id-14)

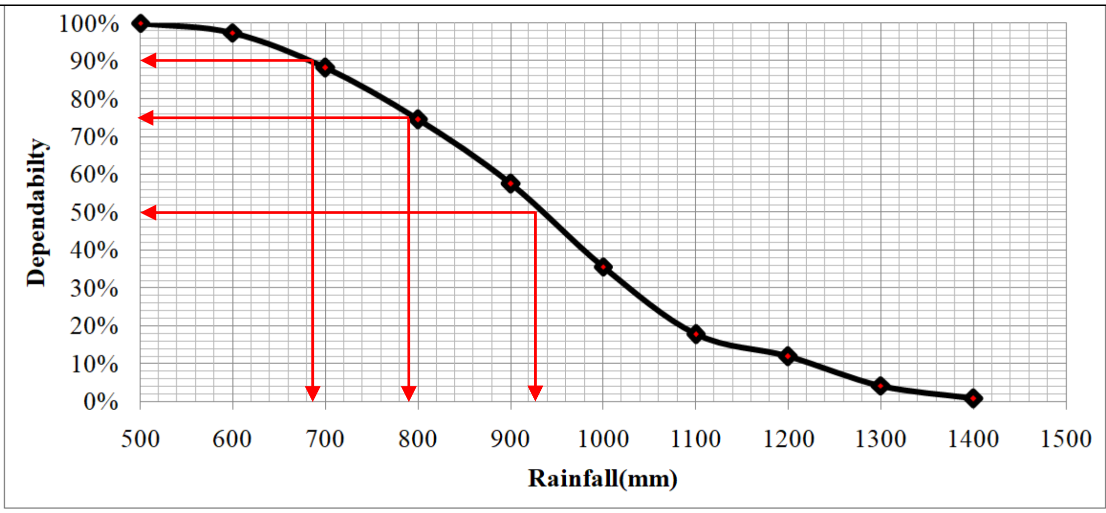


Figure 5.36: Dependability (Id-14)

Dependability (%)	50	75	90
Rainfall (mm)	950	755	638

Table 5.11: Rainfall characteristics (Id-14)

Average (mm)	840	Median (mm)	842
Minimum (mm)	460	Maximum (mm)	1382
Standard Deviation (mm)	192.24	Coefficient of Variation	0.23

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<500	3	0.025	100%	39
500-600	11	0.093	97%	11
600-700	16	0.136	88%	7
700-800	20	0.169	75%	6
800-900	26	0.220	58%	5
900-1000	21	0.178	36%	6
1000-1100	7	0.059	18%	17
1100-1200	9	0.076	12%	13
1200-1300	4	0.034	4%	30
>1300	1	0.008	1%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 336 mm	-	-
Drought	-60% Avg < -20% Avg	336 mm to 672 mm	21.2%	5
Normal rainfall	±20%Avg	672 mm to 1008 mm	61.9%	2
Excess Rainfall	> 20% Avg	> 1008 mm	16.9%	6

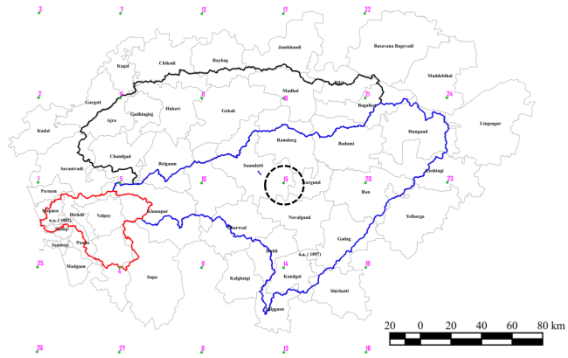


Figure 5.37: Location of Gauged Id-15

Id 15

Coordinates: (75.25°E, 15.75°N)

State: Karnataka

District: Bagalkot, Belgaum, Dharward, Gadag

Taluks: Badami, Ramadurg, Savadatti, Dharwad, Navalgund, Gadag, Nargund, Ron

The average annual rainfall at this grid is about 671 mm, with a COV of 0.23. The lowest rainfall was observed in the year 1905 and the highest in 1956. Trend analysis showed decreasing rainfall with time, i.e., about 43 mm in 100 years, while the number of rainy days almost remained itself.

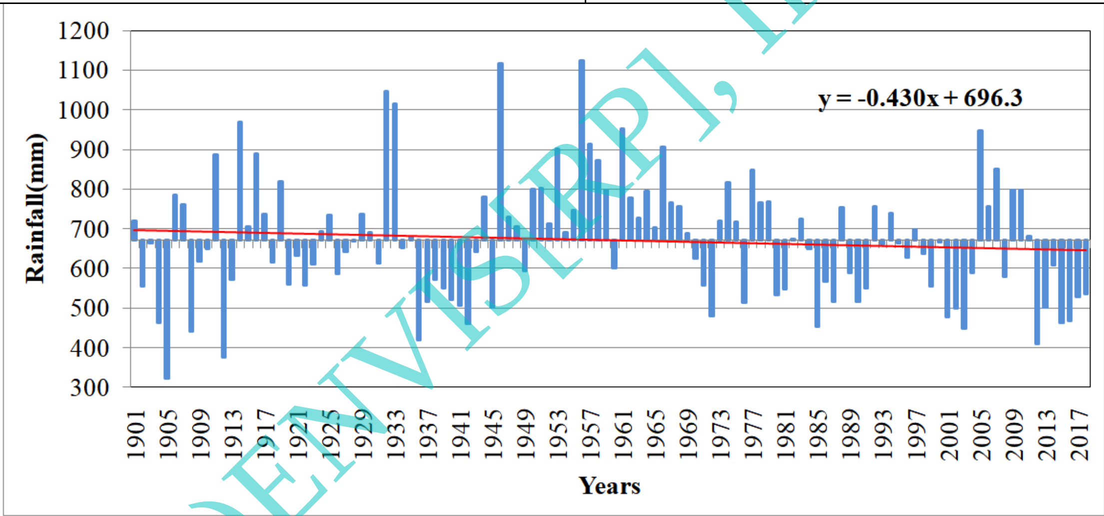


Figure 5.38: Rainfall Trend Analysis (Id-15)

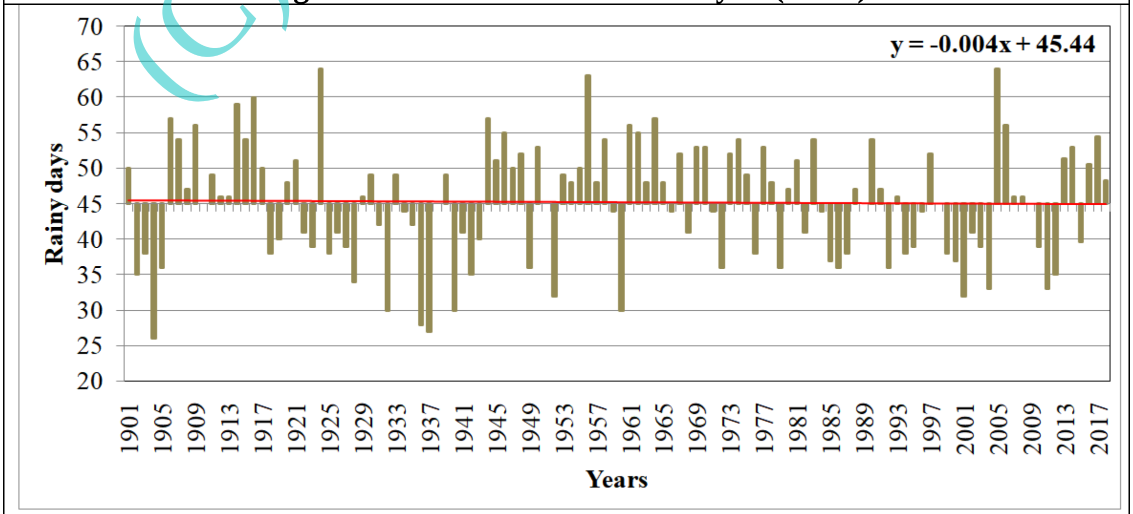


Figure 5.39: Rainy Days Trend Analysis (Id-15)

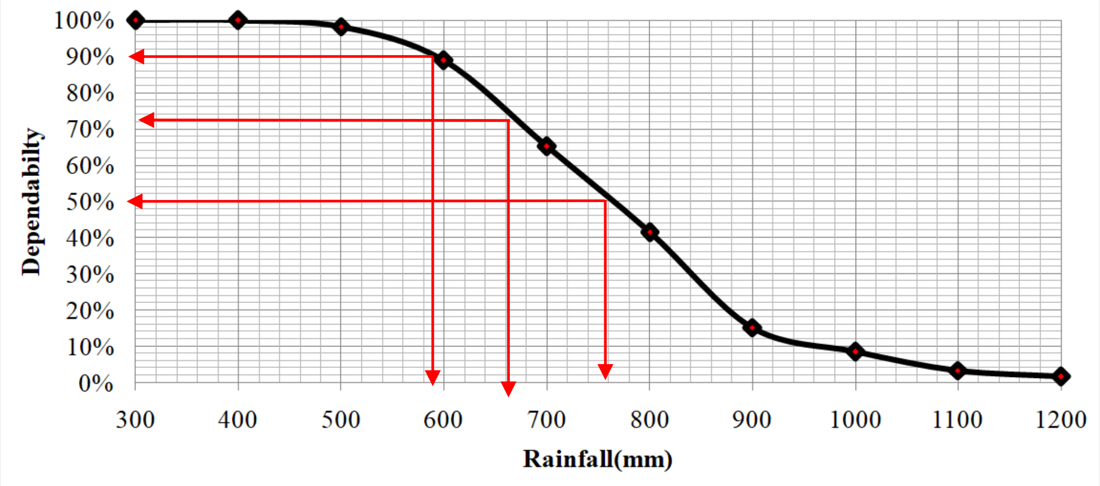


Figure 5.40: Dependability (Id-15)

Dependability (%)	50	75	90
Rainfall (mm)	793	625	524

Table 5.12: Rainfall characteristics (Id-15)

Average (mm)	671	Median (mm)	666
Minimum (mm)	324	Maximum (mm)	1124
Standard Deviation (mm)	154.35	Coefficient of Variation	0.23

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<400	2	0.017	100%	59
400-500	11	0.093	98%	11
500-600	28	0.237	89%	4
600-700	28	0.237	65%	4
700-800	31	0.263	42%	4
800-900	8	0.068	15%	15
900-1000	6	0.051	8%	20
1000-1100	2	0.017	3%	59
>1100	2	0.017	2%	59
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	<268 mm	-	-
Drought	-60% Avg < -20% Avg	268 mm to 536 mm	21.2%	5
Normal rainfall	±20%Avg	536 mm to 804 mm	64.4%	2
Excess Rainfall	> 20% Avg	> 804 mm	14.4%	7

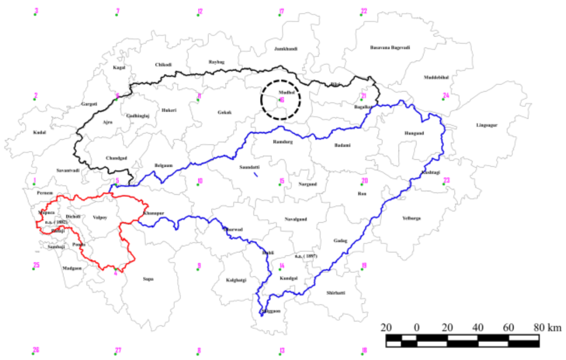


Fig. Location of Gauged Id

Id 16

Coordinates: (75.25°E, 16.25°N)

State: Karnataka

District: Bagalkot, Belgaum, Bijapur

Taluks: Badami, Bagalkot, Bilagi, Jamakhandi, Mudhol, Gokak, Ramadurg, Raibag, Savadatti, Bijapur

The average annual rainfall at this grid is about 716 mm, with a COV of 0.23. The lowest rainfall was observed in the year 1972 and the highest in1956. Trend analysis showed increasing rainfall with time, i.e., about 73 mm in 100 years, whereas the number of rainy days increased by about three days in this period.

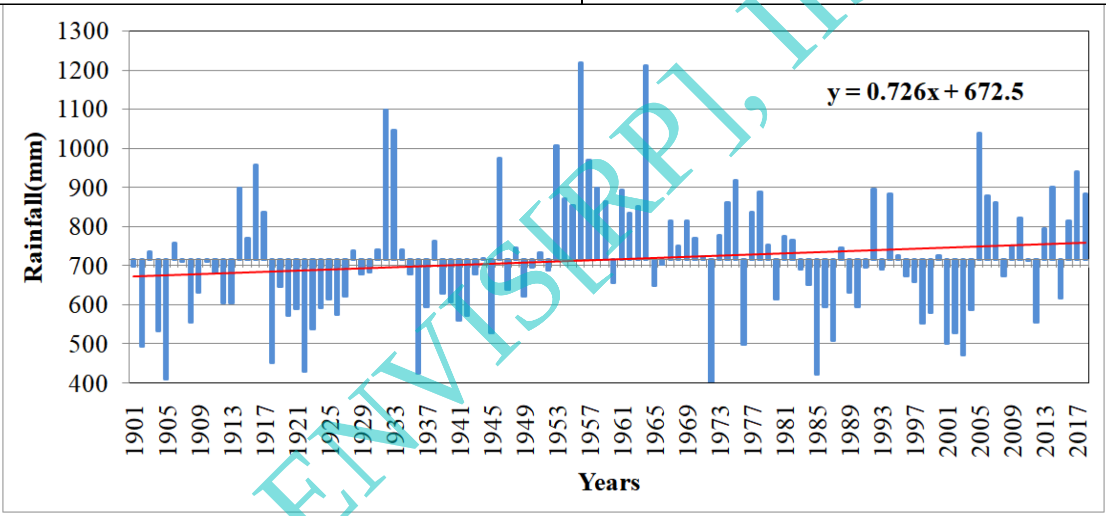


Figure 5.41: Rainfall Trend Analysis (Id-16)

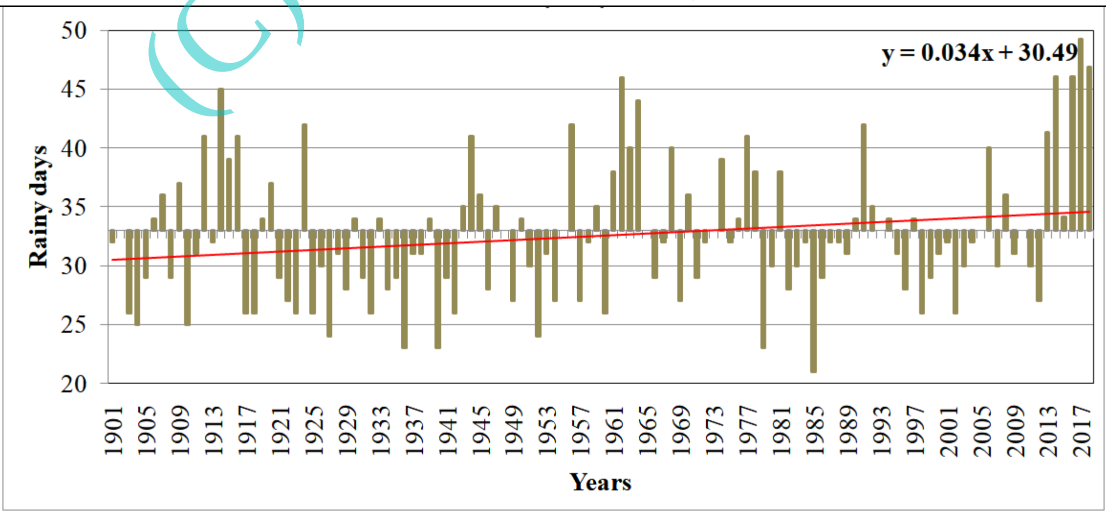


Figure 5.42: Rainy Days Trend Analysis (Id-16)

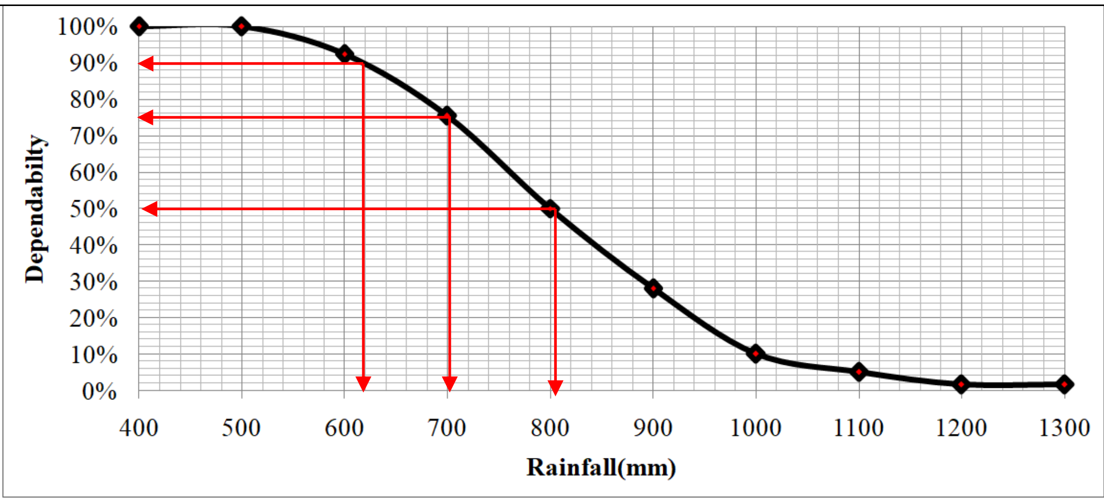


Figure 5.43: Dependability (Id-16)

Dependability (%)	50	75	90
Rainfall (mm)	867	667	547

Table 5.13: Rainfall characteristics (Id-16)

Average (mm)	716	Median (mm)	701	
Minimum (mm)	403	Maximum (mm)	1217	
Standard Deviation (mm)	161.4	Coefficient of Variation	0.23	
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
400-500	9	0.076	100%	13
500-600	20	0.169	92%	6
600-700	30	0.254	75%	4
700-800	26	0.220	50%	5
800-900	21	0.178	28%	6
900-1000	6	0.051	10%	20
1000-1100	4	0.034	5%	30
1100-1200	0	0.000	2%	-
1200-1300	2	0.017	2%	59
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 286 mm	-	-
Drought	-60% Avg < -20% Avg	286 mm to 572 mm	17.8%	6
Normal rainfall	±20%Avg	572 mm to 858 mm	61.9%	2
Excess Rainfall	> 20% Avg	> 858 mm	20.3%	5

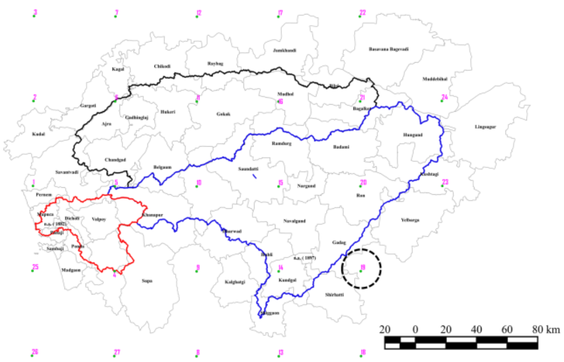


Fig. Location of Gauged Id

Id 19

Coordinates: (75.75°E, 15.25°N)

State: Karnataka

District: Gadag.

Taluks: Gadag.

The average annual rainfall at this grid is about 618 mm, with a COV of 0.22. The lowest rainfall was observed in the year 2016 and the highest in the year 1956. Trend analysis showed decreasing rainfall with time, i.e., about 54 mm in 100 years, accompanied by a decrement in rainy days about two days.

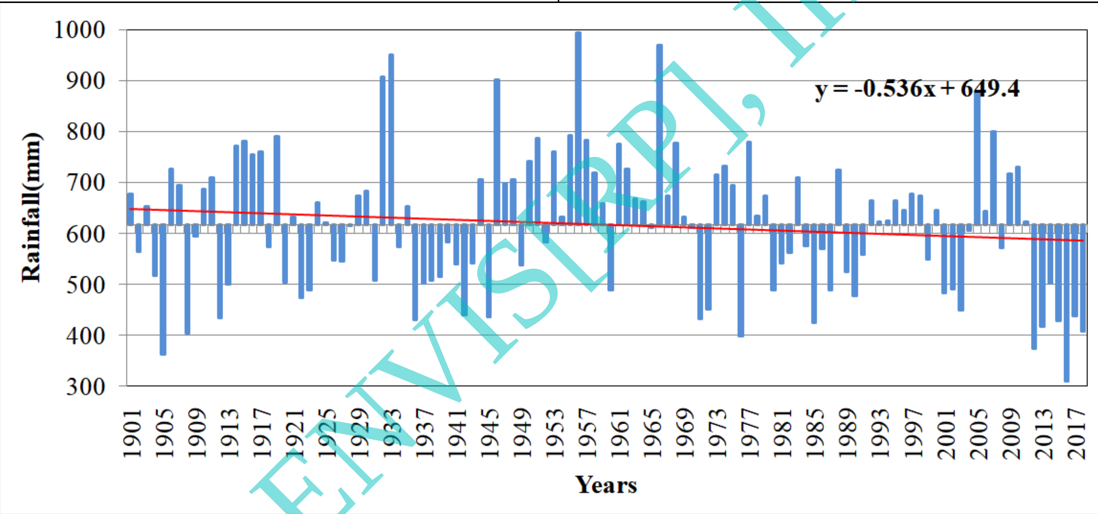


Figure 5.44: Rainfall Trend Analysis (Id-19)

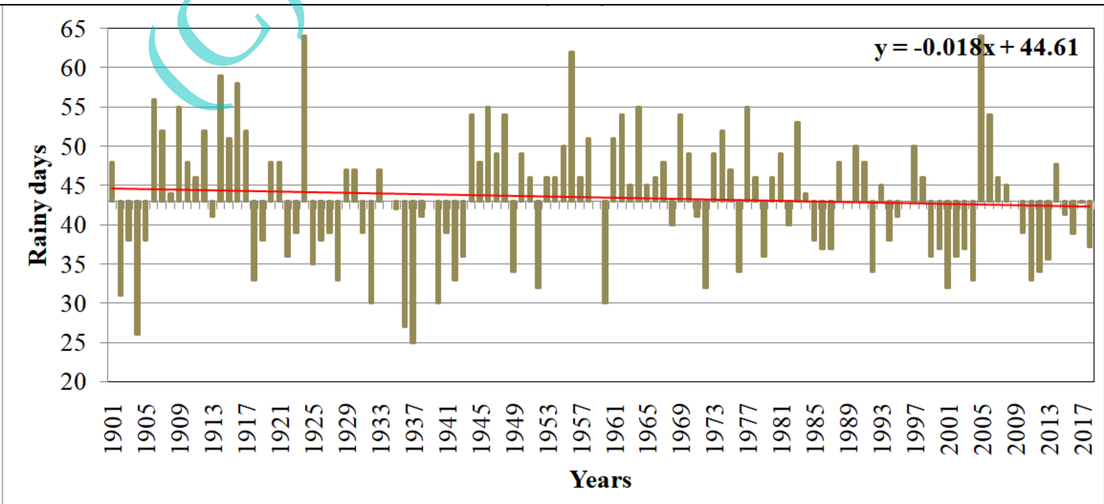


Figure 5.45: Rainy Days Trend Analysis (Id-19)

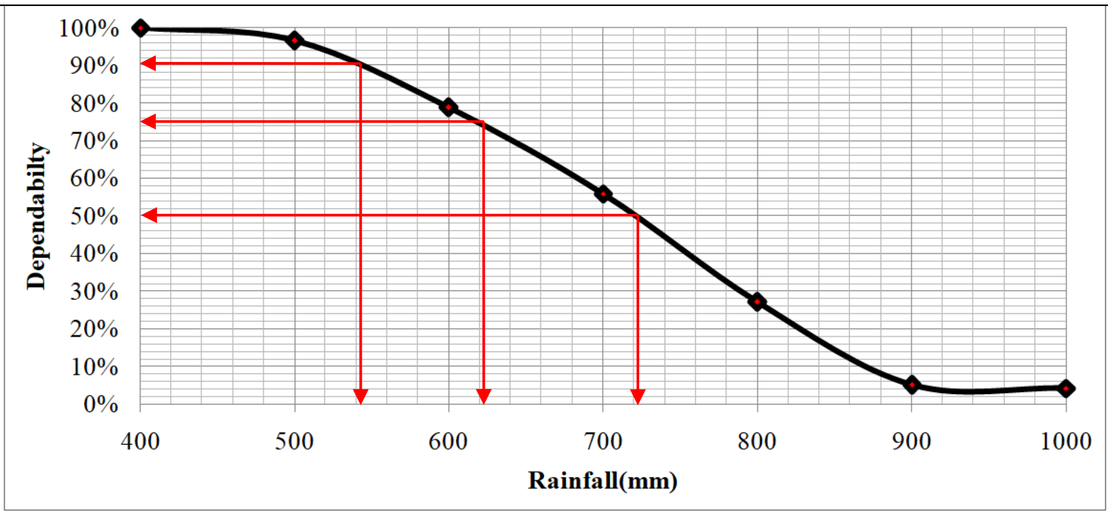


Figure 5.46: Dependability (Id-19)

Dependability (%)	50	75	90
Rainfall (mm)	717	582	502

Table 5.14: Rainfall characteristics (Id-19)

Average (mm)	618	Median (mm)	623
Minimum (mm)	311	Maximum (mm)	994
Standard Deviation (mm)	136.37	Coefficient of Variation	0.22

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<400	4	0.034	100%	30
400-500	21	0.178	97%	6
500-600	27	0.229	79%	4
600-700	34	0.288	56%	3
700-800	26	0.220	27%	5
800-900	1	0.008	5%	118
>900	5	0.042	4%	24

IMD based Classification

IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 247 mm	-	-
Drought	-60% Avg < -20% Avg	247 mm to 494 mm	21.2%	5
Normal rainfall	±20%Avg	494 mm to 741 mm	62.7%	2
Excess Rainfall	> 20% Avg	> 741 mm	16.1%	6

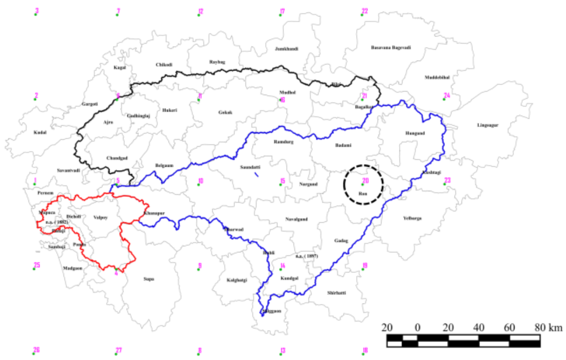


Figure 5.47: Location of Gauged Id-20

Id 20

Coordinates: (75.75°E, 15.75°N)

State: Karnataka.

District: Bagalkot, Gadag, Koppal.

Taluks: Badami, Hunagund, Gadag, Ron, Kushtagi, Yelburga.

The average annual rainfall at this grid is about 547 mm, with a COV of 0.22. The lowest rainfall was observed in the year 1905 and the highest in 1956. The rainfall analysis trend revealed that a very slight increment of about 16 mm was noticed in 100 years, whereas the number of rainy days increased by two days.

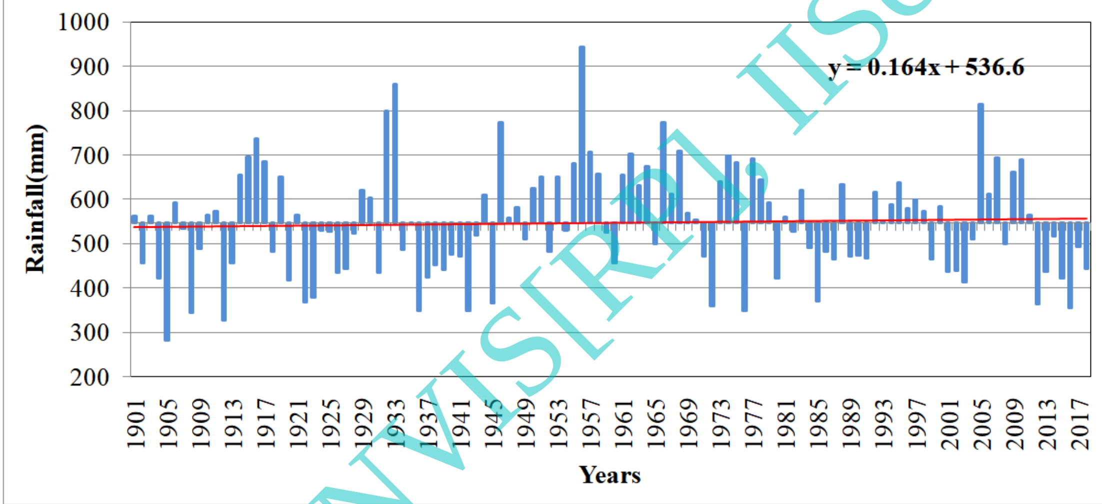


Figure 5.48: Rainfall Trend Analysis (Id-20)

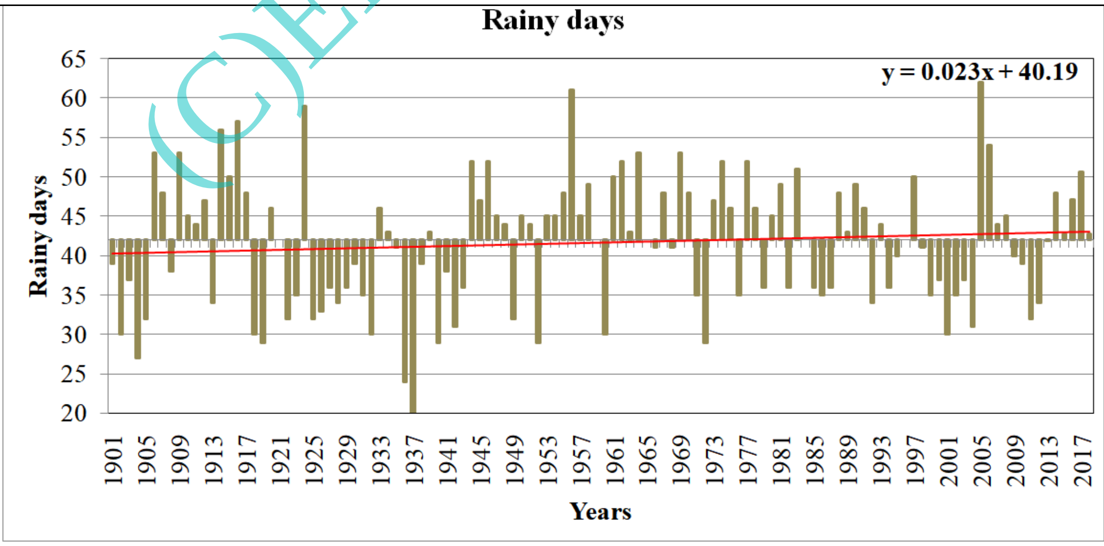


Figure 5.49: Rainy Days Trend Analysis

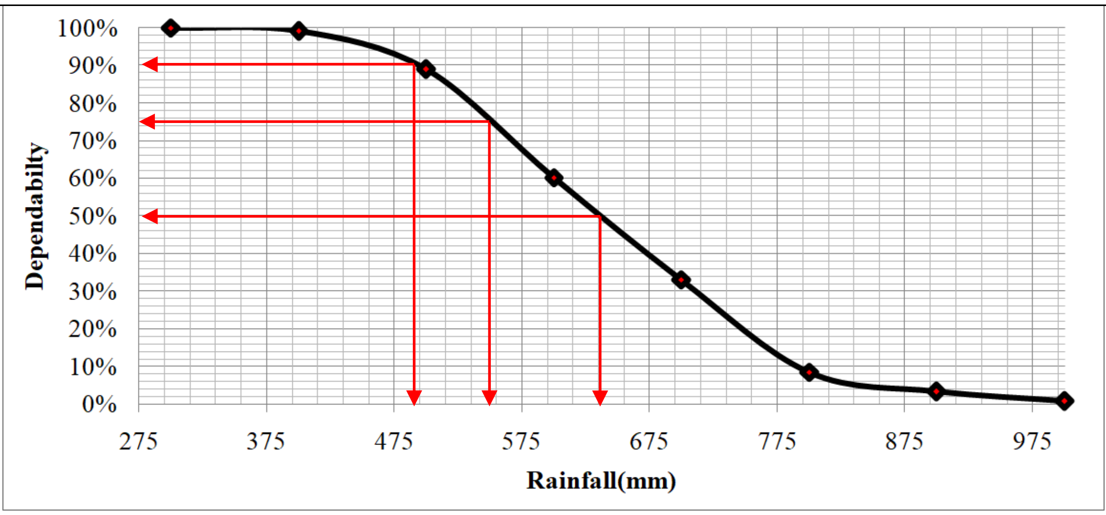


Figure 5.50: Dependability (Id-20)

Dependability (%)	50	75	90
Rainfall(mm)	633	528	465

Table 5.15: Rainfall characteristics (Id-20)

Average (mm)	547	Median (mm)	540	
Minimum (mm)	283	Maximum (mm)	943	
Standard Deviation (mm)	122.86	Coefficient of Variation	0.22	
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<300	1	0.008	100%	118
300-400	12	0.102	99%	10
400-500	34	0.288	89%	3
500-600	32	0.271	60%	4
600-700	29	0.246	33%	4
700-800	6	0.051	8%	20
800-900	3	0.025	3%	39
>900	1	0.008	1%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 219 mm	-	-
Drought	-60% Avg < -20% Avg	219 mm to 437 mm	18.6%	5
Normal rainfall	±20%Avg	437 mm to 656 mm	62.7%	2
Excess Rainfall	> 20% Avg	> 656 mm	18.6%	5

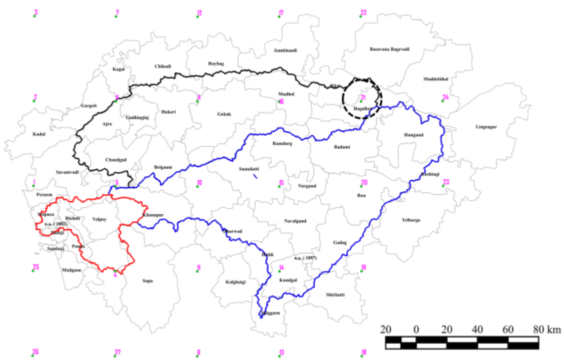


Fig. Location of Gauged Id

Id 21

Coordinates: (75.75°E, 16.25°N)

State: Karnataka

District: Bagalkot, Bijapur

Taluks: Badami, Bagalkot, Bilagi, Hunagund, Basavana Bagewadi, Muddebihal

The average annual rainfall at this grid is about 605 mm, with a COV of 0.26. The lowest rainfall was observed in the year 1905 and highest in the year 1964. Rainfall analysis showed an increasing trend of about 154 mm in 100 years and an increase in rainy days, about four days.

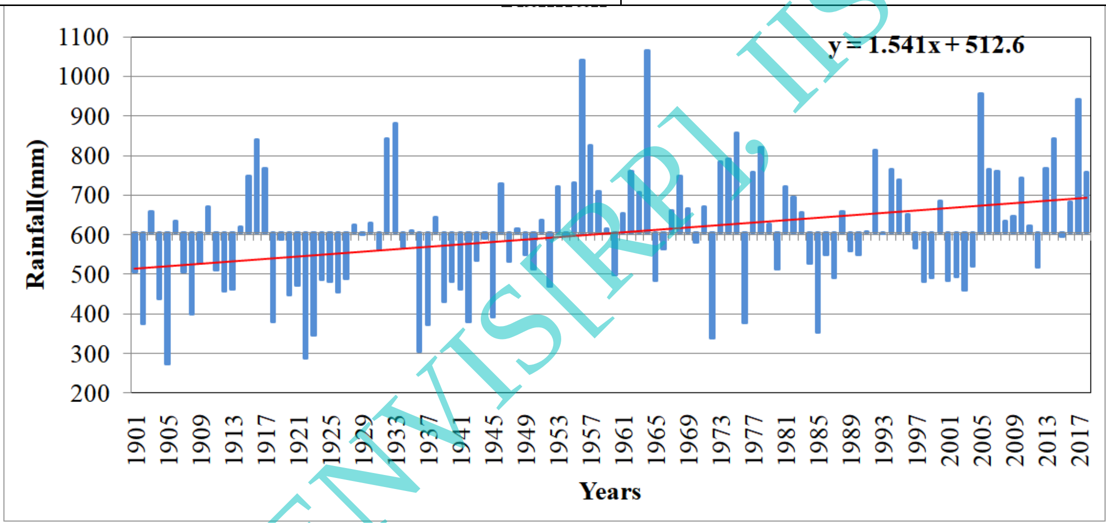


Figure 5.51: Rainfall Trend Analysis (Id-21)

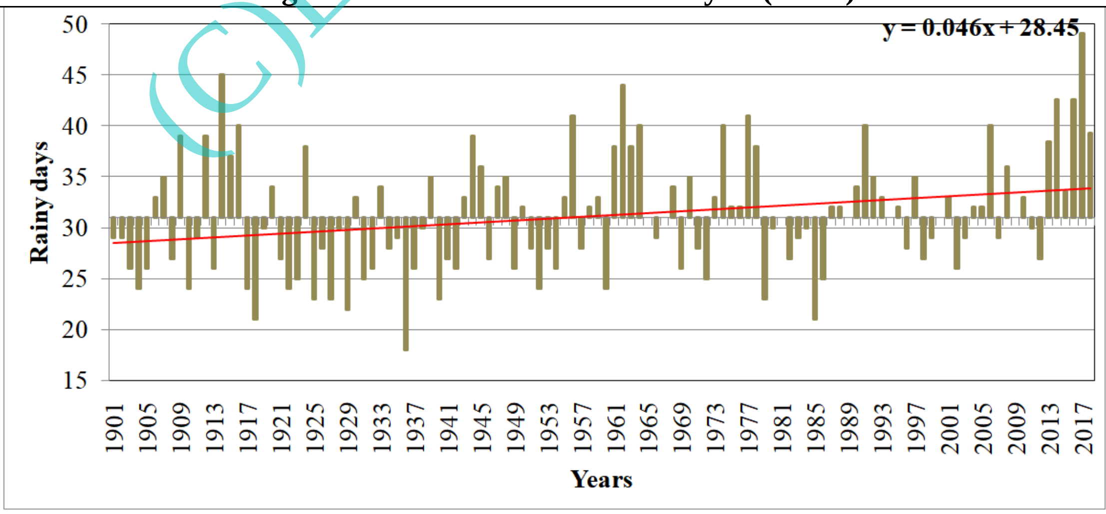


Figure 5.52: Rainy Days Trend Analysis (Id-21)

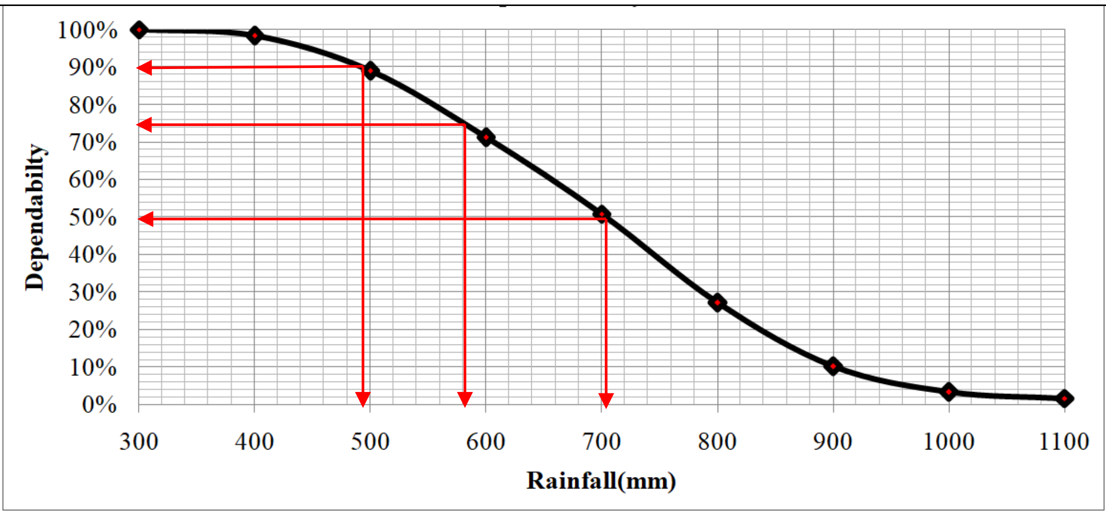


Figure 5.53: Dependability (Id-21)

Dependability (%)	50	75	90
Rainfall (mm)	700	535	435

Table 5.16: Rainfall characteristics (Id-21)

Average (mm)	605	Median (mm)	602
Minimum (mm)	275	Maximum (mm)	1066
Standard Deviation (mm)	157.12	Coefficient of Variation	0.26

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<300	2	0.017	100%	59
300-400	11	0.093	98%	11
400-500	21	0.178	89%	6
500-600	24	0.203	71%	5
600-700	28	0.237	51%	4
700-800	20	0.169	27%	6
800-900	8	0.068	10%	15
900-1000	2	0.017	3%	59
>1000	2	0.017	2%	59
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 242 mm	-	-
Drought	-60% Avg < -20% Avg	242 mm to 484 mm	22.0%	5
Normal rainfall	±20%Avg	484 mm to 725 mm	54.2%	2
Excess Rainfall	> 20% Avg	> 725 mm	23.7%	4

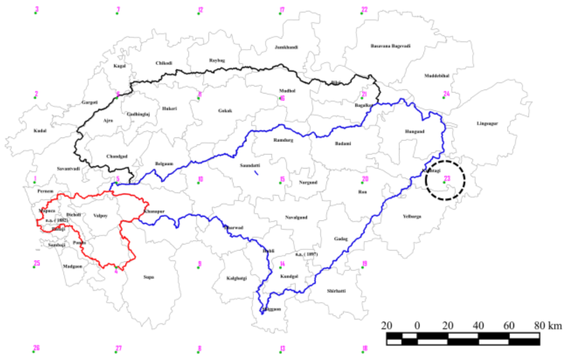


Figure 5.54: Location of Gauged Id-23

Id 23

Coordinates: (76.25°E, 15.75°N)

State: Karnataka

District: Bagalkot, Koppal

Taluks: Hunagund, Kushtagi

The average annual rainfall at this grid is about 499 mm, with a COV of 0.25. The lowest rainfall was observed in the year 1922 and the highest in the year 1956. Trend analysis showed an increase in precipitation with time, i.e., about 45 mm in 100 years, whereas the number of rainy days increased by half fold

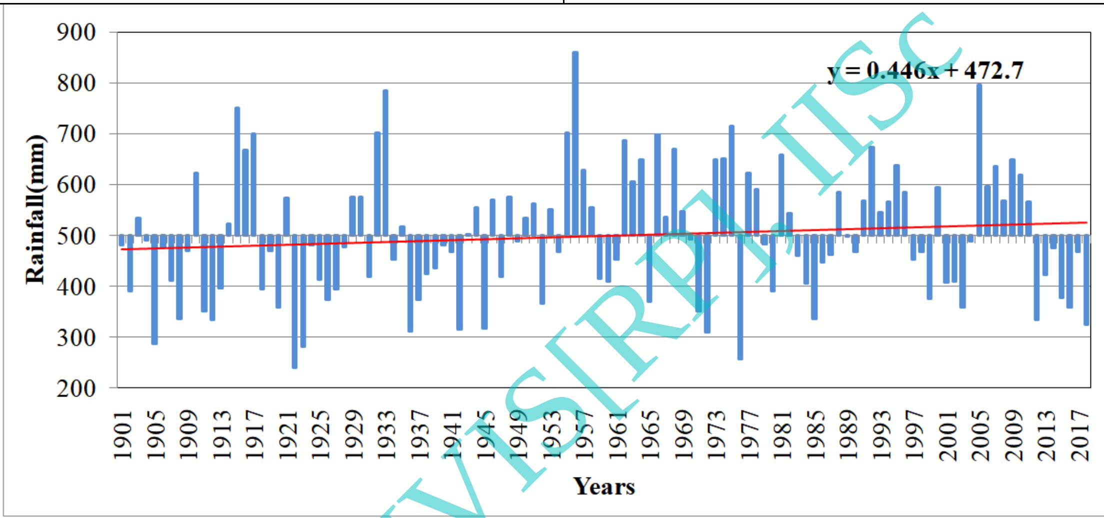


Figure 5.55: Rainy Days Trend Analysis (Id-23)

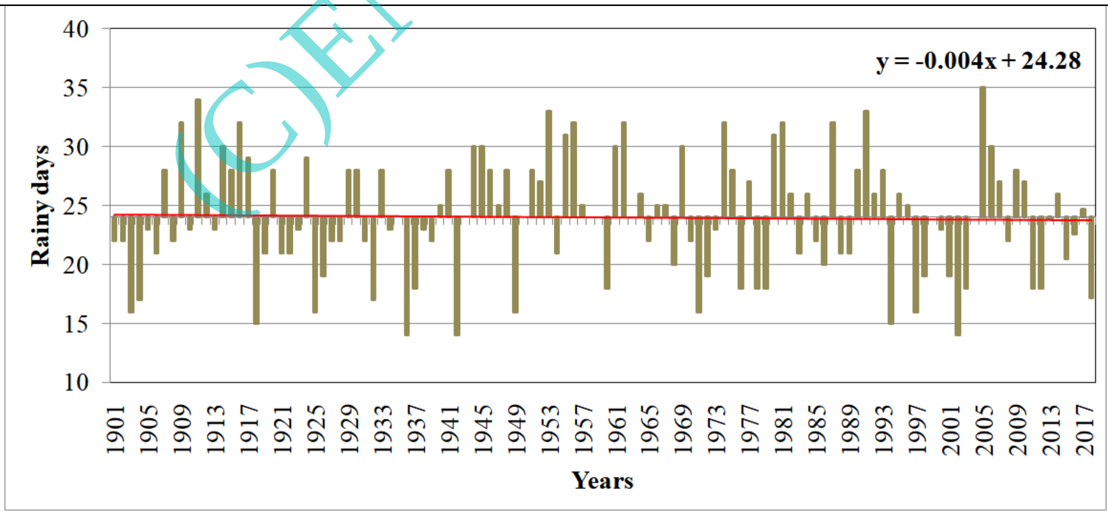


Figure 5.56: Rainy Days Trend Analysis (Id-23)

Figure 5.57: Dependability (Id-23)

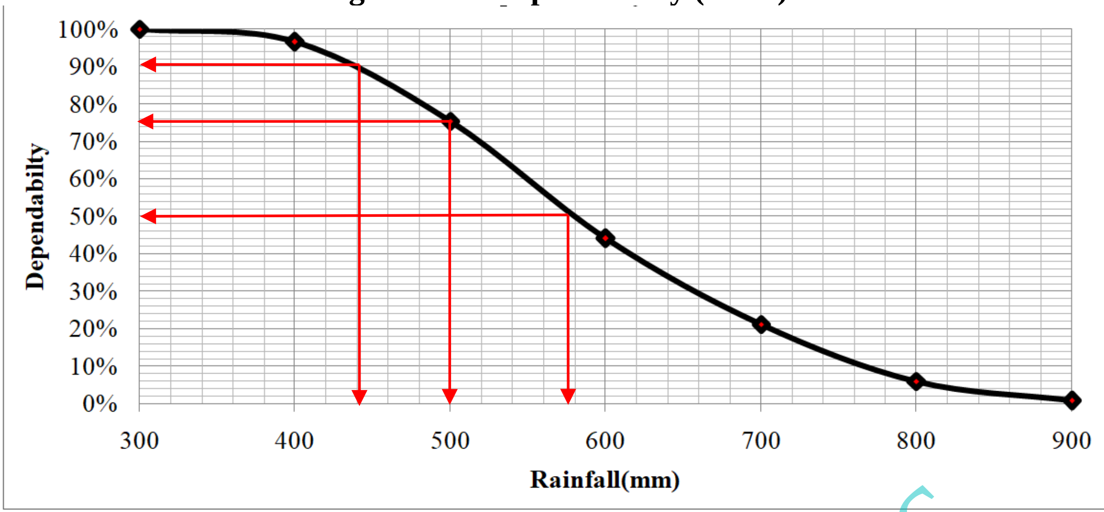


Figure 5.58: Dependability (Id-23)

Dependability (%)	50	75	90
Rainfall (mm)	582	465	392

Table 5.17: Rainfall characteristics (Id-23)

Average (mm)	499	Median (mm)	481
Minimum (mm)	241	Maximum (mm)	860
Standard Deviation (mm)	126.76	Coefficient of Variation	0.25

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<300	4	0.034	100%	30
300-400	25	0.212	97%	5
400-500	37	0.314	75%	3
500-600	27	0.229	44%	4
600-700	18	0.153	21%	7
800-900	6	0.051	6%	20
>900	1	0.008	1%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 200 mm	-	-
Drought	-60% Avg < -20% Avg	200 mm to 400 mm	24.6%	4
Normal rainfall	±20%Avg	400 mm to 600 mm	54.2%	2
Excess Rainfall	> 20% Avg	> 600 mm	21.2%	5

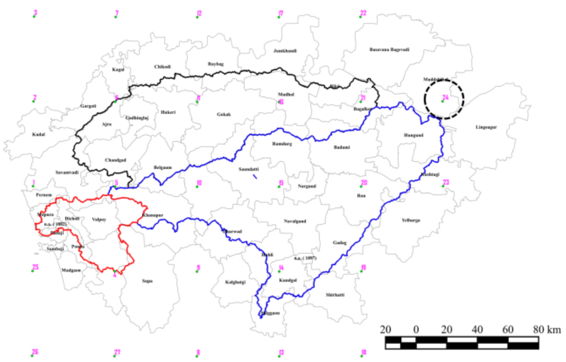


Figure 5.59: Location of Gauged Id-24

Id 24

Coordinates: (76.25°E, 16.25°N)

State: Karnataka

District: Bagalkot, Bijapur

Taluks: Hunagund, Muddebihal

The average annual rainfall at this grid is about 587 mm, with a COV of 0.25. The lowest rainfall was observed in the year 1922 and the highest in the year 1964. Trend analysis showed increasing rainfall with time, i.e., about 150 mm in 100 years, accompanied by an increase in rainy days to half fold.

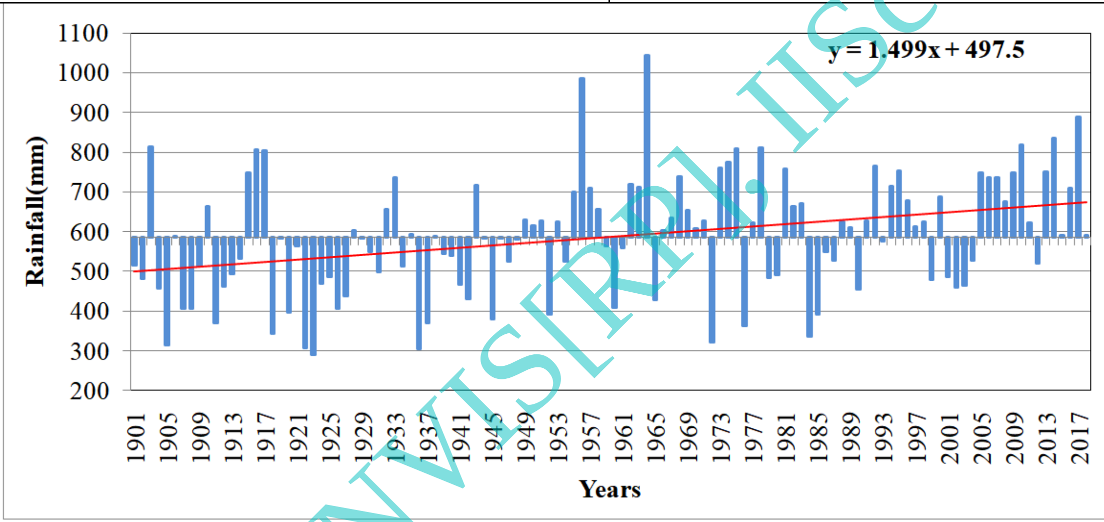


Figure 5.60: Rainfall Trend Analysis (Id-24)

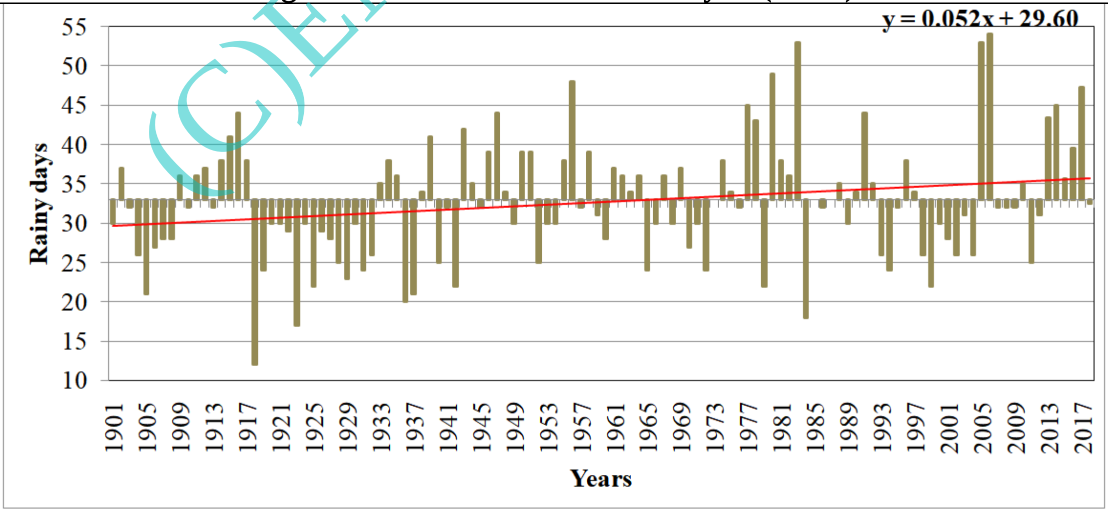


Figure 5.61: Rainy Days Trend Analysis (Id-24)

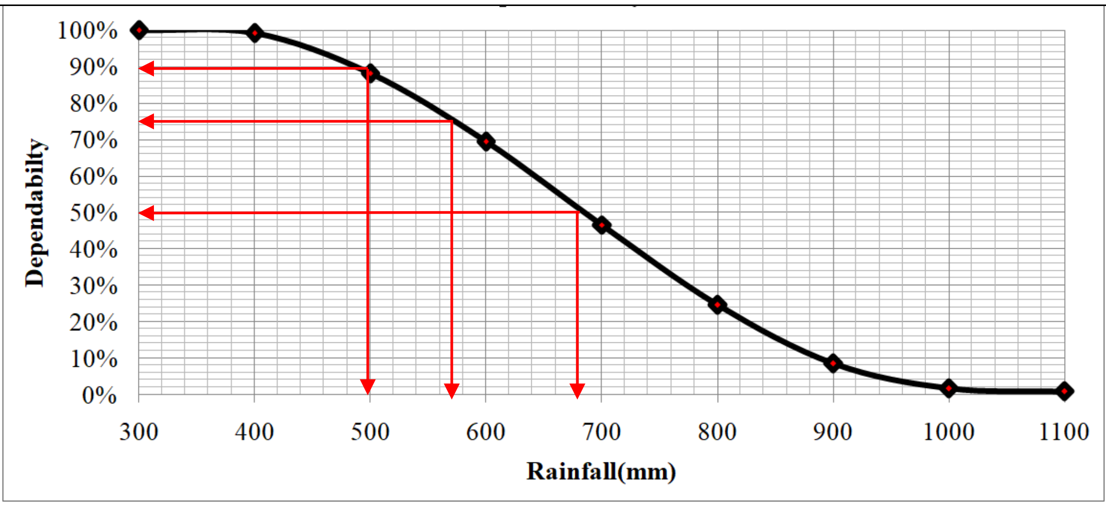


Figure 5.62: Dependability (Id-24)

Dependability(%)	50	75	90
Rainfall (mm)	725	540	430

Table 5.18: Rainfall characteristics (Id-24)

Average (mm)	587	Median (mm)		588
Minimum (mm)	290	Maximum (mm)		1043
Standard Deviation (mm)	149	Coefficient of Variation		0.25
Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<300	1	1%	100%	118
300-400	13	11%	99%	9
400-500	22	19%	88%	5
500-600	27	23%	69%	4
600-700	26	22%	47%	5
800-900	19	16%	25%	6
900-1000	8	7%	8%	15
>1000	1	1%	2%	118
IMD based Classification				
IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 235 mm	-	-
Drought	-60% Avg < -20% Avg	235 mm to 470mm	23.7%	4
Normal rainfall	±20%Avg	470 mm to 704 mm	51.7%	2
Excess Rainfall	> 20% Avg	> 705 mm	24.6%	4

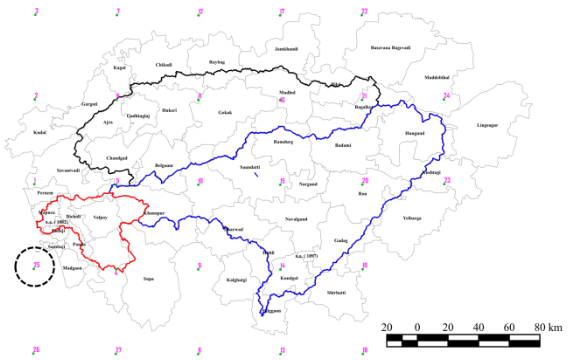


Figure 5.63: Location of Gauged Id-25

Id 25

Coordinates: (73.75°E, 15.25°N)

State: Goa

District: North Goa

Taluks: Bardez, Tiswadi, Ponda

The average annual rainfall at this grid is about 2258 mm, with a COV of 0.18. The lowest rainfall was observed in the year 1941 and highest in 1961. Trend analysis showed increasing rainfall with time, i.e., about 297 mm in 100 years, whereas the number of rainy days decreased about 1.5 days in this period

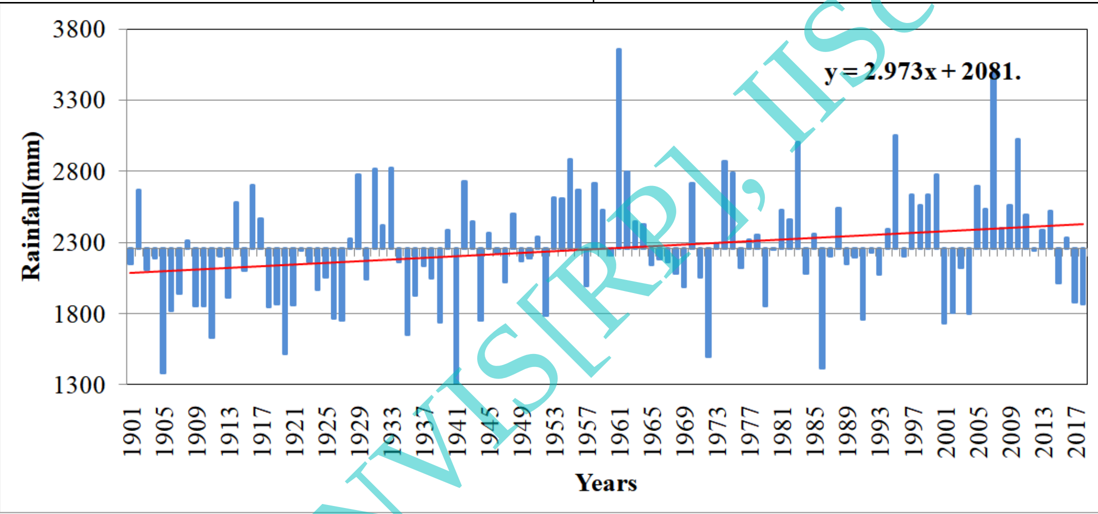


Figure 5.64: Rainfall Trend Analysis (Id-25)

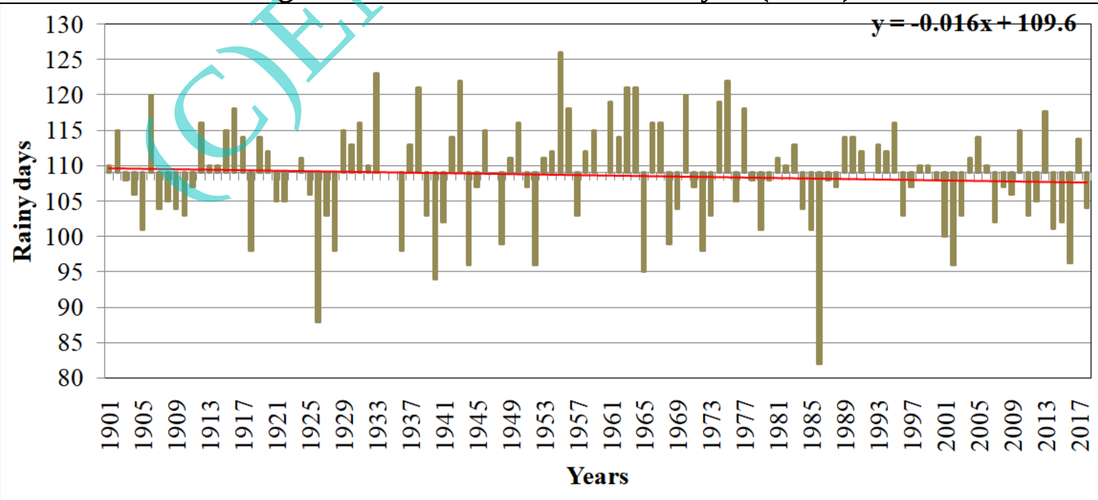


Figure 5.65: Rainy Days Trend Analysis (Id-25)

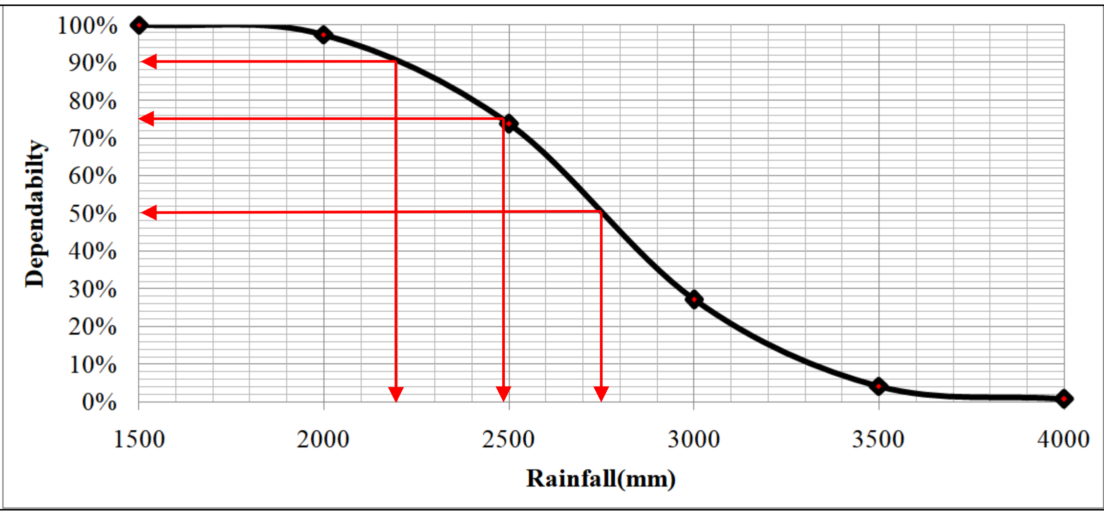


Figure 5.66: Dependability (Id-25)

Dependability (%)	50	75	90
Rainfall (mm)	2756	2240	1929

Table 5.19: Rainfall characteristics (Id-25)

Average (mm)	2258	Median (mm)	2207
Minimum (mm)	1311	Maximum (mm)	3655
Standard Deviation (mm)	410.87	Coefficient of Variation	0.18

Rainfall	Frequency	Probability of Occurrence	Dependability	Return Period
<1500	3	0.025	100%	39
1500-2000	28	0.237	97%	4
2000-2500	55	0.466	74%	2
2500-3000	27	0.229	27%	4
3000-3500	4	0.034	4%	30
>3500	1	0.008	1%	118

IMD based Classification

IMD Classification	Condition	Range	Probability of Occurrence	Return Period
Severe Drought	< -60% Avg	< 903mm	-	-
Drought	-60% Avg < -20% Avg	903 mm to 1806 mm	13%	8
Normal rainfall	±20%Avg	1806 mm to 2709 mm	74%	1
Excess Rainfall	> 20% Avg	> 2709 mm	14%	7

5.2 Landscape dynamics of Ghataprabha catchment

Spatial and temporal land-use changes in Ghataprabha catchment were analyzed for 1972 and 2018 using remote sensing data obtained from Landsat 1 and Landsat 8 [52]. Results of land use dynamics are depicted in Figure 5.67, and land use details are listed in Table 5.20

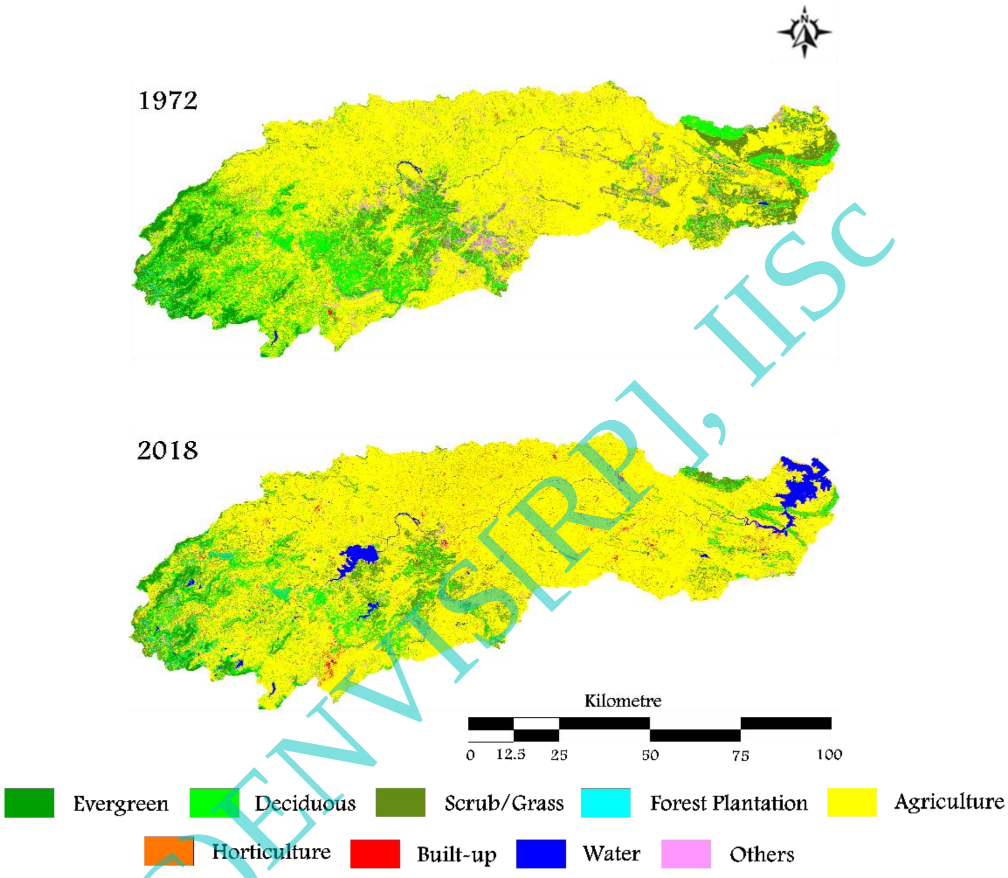


Figure 5.67: Landscape dynamics of Ghataprabha catchment

Temporal analysis of data reveals about a 40 % decline in forest cover, including evergreen forest, deciduous forest, scrub forest, and grasslands. The major regions of Ajra and Chandagad of Kholapur district (KSNU018 and KSNU019), which are part of Western Ghats, have undergone serious changes from 1972 to 2018 conversion of native forest to plantations and agriculture activities. Similarly, the regions of Belgaum district have transformed deciduous forest to agriculture and horticulture activities. The catchment is dominated by agriculture, about 76.28% (2018).

On the other side, water bodies in the catchment have increased from 0.26% to 2.61%. Damming activities in the catchment are the main reasons for the increase in the water bodies. Construction of major dams such as Hidkal reservoir (i.e., Ghataprabha dam), Shirur dam, Rakashop dam, Jangamhatti dam, etc., have changed the catchment landscapes.

The sub-catchments of Belgaum taluk (KSNU027), Mudhol taluk (KSNU031), and Bagalkot taluk (KSNU032) have undergone large-scale changes in built-up activities in the catchment from 0.02 %(1972) to 1.04 %(2018). Open spaces in the regions of Gokak and Mudhol taluks have changed to croplands from 1972 to 2018.

The overall catchment assessment reveals the dominance of forest in the Ghats regions and agriculture and horticulture activities on plain lands and valleys

Table 5.20: Land use analysis of Ghataprabha catchment (1972-2018)

Sl.no.	Land use	1972		2018	
		Area (sq.km)	Area (%)	Area (sq.km)	Area (%)
1	Evergreen forest	296.47	3.38	185.07	2.11
2	Deciduous forest	1199.91	13.68	621.00	7.08
3	Scrub forest/Grasslands	820.11	9.35	596.44	6.8
4	Forest Plantations	20.17	0.23	90.34	1.03
5	Agriculture	5997.77	68.37	6690.70	76.28
6	Horticulture	92.98	1.06	150.87	1.72
7	Built up	1.75	0.02	91.22	1.04
8	Water	22.81	0.26	228.93	2.61
9	Others	319.27	3.64	118.41	1.35

5.3 Eco-hydrological assessment of Ghataprabha Catchment from 1972-2018

Hydrological parameters such as rainfall, runoff, interception, infiltration, ground water recharge, base flow, pipe flow etc., are quantified in the catchment monthly, as explained in detail below.

Gross rainfall was calculated based on catchment area and rainfall. The catchment mainly receives rainfall from May to October. The monthly variations in the rainfall is as shown in Figure 5.69, reveal that the forested regions of catchment especially KSNU018, KSNU019 sub-catchments receive heavy rainfall, i.e., in the Ghats contributing to higher rainfall volume in the sub-basin in July varying from1000 $Mm^3$to 1500 Mm^3.

The intercepted rainfall, i.e., the portion of rainfall which doesn't reach the earth's surface is contributing to about 15- 30% based on the literature studies [10], [41], [44], which is considered for the hydrological assessment. The monthly interception variations in the catchment are as shown in Figure 5.71, which reveals that the regions with high forest cover especially KSNU018, KSNU019 have high interception rates. KSNU019 has higher interception rates varying from 13.62 Mm^3(May) to 138.26 Mm^3(July). The remaining basins KSNU031, KSNU032, etc., with the minimal forest cover, have interception rates up to 12.5 Mm^3. The overall assessment of interception analysis indicates that the interception volume has decreased about 40 % from 1157.94 Mm^3(1972) to 676.85 Mm^3(2018), due to changes in the landscape activities driven by anthropogenic activities.

The monthly runoff variations are depicted in the Figure 5.72 which explains that the regions with higher forest cover have less runoff over plain lands. The runoff variations from 1972 to 2018 show that there is about 80% increment in the overland flows (surface runoff) in the monsoons from 2500.87Mm^3 (1972) to 4542.77Mm^3(2018) in this region. The landscape changes are the major drivers for the increment in these overland flows. This percentage change reveals that the recharging of the soil has decreased drastically, leading to lesser infiltration rates, ground water resources.

Ground water recharge accounts for about 2430Mm^3 in the year 2018 Table 5.22. Water is stored in the vadose zone or the sub-surface zone moves laterally in the post-monsoons with the cessation of rain. The vadose water has decreased by 26.4%, from 2125.48 Mm^3 to 1564.55 Mm^{3,} because of landscape changes involving the decline of forest cover from 1972 to 2018.

Evapotranspiration in the catchment depends on the land-use characteristics, extra-terrestrial solar radiation, variations in temperature, precipitation, etc. As shown in Figure 5.68, potential evapotranspiration varies from 88 mm/month to 170 mm/month from non-monsoons to monsoons.

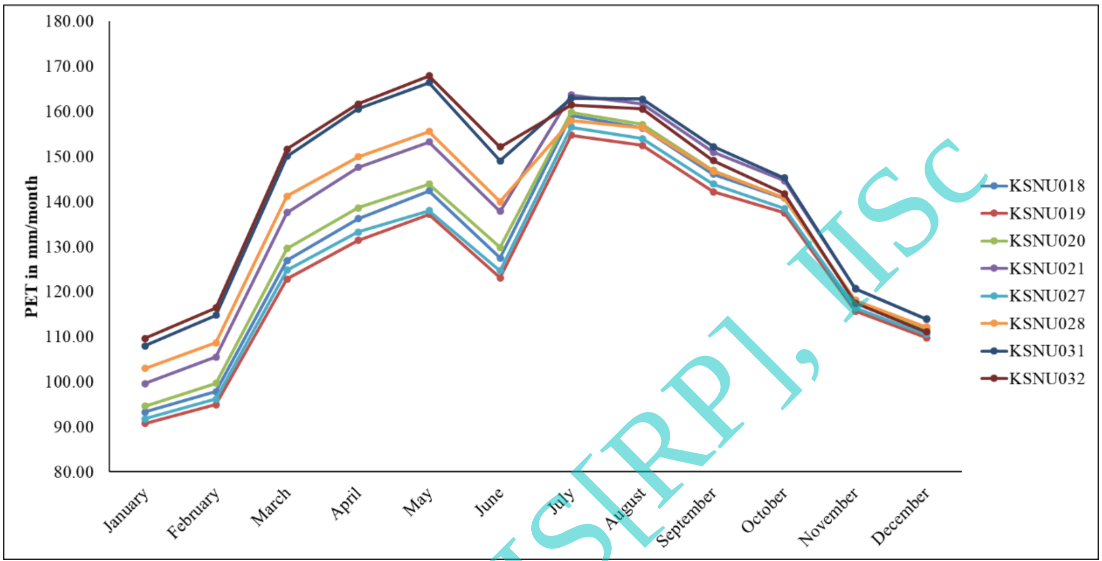


Figure 5.68: Potential evapotranspiration

Based on the various land use categories, the actual evapotranspiration is calculated. Net evaporation was calculated as the difference between actual evapotranspiration and interception, emphasizing that the intercepted water accounts for evaporation during monsoon. Similarly, the evaporation from the crops, i.e., agriculture and horticulture, are considered under the crop water demands based on the different phases of the growth. Actual evapotranspiration accounts for about 1300 Mm^3 (1972) and 731 Mm^3 (2018), as shown in Table 5.21 and Table 5.22. The large-scale destruction of forest regions has decreased the evaporation rates.

Agriculture demand or the crop water requirement was calculated based on the crops grown in the catchment considering its crop pattern, the area under each crop, water requirement for various growth phases, which were collated as explained in method section. Monthly variations in the agriculture water requirement reveal that the basins Gokak (KSNU021), Mudhol (KSNU031), Bagalkot (KSNU032) regions, where the catchment is dominated by agriculture, require a higher quantum of water. The area under agriculture has increased from 1972 to 2018 by 11.56%, with increase in the water requirement for agriculture by 14.83% from 4433.75 Mm^3 (1972) to 5091.57 Mm^3 (2018) as shown in the Table 5.21 and Table 5.22.

Domestic water requirement was calculated based on the population in catchment interpolated for the basins from the taluks data obtained from the census of India for the years 2001 and 2011, projected geometrically to 2018. The domestic water requirement has increased from 98.23 Mm^3 (1972) to 142.76 Mm^3 (2018), about 45.33 %, as shown in Table 5.21 and Table 5.22. In the catchment, especially in the regions of Belgaum, Mudhol, Gokak, and Bagalkot.

The Tenant method was adopted in the current study [10] to determine the ecological requirement. It accounts for about 20-30% of the mean annual runoff. Similarly, the National green tribunal states that about 15-20% must be maintained for the ecological sustenance based on the locality and region-specific. The ecological water requirement of the region is about 92.2 Mm^3 (2018), as shown in Table 5.22. The eco-hydrological footprint is computed considering all hydrologic parameters is explained in the next section 5.4.

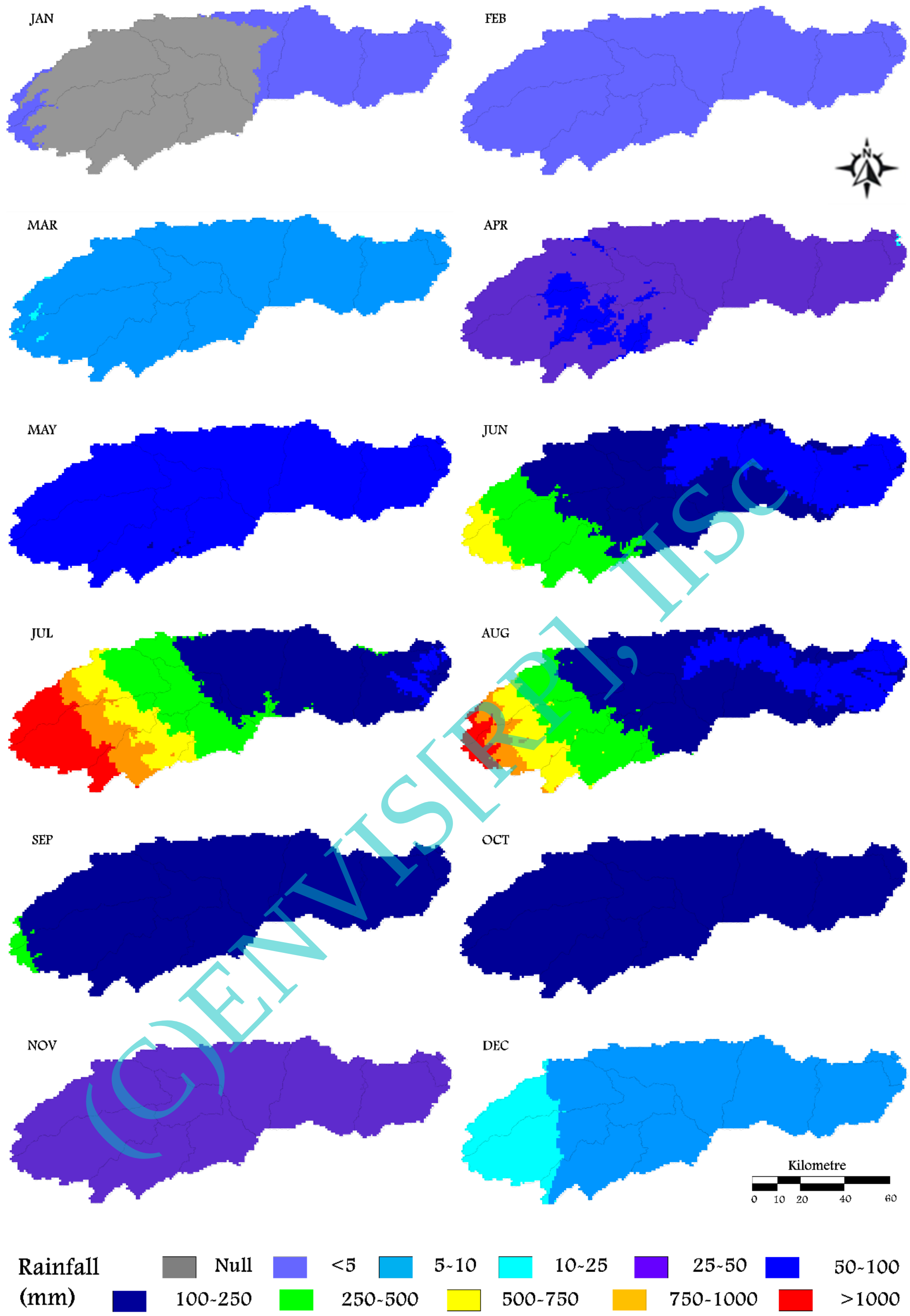


Figure 5.69: Monthly rainfall variations in Ghataprabha catchment

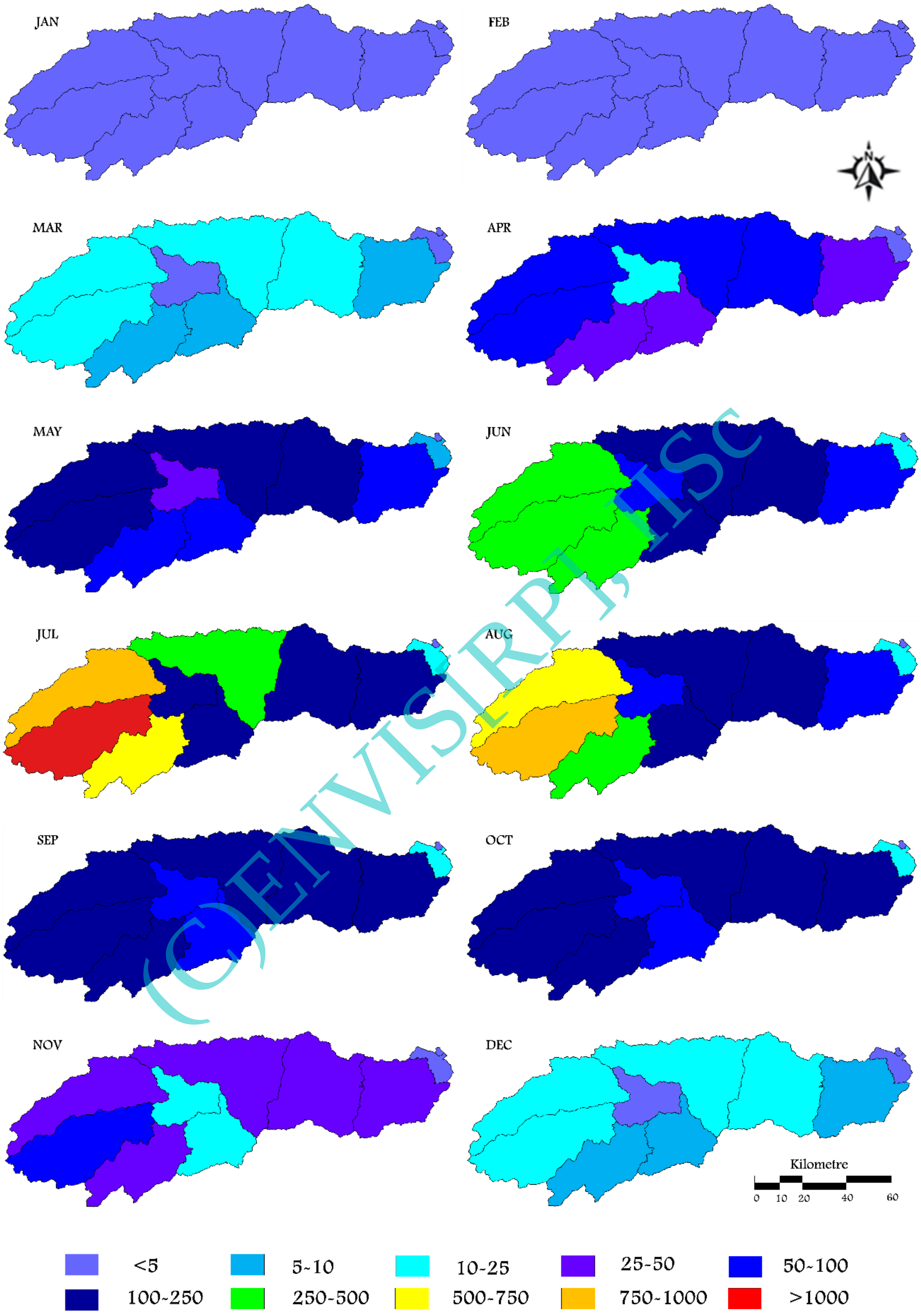


Figure 5.70: Gross Rainfall (in Mm^3)-Ghataprabha catchment

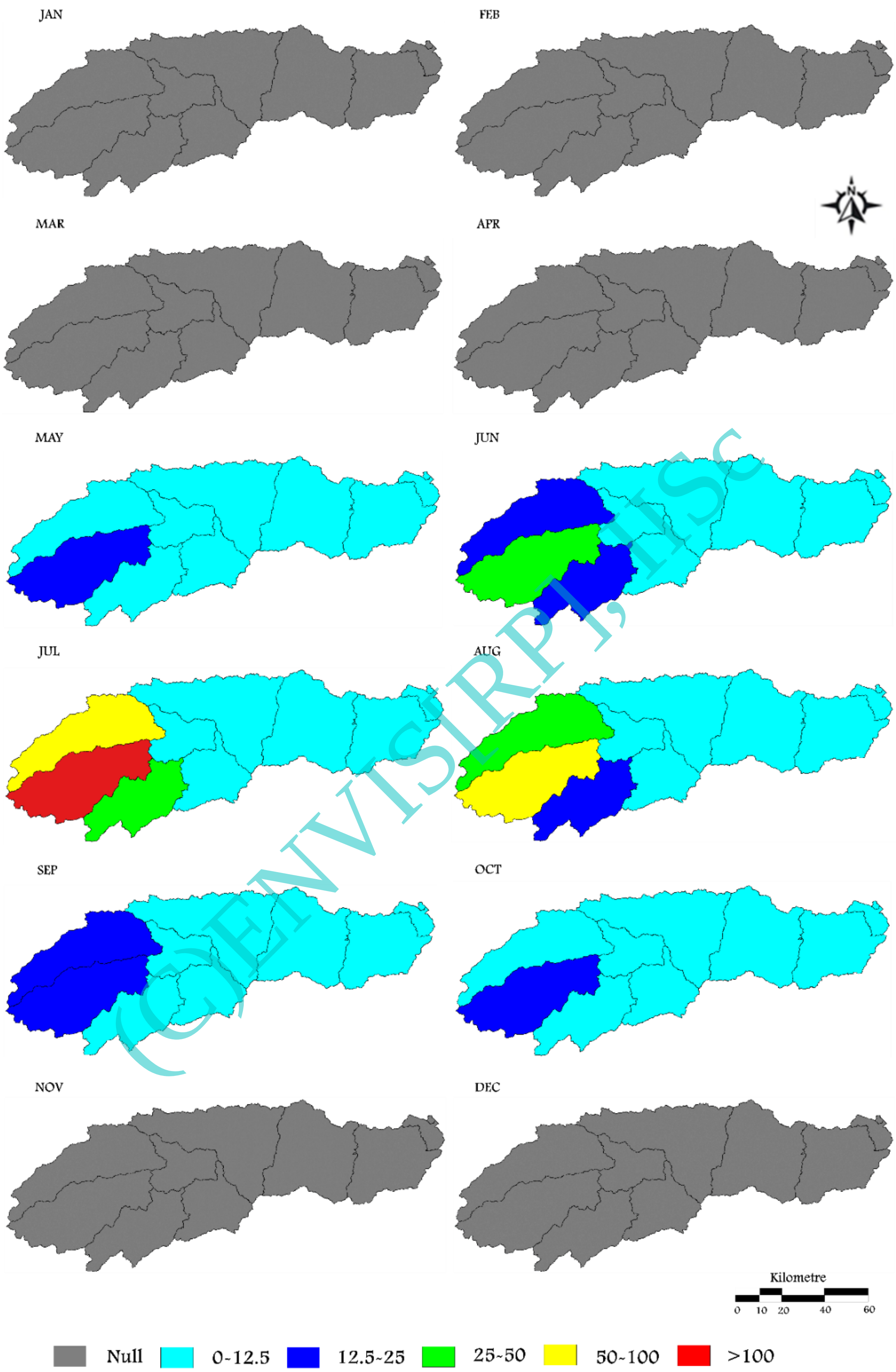


Figure 5.71: Interception (in Mm^3)-Ghataprabha catchment

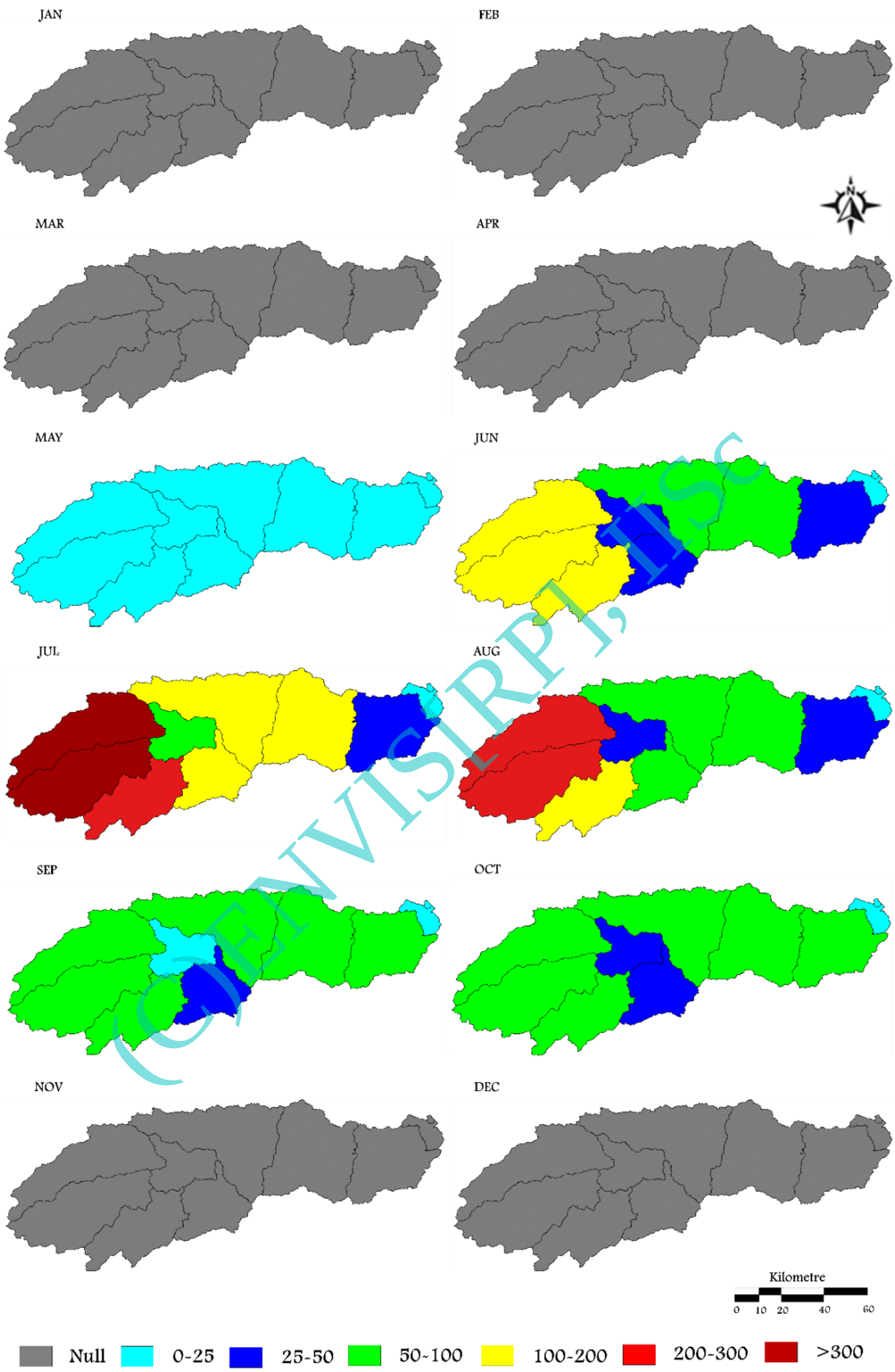


Figure 5.72: Runoff (in Mm^3)-Ghataprabha catchment

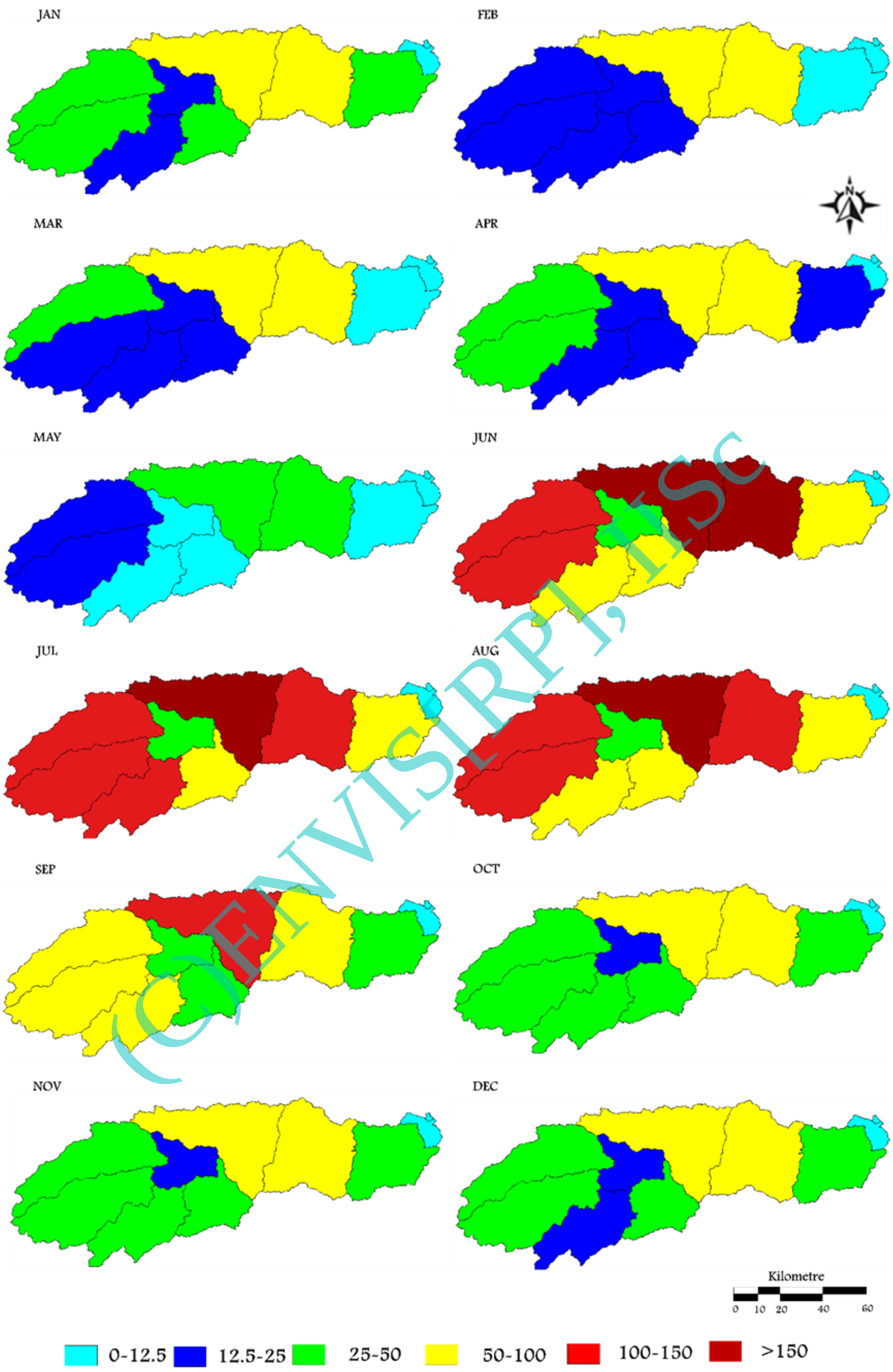


Figure 5.73: Crop water demand (in Mm^3) - Ghataprabha catchment

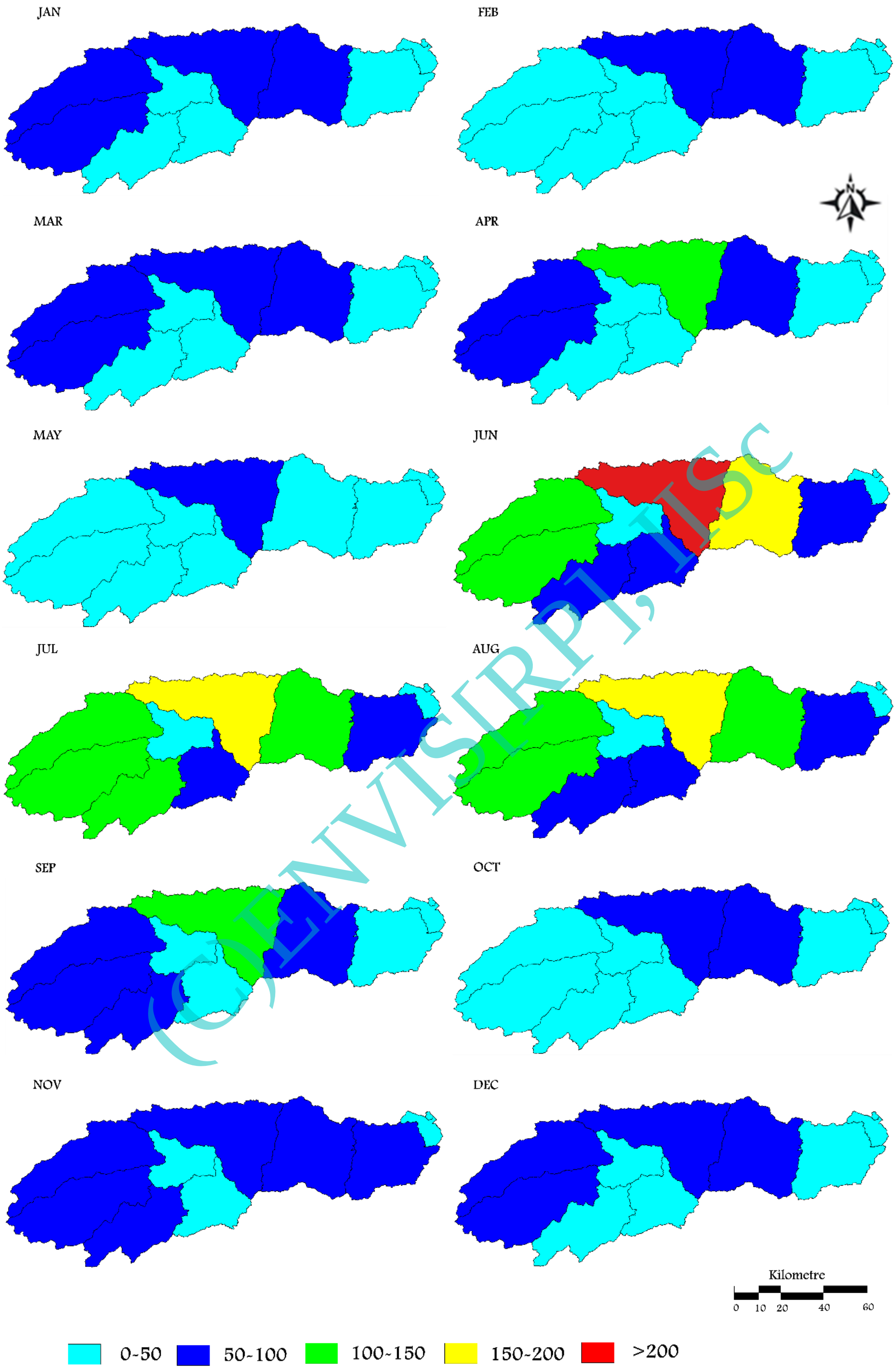


Figure 5.74: Total demand (in Mm^3)-Ghataprabha catchment

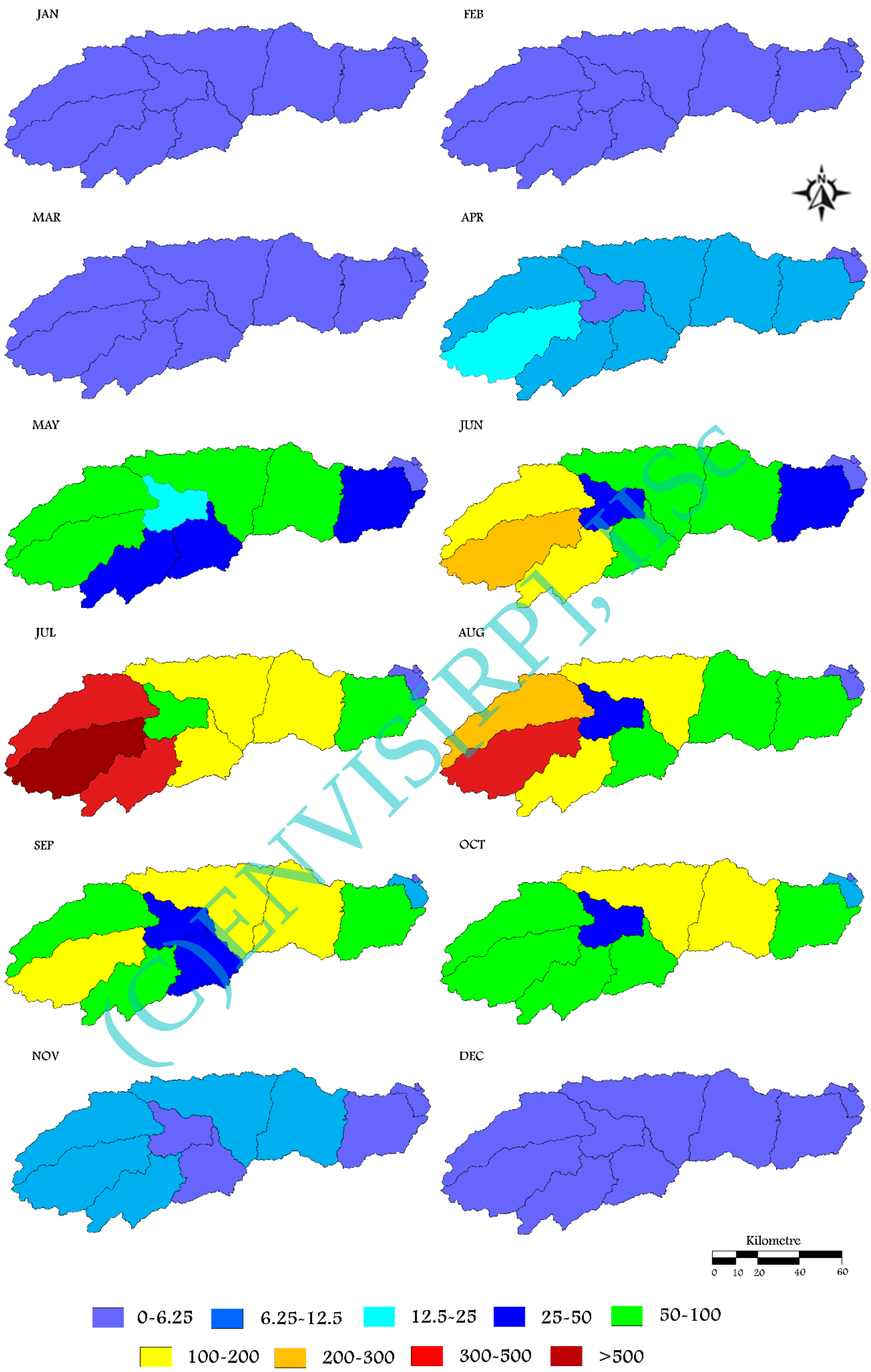


Figure 5.75: Water available (in Mm^3)- Ghataprabha catchment

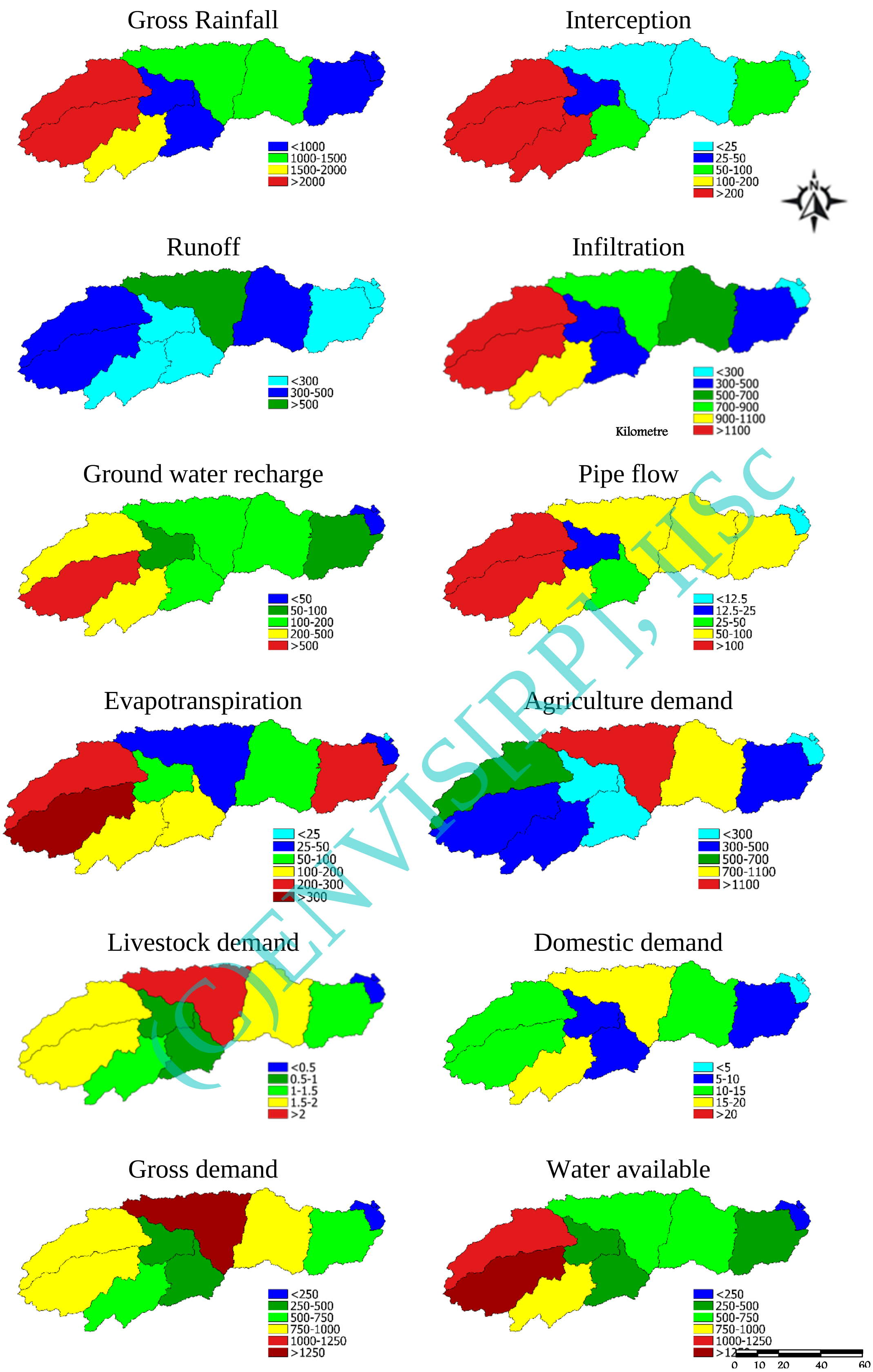


Table 5.21: Eco-hydrological assessment in Ghataprabha catchment (in Mm^3)-1972

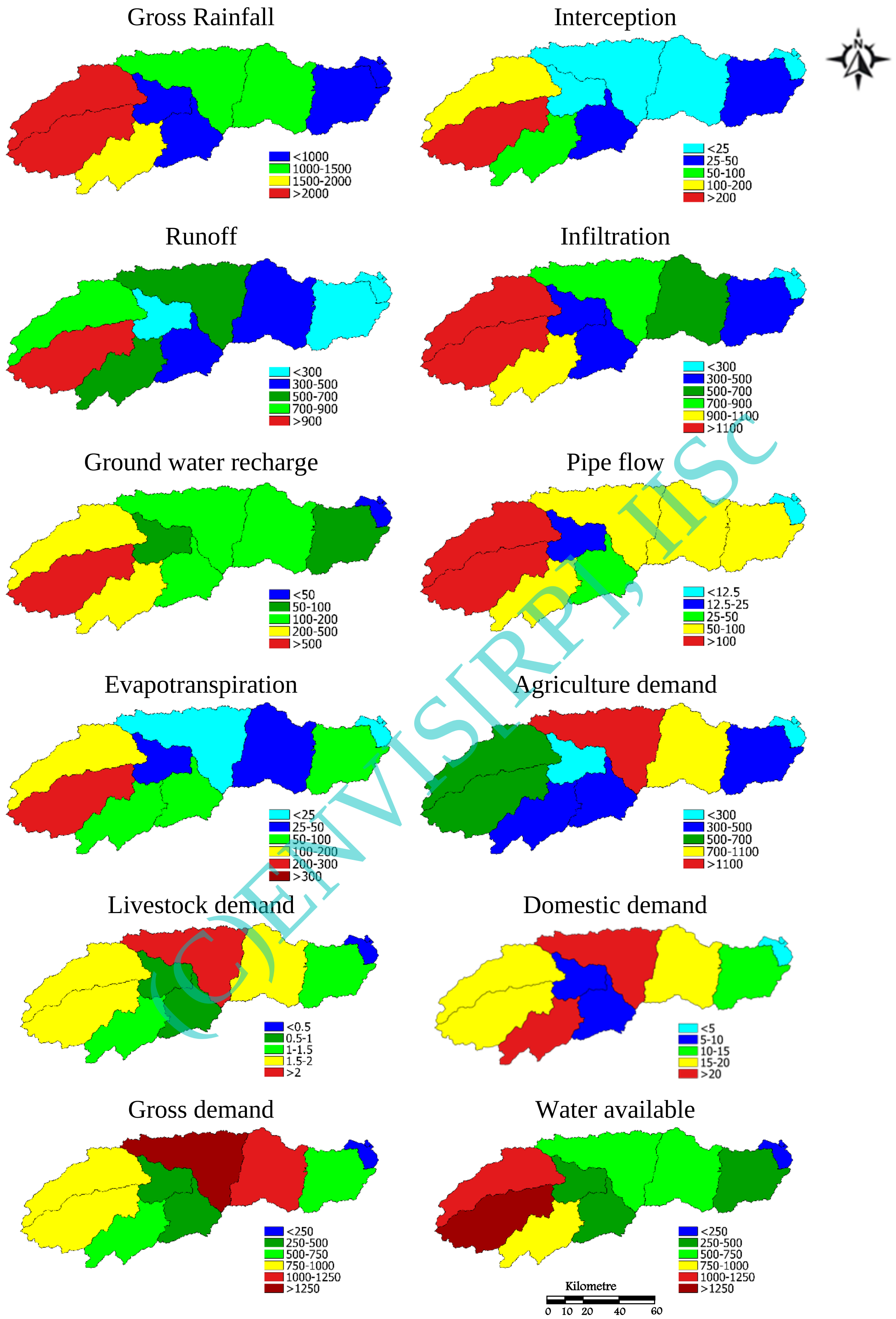
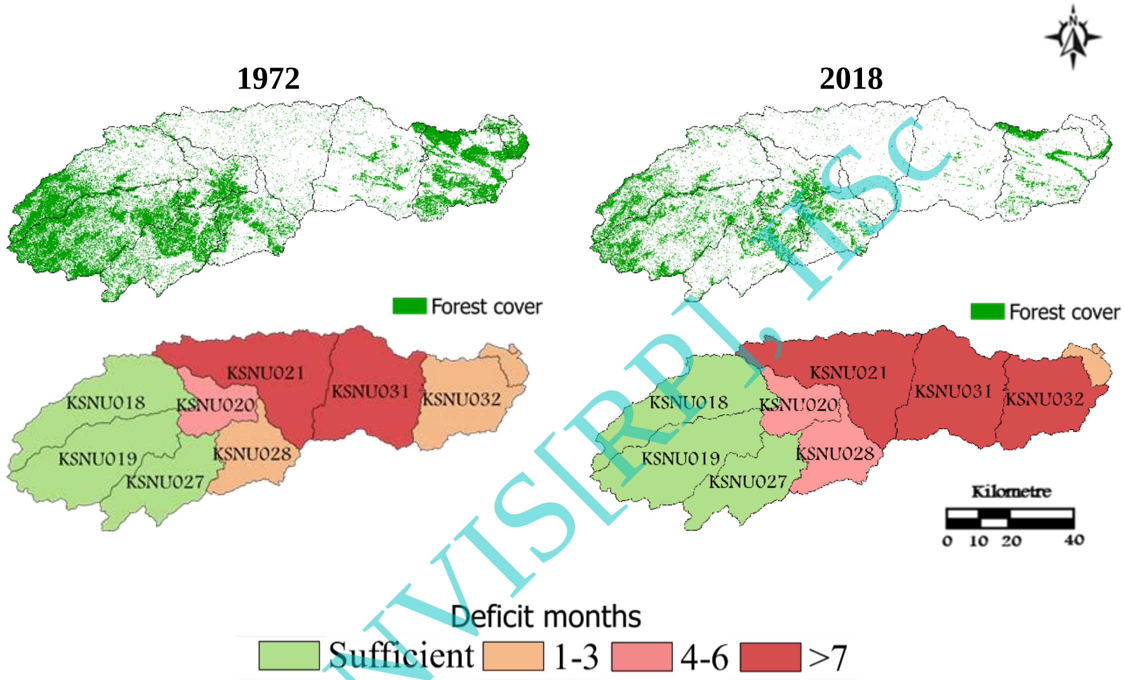


Table 5.22: Eco-hydrological assessment in Ghataprabha catchment (in Mm3)-2018

5.4 Eco-hydrological footprint of Ghataprabha Catchment from 1972-2018

Eco- hydrological footprint of the river basin is evaluated based on the hydrologic regime, and it represents the water required for the sustenance of the biotic component. For society's benefit, the developmental activities in the catchment have altered the catchment properties, as explained in the earlier section.

Table 5.23: Forest cover changes in Ghataprabha catchment(1972-2018)



Basin Id	1972	2018	% decrement of forest (1972-2018)
KSNU018	30.46	22.33	26.68
KSNU019	53.56	30.89	42.31
KSNU020	29.48	19.81	32.77
KSNU021	5.60	2.99	46.41
KSNU027	43.27	20.90	51.69
KSNU028	31.70	21.06	33.54
KSNU031	9.74	3.54	63.65
KSNU032	43.33	16.12	62.80

Temporal analysis to determine the landscape changes revealed the decrement in forest cover, as shown in Table 5.23. The regions with higher forest cover (i.e., KSNU018, KSNU019, KSNU027), have retained the water for all the 12 months satisfying the ecological and societal requirements from 1972 to 2018, whereas plain lands, especially the regions of Bagalkot with an increase in population densities and decrease in forest cover about 62.80% have faced the acute shortages from 1972 to 2018 increasing the water-scarce period in the basin. Especially the basins KSNU028 and KSNU032 have experienced the change of phase conditions. KSNU028 has experienced from scarce to medium scarce conditions. Drastic changes in the basin KSNU032 comprising Bagalkot taluk have experienced the change of phases from scarce to extreme scarce conditions leading to acute shortages in the catchment. This eco-hydrological footprint (Figure 5.76) assessment reveals the importance of forests in retaining the water and catering the ecological and societal requirements.

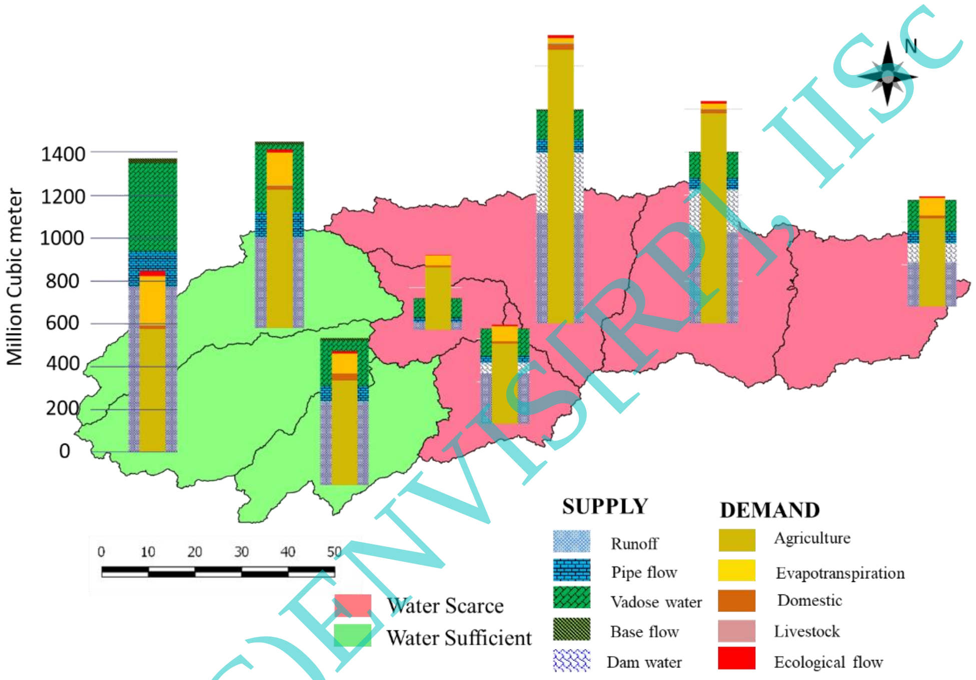


Figure 5.76: Eco-hydrological footprint (Ghataprabha catchment)

5.5 Landscape dynamics of Malaprabha catchment

Landscape dynamics of the region reveal that the major changes from 1972 to 2018 (Figure 5.77 and Table 5.24) is the increment in built-up activities about eight folds from 1972, especially in the regions of Hubli and Gadag, which have become densely populated about 1600 persons per km^2 over a period of time. The catchment has lost its forest cover about 33.35%, mostly towards Belgaum and Bagalkot districts of the sub-catchments, i.e., KSNU030 and KSNU045. This transformation of landscapes to agriculture is commonly seen in these regions. The major crops here are jowar, paddy, maize, bajra, wheat, sugarcane, sunflower, pulses, groundnuts, etc. More than three-fourths of the catchment, about 83.24%, is dominated by agricultural activities. The regions of Khanapur taluk contributing to the Western Ghats have transformed the forest landscapes to plantation activities in the basins KSNU025 and KSNU026 from 0.05%(1972) to 1.07%(2018).

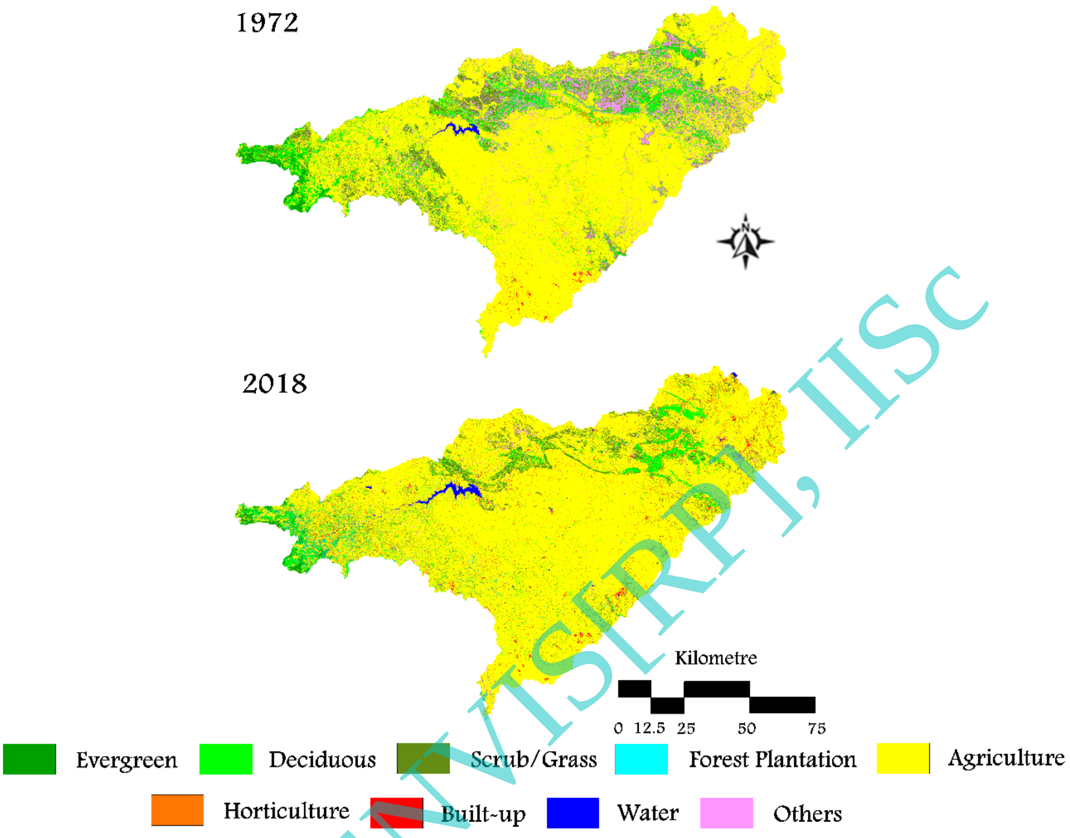


Figure 5.77: Landscape dynamics of Malaprabha catchment

Water bodies in the region has increased from 0.24%(1972) to 0.58%(2018). Dams in this catchment, such as Renukasagar dam, Tigadi dam etc., have contributed to the higher volumes of water in the catchment, satisfying the societal needs. Open spaces in the basins KSNU044, KSNU045, KSNU046, i.e., the regions of Badami taluk, Ron taluk, Hungund taluk, have transformed to agricultural activities over a period of time, decreasing the open space from 7.63%(1972) to 1.19%(2018) accounting about 84% decrement.

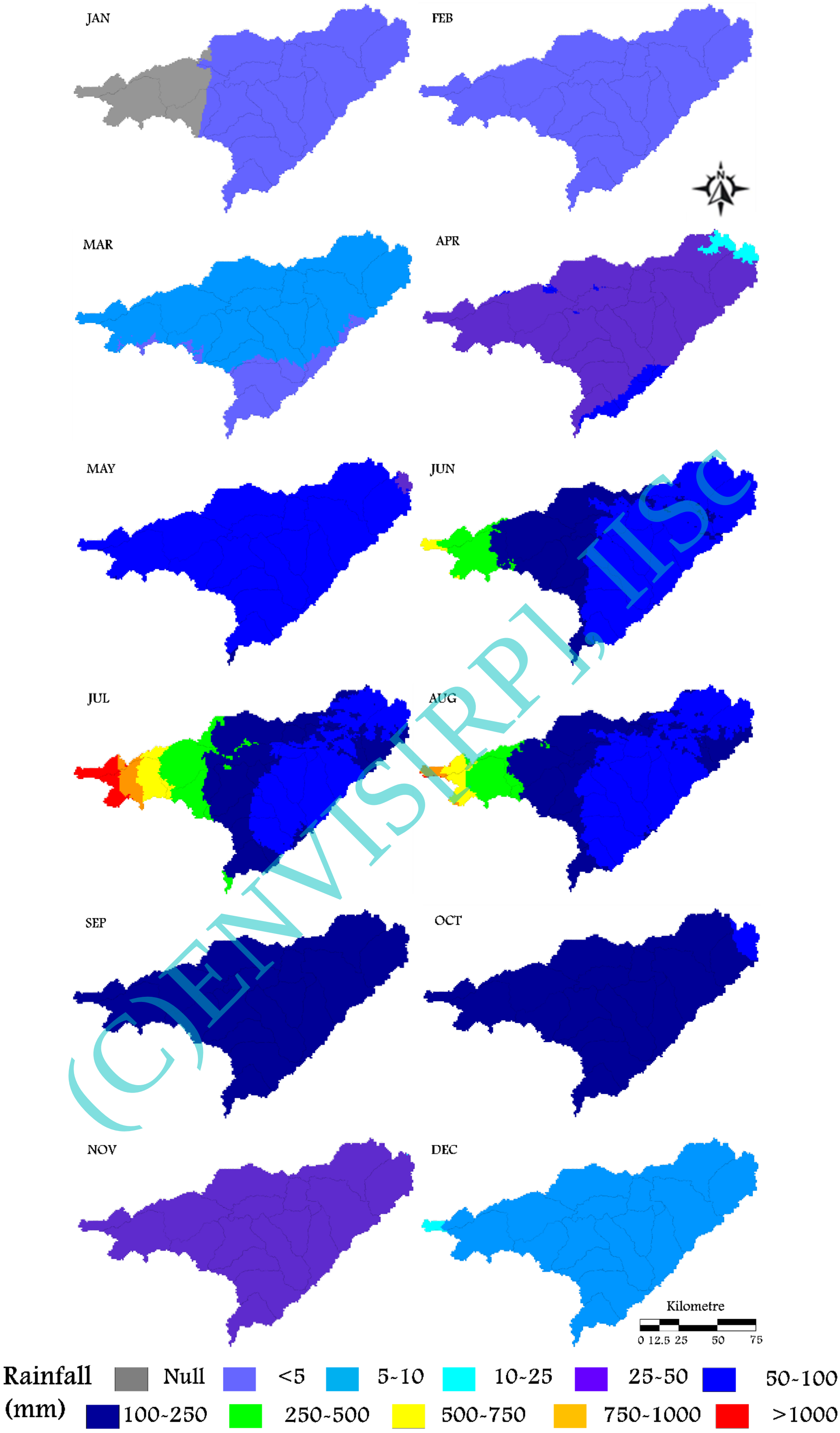
The overall assessment of catchment from 1972 to 2018 reveals the large-scale changes in forest cover, with an increase in agricultural and horticultural activities. An increase in population has contributed to higher demands in the catchment with the conversions of open spaces to agricultural activities and construction of dams in the catchment.

Table 5.24: Land use analysis of Malaprabha catchment (1972-2018)

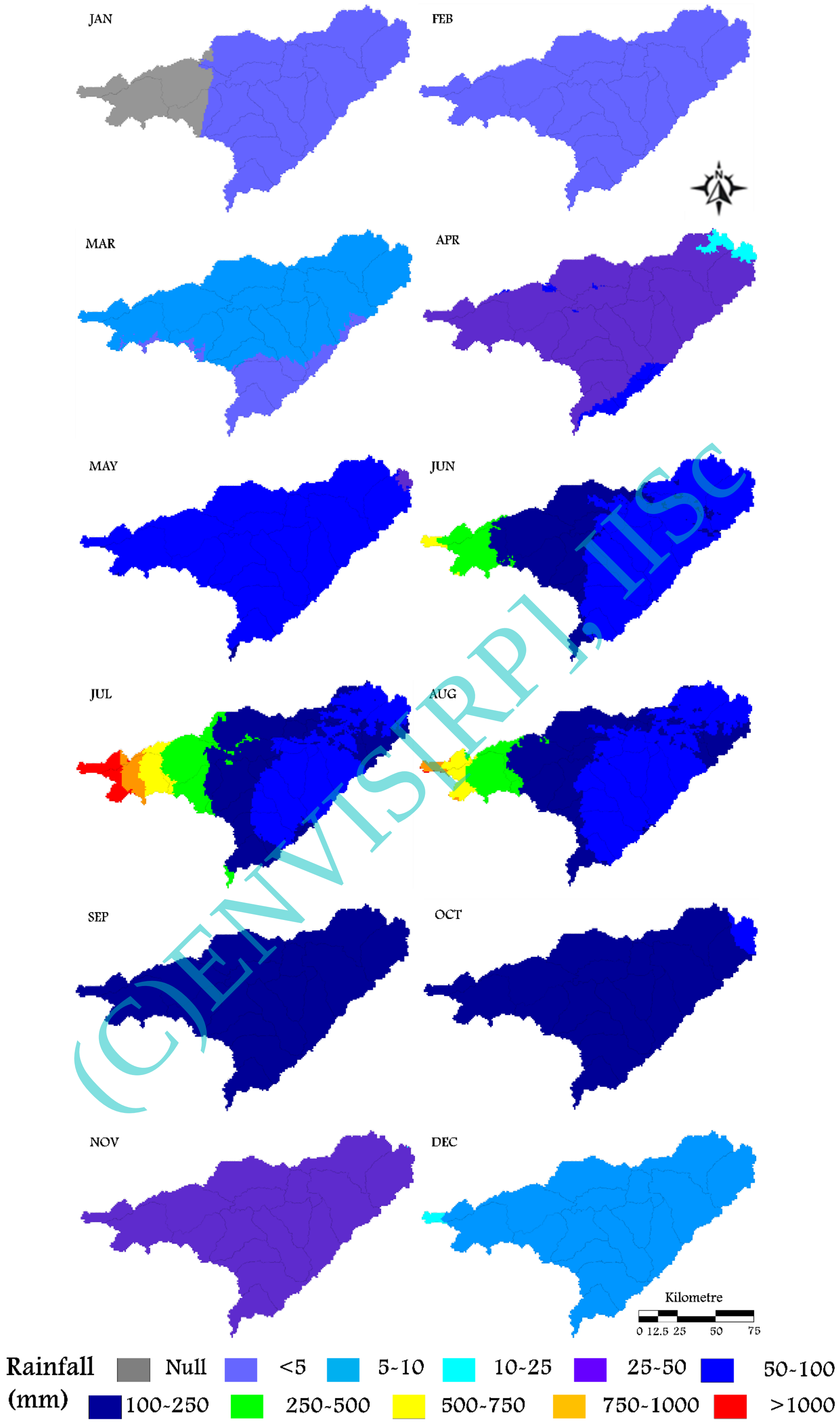
Sl.no.	Land use	1972		2018	
		Area (sq.km)	Area (%)	Area (sq.km)	Area (%)
1	Evergreen forest	121.06	0.97	89.86	0.72
2	Deciduous forest	1134.51	9.09	594.09	4.76
3	Scrub forest/Grasslands	933.57	7.48	775.06	6.21
4	Forest Plantations	6.24	0.05	133.55	1.07
5	Agriculture	9193.40	73.66	10389.07	83.24
6	Horticulture	94.85	0.76	146.03	0.76
7	Built up	13.73	0.11	129.80	1.04
8	Water	29.95	0.24	73.64	0.59
9	Others	952.29	7.63	148.52	1.19

5.6 Eco-hydrological assessment of Malaprabha Catchment from 1972-2018

Hydrological parameters such as rainfall, runoff, interception, infiltration, groundwater recharge, baseflow, pipe flow etc., were quantified in the catchment monthly, as explained in detail below. Gross rainfall was calculated based on catchment area and rainfall. The catchment mainly receives rainfall from May to October. The monthly variations in the rainfall are as shown in **Figure 5.79**



JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Kilometre
0 12.5 25 50 75
Rainfall (mm)
Null
<5
5-10
10-25
25-50
50-100
100-250
250-500
500-750
750-1000
>1000


JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Kilometre
0 12.5 25 50 75
Rainfall (mm)
Null
<5
5-10
10-25
25-50
50-100
100-250
250-500
500-750
750-1000
>1000

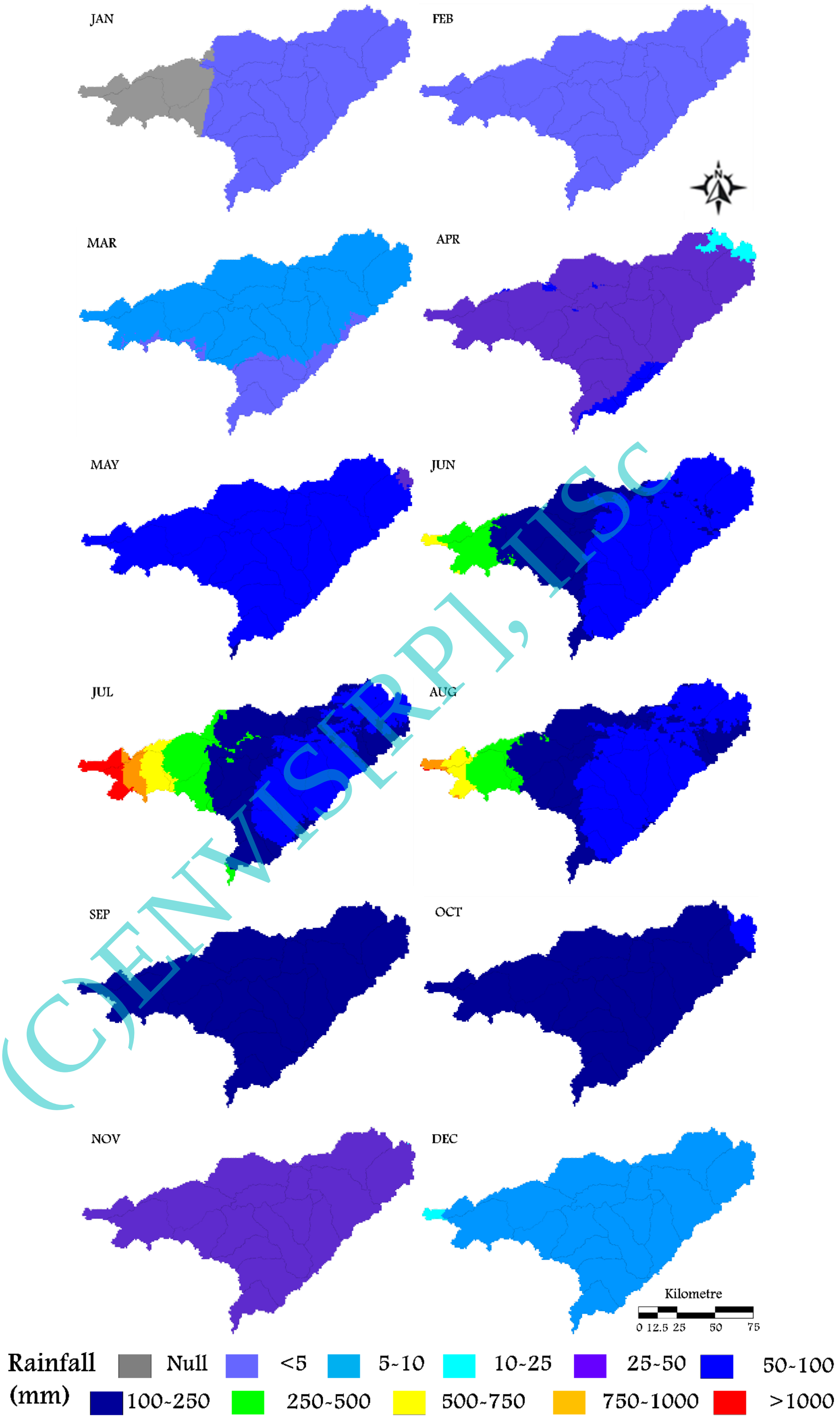

JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Kilometre
0 12.5 25 50 75
Rainfall (mm)
Null
<5
5-10
10-25
25-50
50-100
100-250
250-500
500-750
750-1000
>1000

Figure 5.79

Figure 5.79, reveal that the forested regions of catchment especially KSNU026, receive heavy rainfall, i.e., in the Ghats, contributing to higher rainfall volume in the sub-basin in July varying from 40 $Mm^3$to 750 Mm^3.

The monthly interception variations in the catchment is shown in Figure 5.81, which reveals that the regions with high forest cover especially KSNU025, KSNU026, KSNU029, and KSNU035 have high interception rates in the regions of Belgaum district varying up to 67 Mm^3 in July. The overall annual assessment reveals that the decrement of interception rates from 1972 – 2018 about 30.15% due to decrement in forest cover in the catchment caused by anthropogenic activities.

The monthly runoff variations are depicted in Figure 5.82, explaining that the regions with higher forest cover have less runoff over plain lands. The runoff variations from 1972 to 2018 show that there is about 7.61% increment in the overland flows (surface runoff) in the monsoons from 4128.37 Mm^3 (1972) to 4442.54 Mm^3(2018) in this region. This percentage change reveals that the recharging of the soil is decreased drastically, leading to lesser infiltration rates, groundwater resources.

Groundwater recharge accounts for about 1815.12 Mm^3 in the year 2018 Table 5.26. Water is stored in the vadose zone, or the sub-surface zone moves laterally in the post-monsoons with cessation of rain. The vadose water has decreased to about 16.48% from 1972 to 2018 from 1982.07 Mm^3(1972) to 1655.29 Mm^3(2018) because of landscape changes in decreasing forest cover in the catchment.

Evapotranspiration in the catchment depends on the lands use characteristics, extra-terrestrial solar radiation, variations in temperature, precipitation, etc. Potential evapotranspiration, as shown in the Figure 5.78 varies from 86 mm/month to 180 mm/month from non-monsoons to monsoons. The actual evapotranspiration is calculated considering the evapotranspiration coefficient, based on the various land use categories. Net evaporation was calculated as the difference between actual evapotranspiration and interception, emphasizing the fact that the intercepted water accounts for evaporation during monsoon.

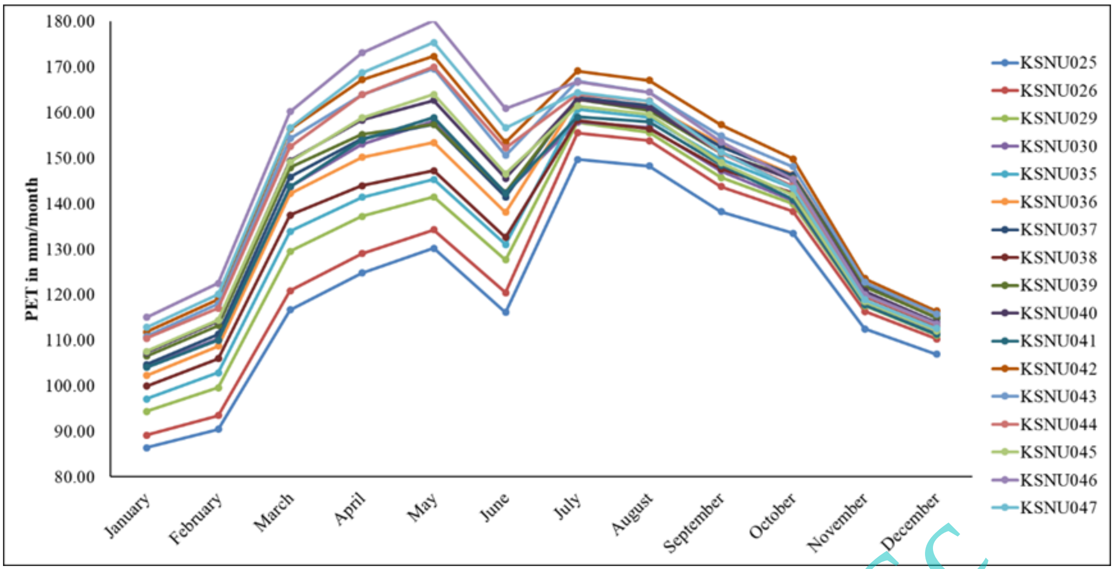


Figure 5.78: Potential evapotranspiration

Similarly, the evaporation from the crops, i.e., agriculture and horticulture, are considered based on the different phases of the growth. Actual evapotranspiration accounts for about 1093.52 Mm^3(1972) and 986.67 Mm^3(2018), as shown in Table 5.25 and Table 5.26.

Monthly variations in the agriculture water requirement reveal that, especially in July, based on the crops grown, a higher quantum of water is required to meet the demand and goes up to 5455.91 Mm^3(2018) from 4794.42 Mm^3 (1972). The area under agriculture has increased from 1972 to 2018 about 13%, with an increase in water requirements about 13.79%.

Domestic water requirement has increased from 119.39 Mm^3 (1972) to 174.99 Mm^3 (2018), about 46.57 % as shown in Table 5.25 and Table 5.26. Regions of Bagalkot district i.e., Hungund, Badami taluks, have undergone intense urbanization leading to greater domestic needs in the catchment.

The ecological water requirement of the region is about 96.64 Mm^3 (2018), as shown in Table 5.25 and Table 5.26. About 10.52%. KSNU025 has a major forest cover of about 69.60% (1972) has decreased to 36.31% (2018), accounting 47.82% reduction in a forest in this basin, which has led to increasing in ecological water requirement from 2.07 mm^3 (1972) to 3.15 Mm^3 (2018). The fragmentation activities of the forest have led to disturbances and imbalances in the ecosystem. The establishment of the eco-hydrological footprint considering all hydrological parameters is as explained in the next section 5.7.

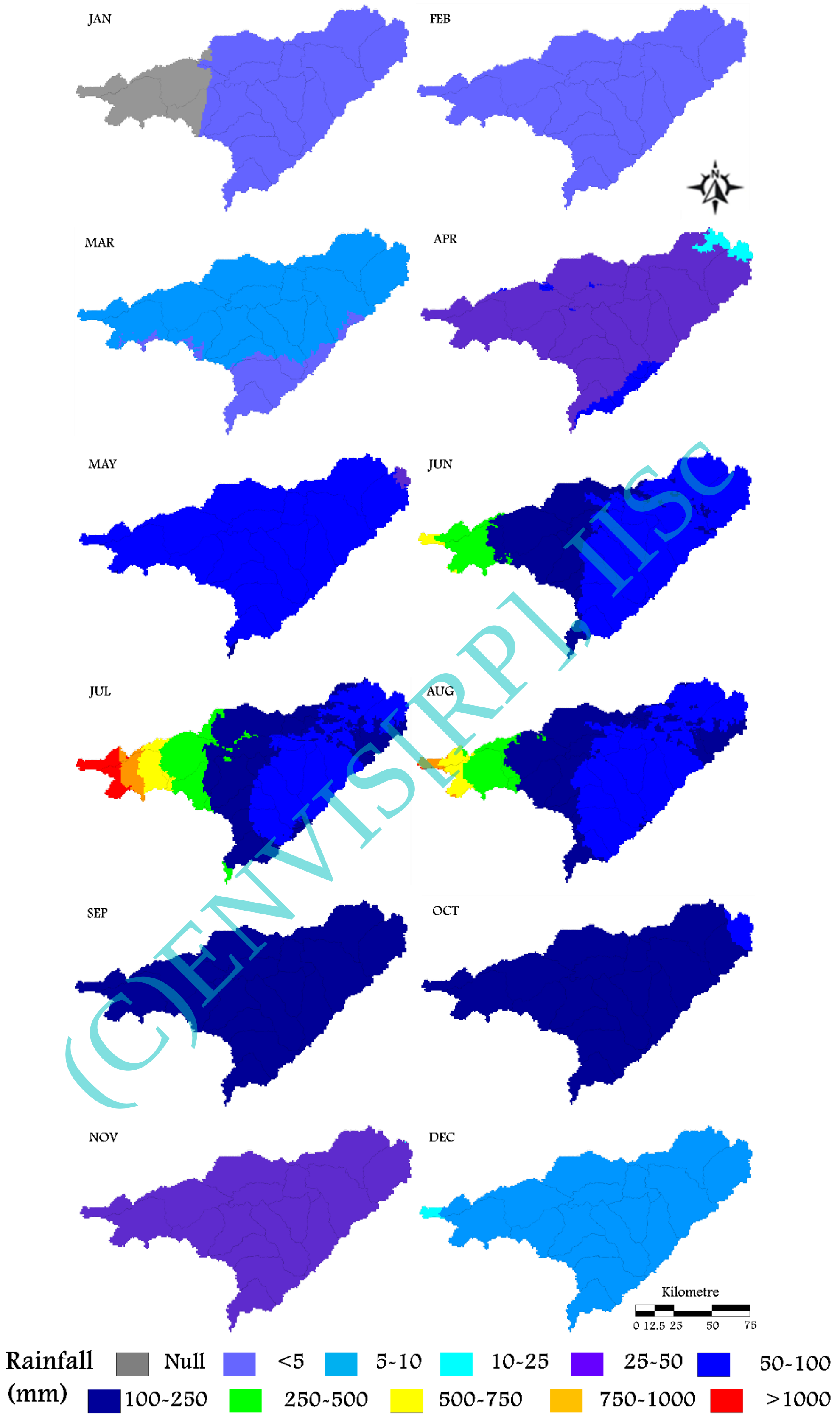


Figure 5.79: Monthly rainfall variations in Malaprabha catchment

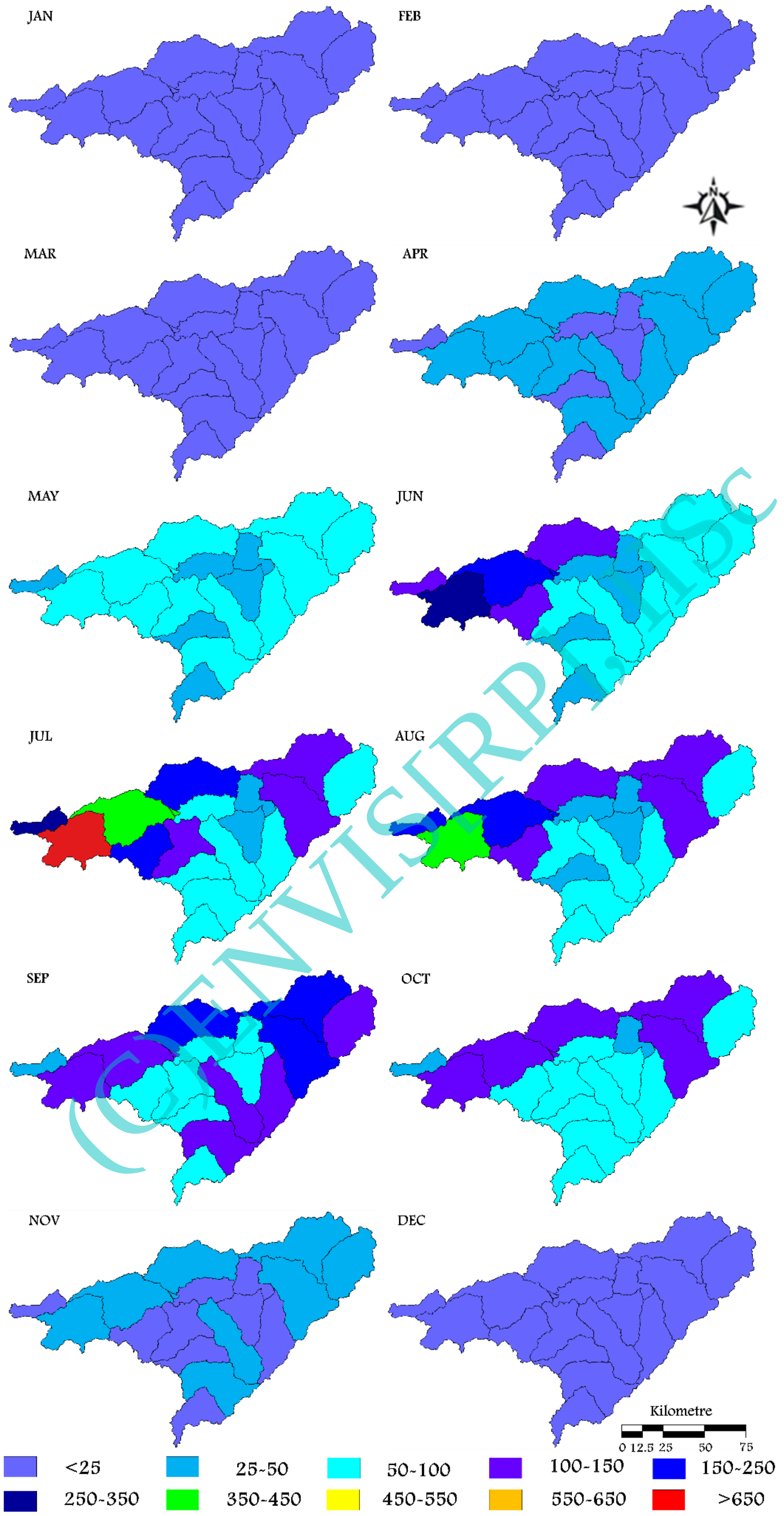


Figure 5.80: Gross Rainfall (in Mm3)- Malaprabha catchment

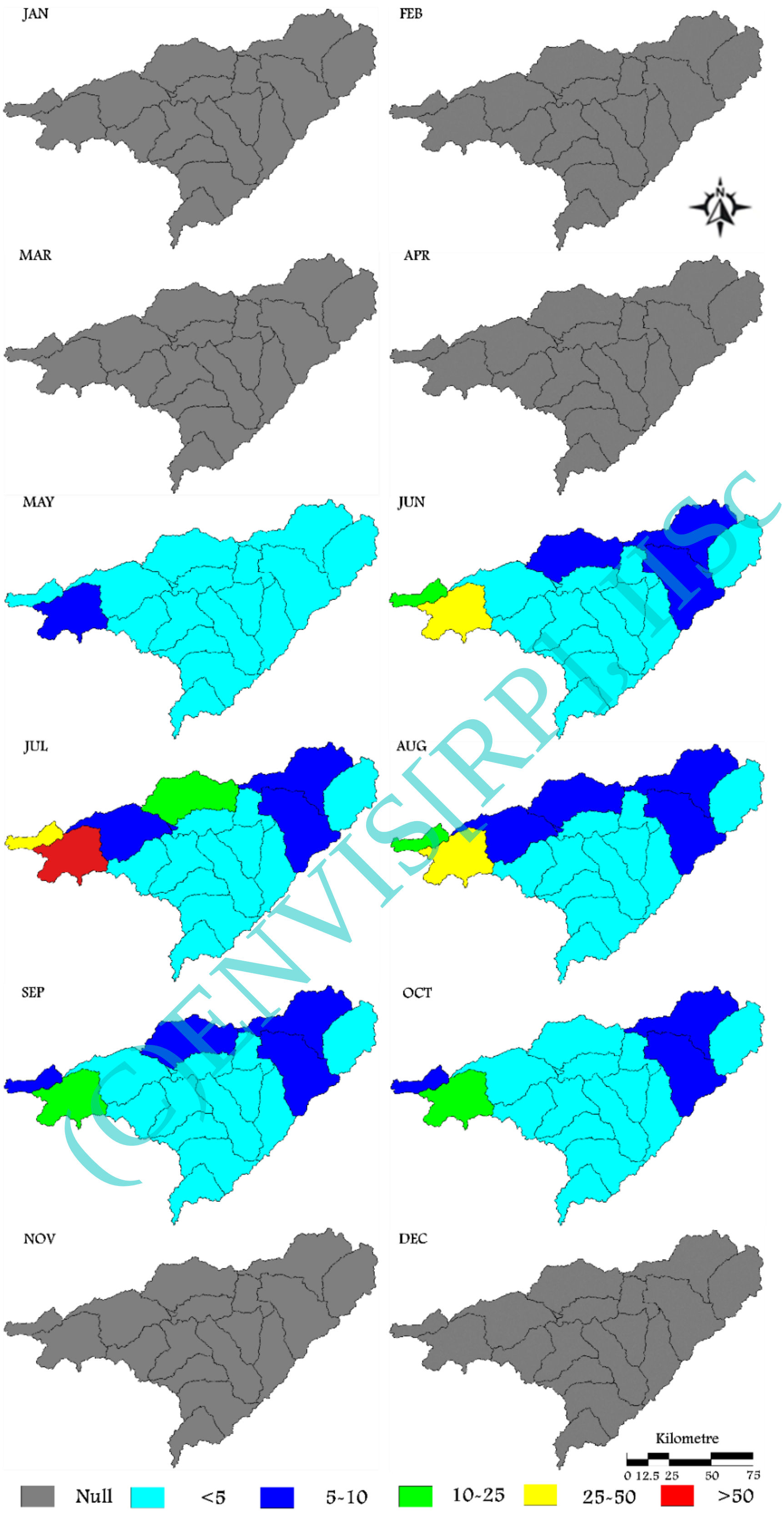


Figure 5.81: Interception (in Mm^3)-Malaprabha catchment

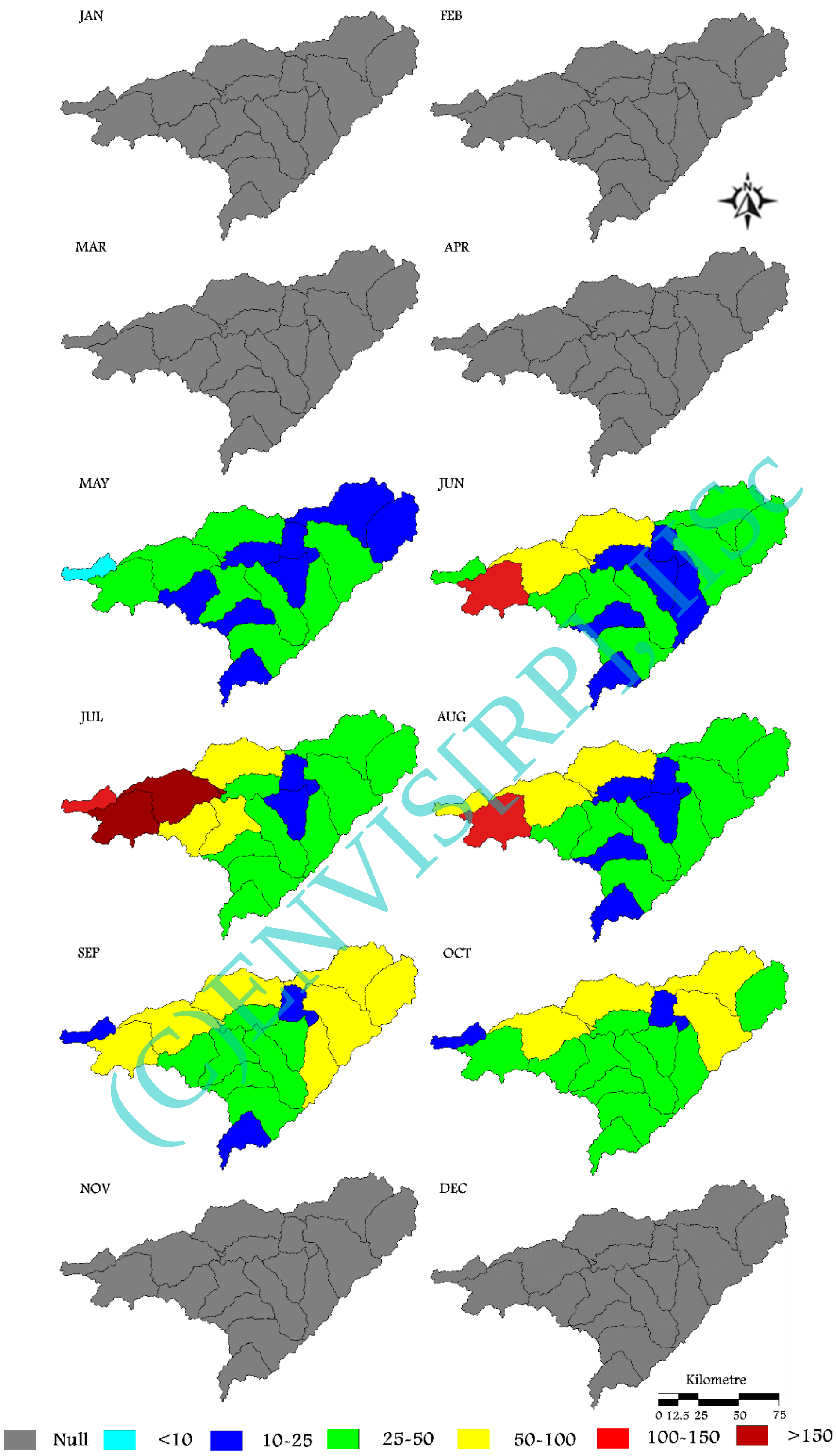


Figure 5.82: Runoff (in Mm3)-Malaprabha catchment

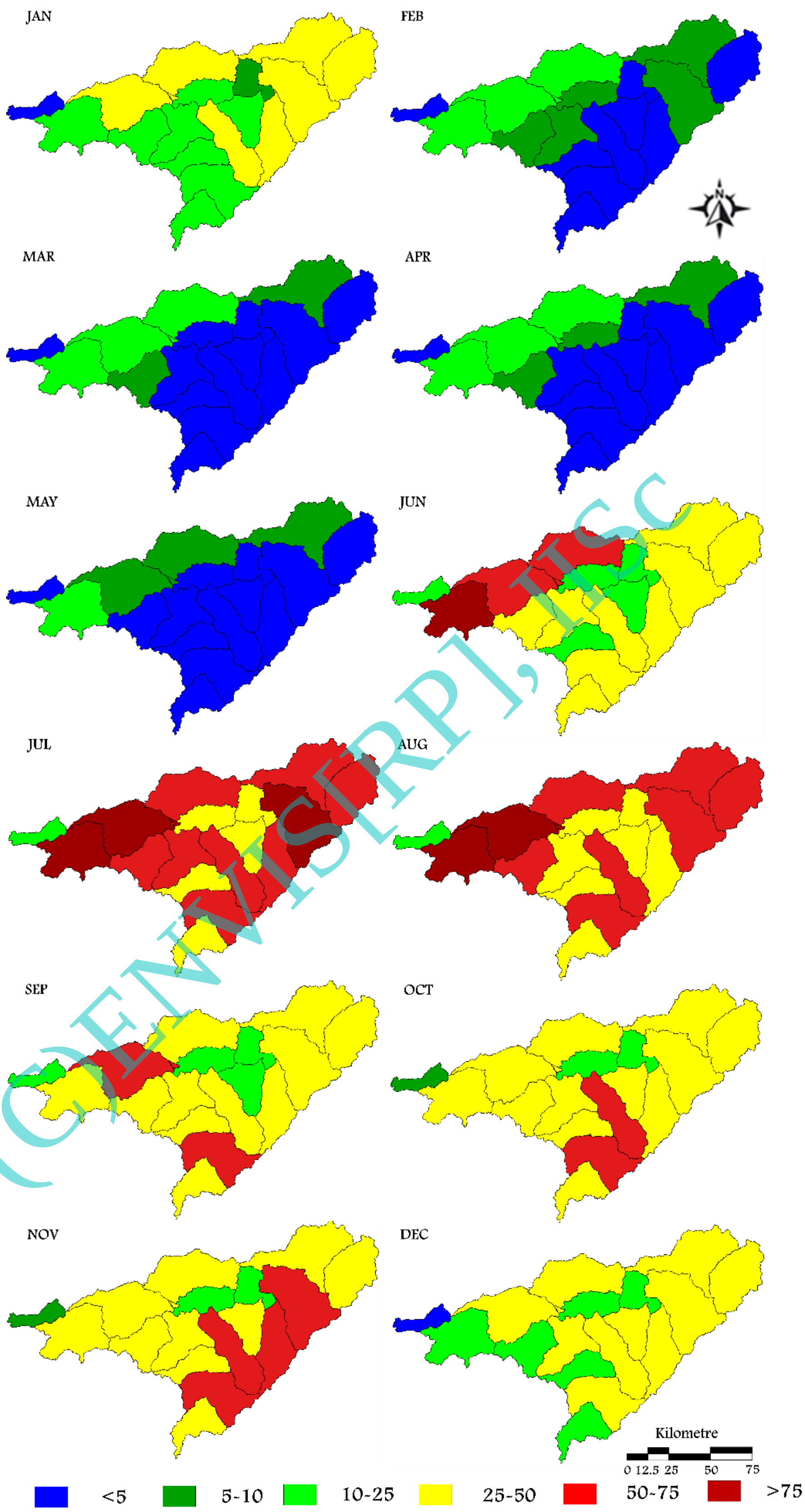


Figure 5.83: Crop water demand (in Mm^3) - Malaprabha catchment

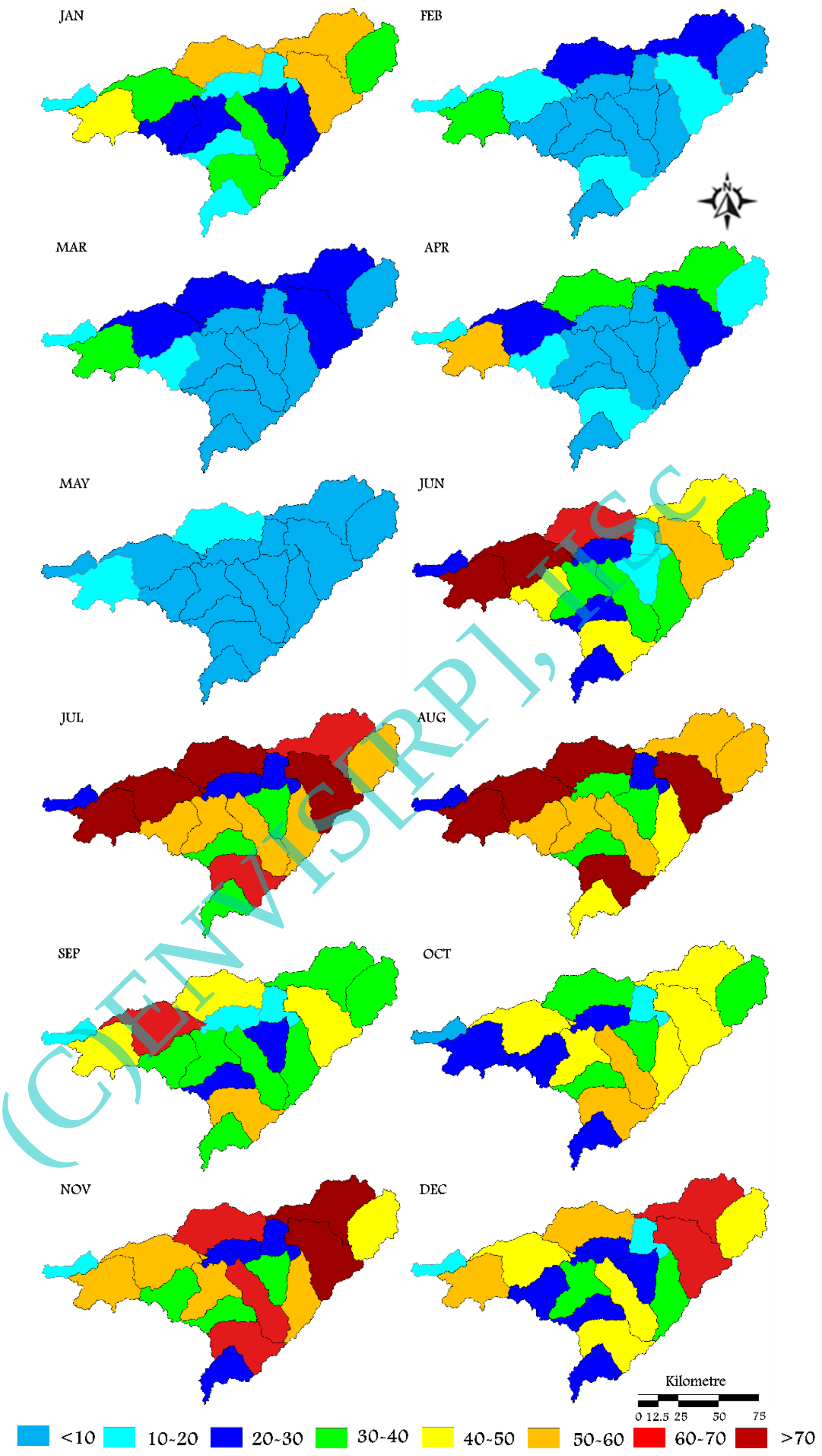


Figure 5.84: Total demand(in Mm^3)-Malaprabha catchment

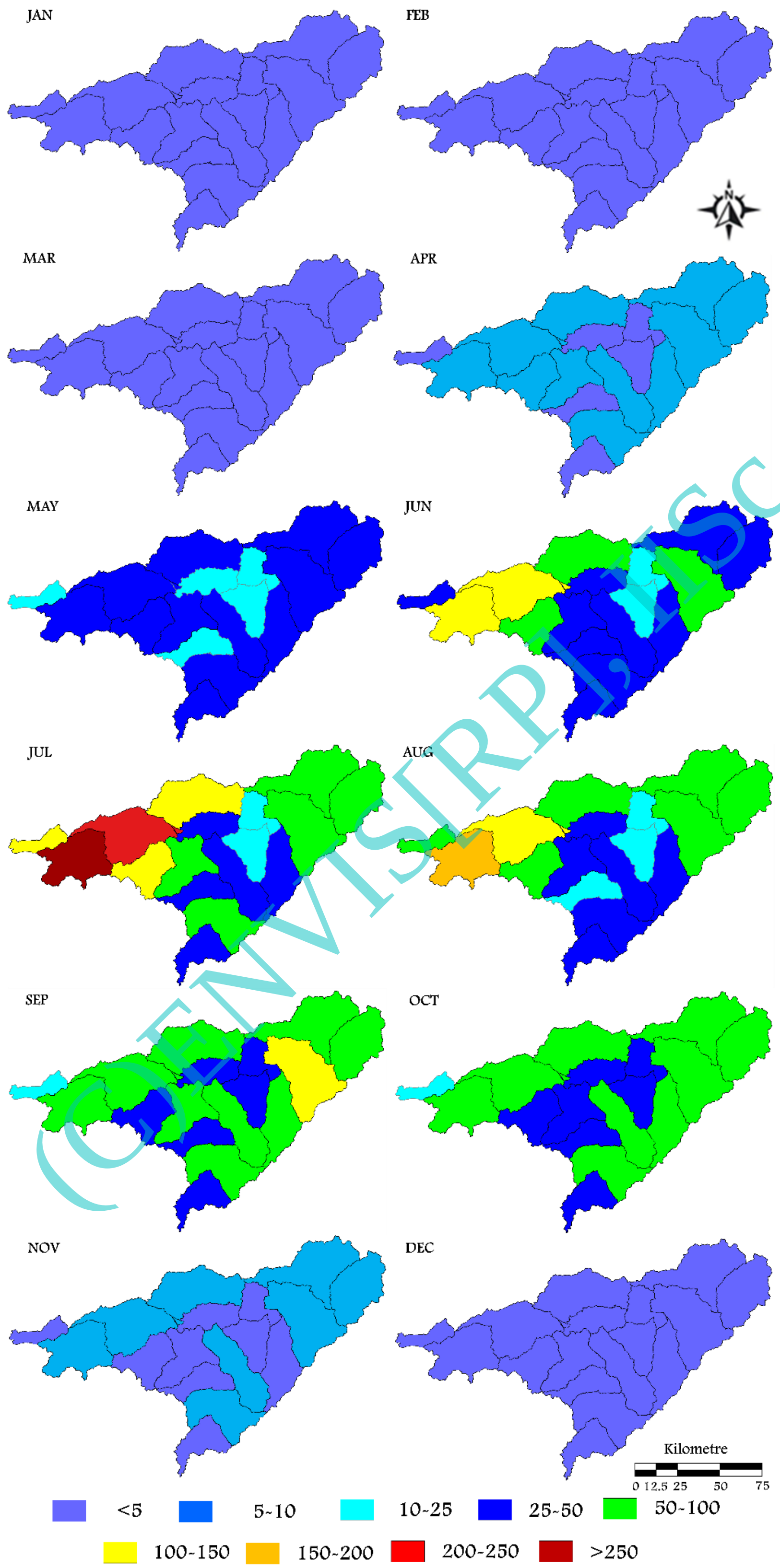


Figure 5.85: Water available (in Mm^3)- Malaprabha catchment

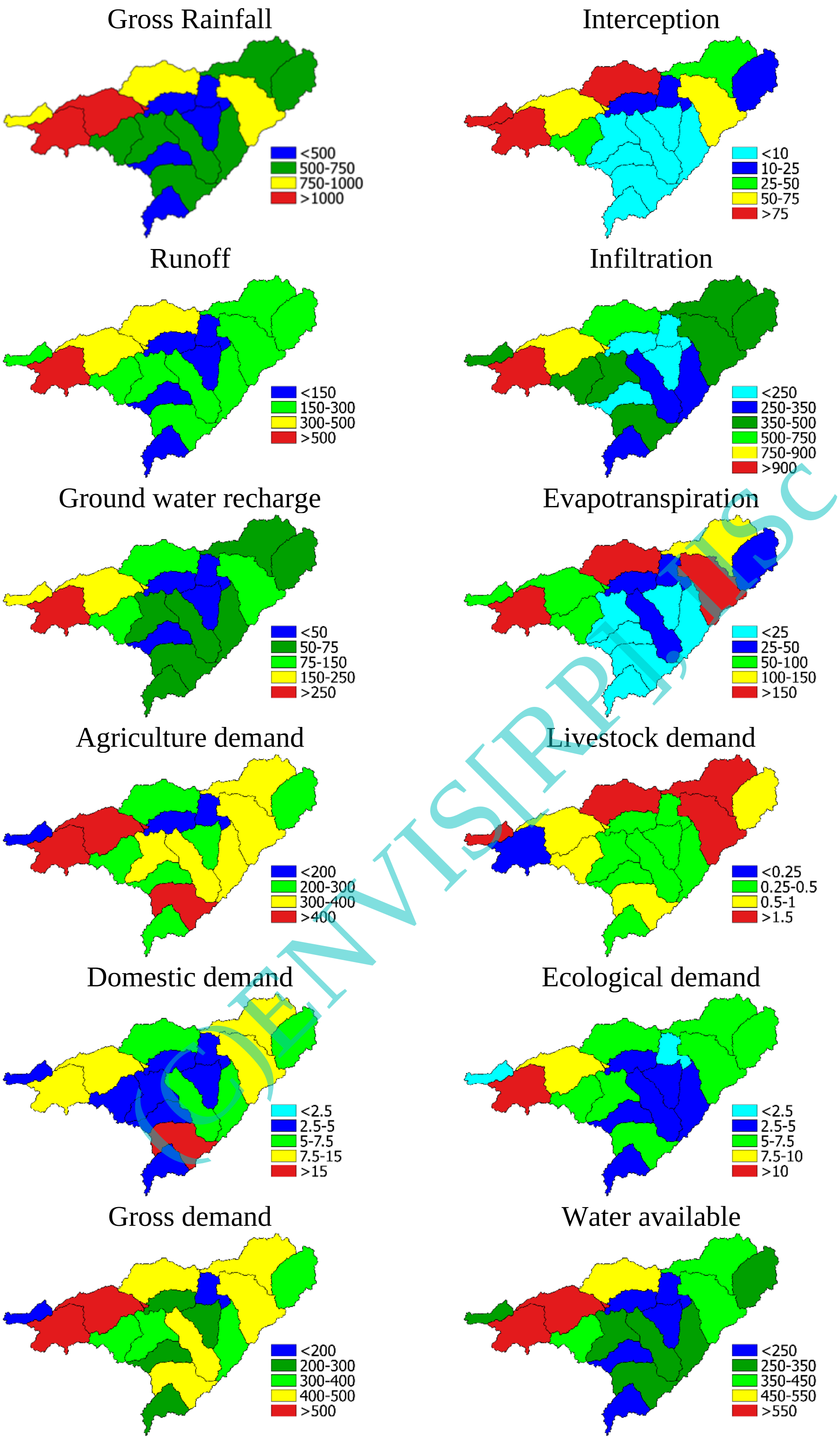


Table 5.25: Eco-hydrological assessment in Malaprabha catchment (in Mm^3) – 1972

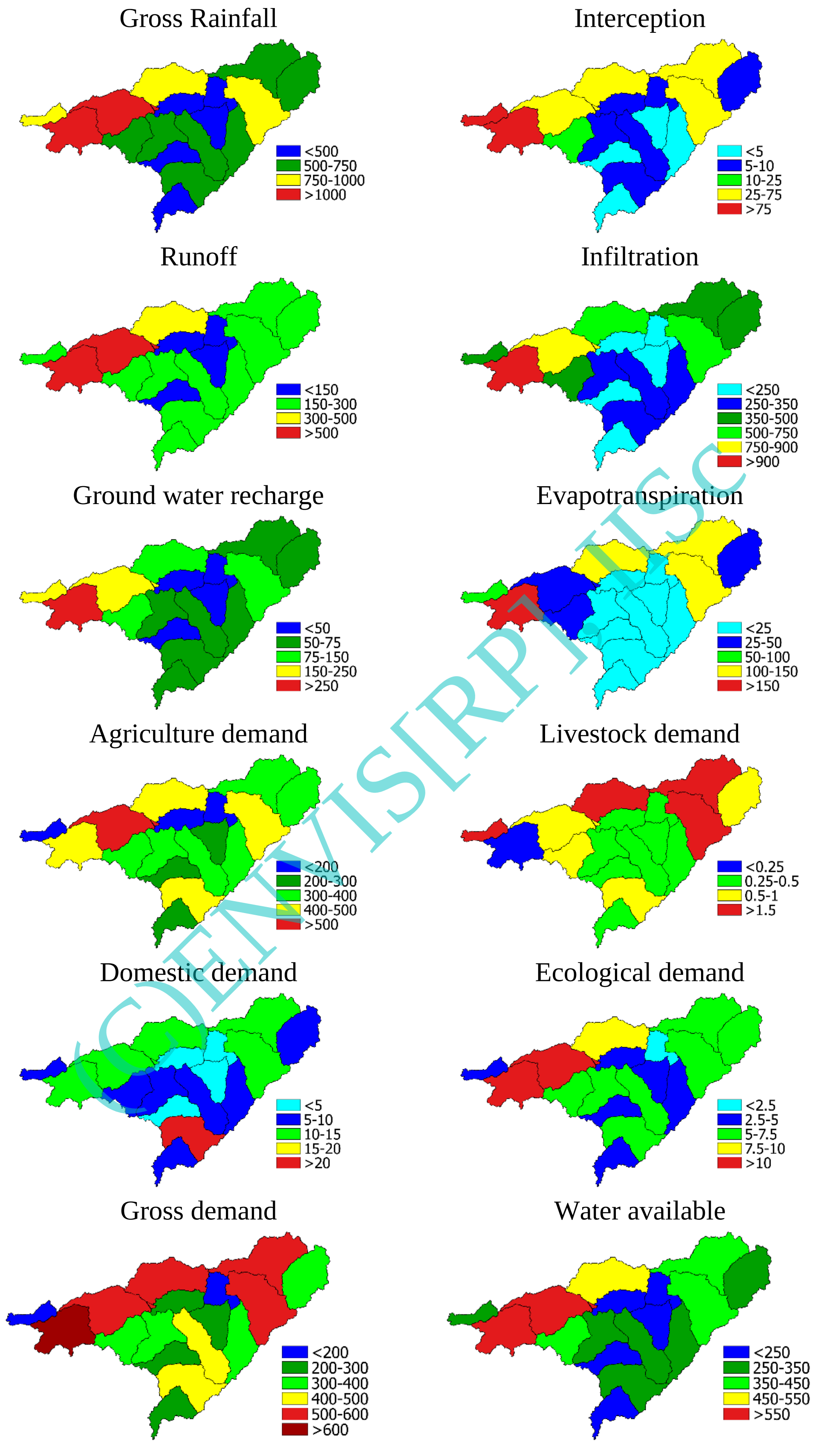
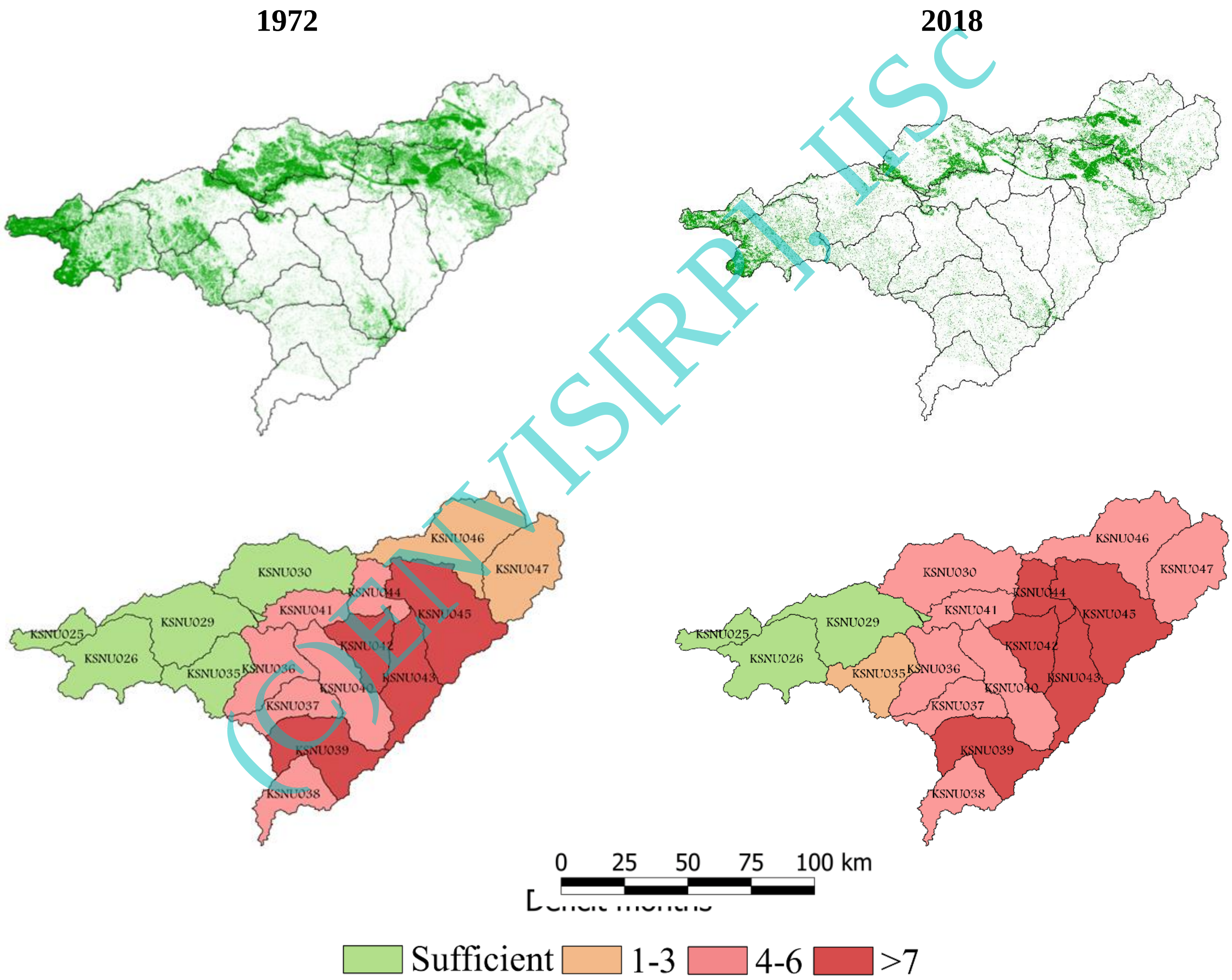


Table 5.26: Eco-hydrological assessment in Malaprabha catchment (in Mm^3) – 2018

5.7 Eco-hydrological footprint of Malaprabha Catchment from 1972-2018

Eco- hydrological footprint which is required for the sustenance of the biotic component of the river basin is evaluated based on the hydrologic regime. The developmental activities in the catchment for society's benefit have altered the catchment properties, as explained in the earlier section.

Table 5.27: Forest cover changes in Malaprabha catchment(1972-2018)



Basin Id	1972	2018	% decrement of forest (1972-2018)
KSNU025	69.60	36.31	47.82
KSNU026	34.94	25.84	26.04

KSNU029	19.43	9.02	53.61
KSNU030	35.99	20.00	44.42
KSNU035	21.13	7.71	63.53
KSNU036	4.67	4.44	4.99
KSNU037	5.33	4.27	19.84
KSNU038	1.68	0.55	67.55
KSNU039	4.84	2.37	51.00
KSNU040	6.44	4.32	32.98
KSNU041	13.92	9.24	33.59
KSNU042	2.02	1.25	38.08
KSNU043	4.04	2.69	33.46
KSNU044	24.07	11.07	53.99
KSNU045	25.88	18.28	29.37
KSNU046	22.15	20.89	5.70
KSNU047	9.90	7.46	24.65

Temporal analysis to determine the landscape changes revealed the decrement in forest cover as shown in Table 5.27 from 1972 to 2018. The regions with higher forest cover are KSNU025, KSNU026, KSNU029, KSNU035, i.e., Khanapur taluk, Bailhongal, Saundatti, Dharward taluks having a forest cover about 30 % of the sub-catchments have retained the water for all months in the year 1972 as shown in the Table 5.27. The changes in the landscape of Dharwad leading to higher urbanization from 1972 to 2018 with the construction of roads, buildings etc. which has changed the phase of "water sufficient condition" to "scarce condition" based on the deficit months. A similar trend could be seen in the basin KSNU030 comprising of Ramdurg taluk.

KSNU044 comprising Ron, Nargund, and Badami taluks have also experienced the change of phase from "medium scarce to extreme scarce" conditions. KSNU046 and KSNU47 comprising of Bagalkot and Hungund taluks have experienced the change of phase from "scarce to medium scarce conditions". If a similar trend is continued, then the medium scarce basins would turn to extreme scarce conditions leading to acute shortage of water resources.

This eco-hydrological footprint (Figure 5.86) established in determining the hydrological status reveals the importance of forest in retaining the water and catering to the ecological and societal requirements.

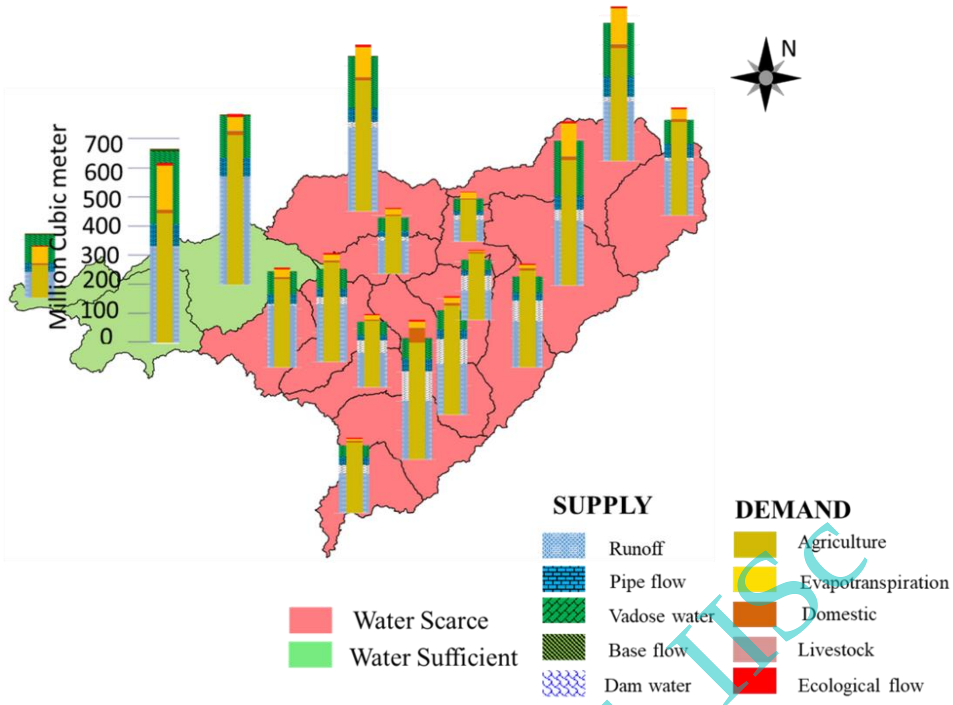


Figure 5.86: Eco-hydrological footprint (Malaprabha Catchment)

5.8 Landscape dynamics of Mahadayi catchment

Spatial and temporal analysis of land-use changes in Mahadayi catchment was analyzed for the years 1972 and 2018 using remote sensing data obtained from Landsat 1 and Landsat 8 [52]. Results of multi-temporal Land use dynamics is depicted in Figure 5.87.

Temporal analysis of the data reveals that there is large-scale degradation of forest cover from 78.37%(1972) to 50.7%(2018), especially in the regions of Khanapur taluk and Sangeum taluk which is part of Western Ghats. The major drivers are the anthropogenic activities that have caused these transformations in the regions. The conversion of forest cover to agriculture and horticulture activities have taken place during the study period from 1972 to 2018. The major crops grown here are paddy, cereals, millets, pulses, oilseeds, sugarcane, coconut, areca nut, cashew nut, etc. The regions of Bicholim, Panaji have turned densely populated from 0.22%(1972) to 0.56%(2018). The overall catchment assessment reveals that about 41.04% is from agriculture and horticulture activities. The detailed analysis is given in Table 5.28.

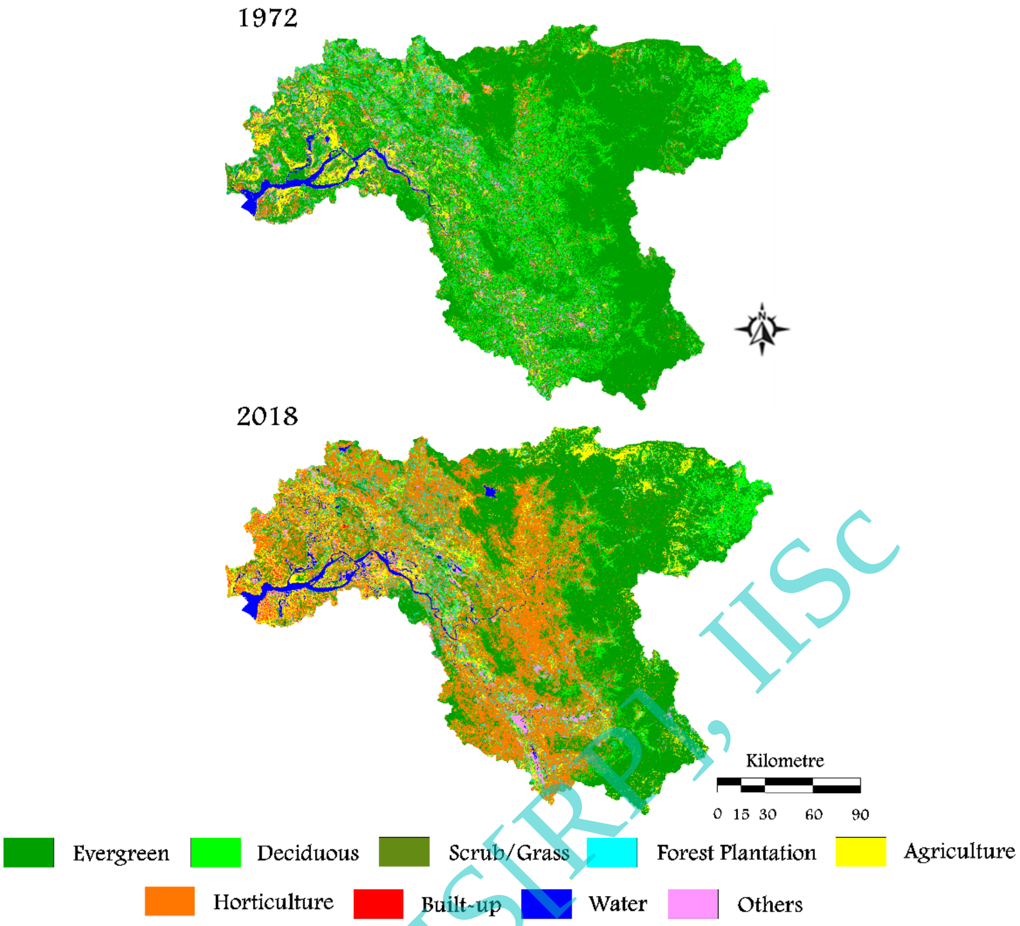


Figure 5.87: Landscape dynamics of Mahadayi catchment

Table 5.28: Land use analysis of Mahadayi catchment (1972-2018)

Sl.no.	Land use	1972		2018	
		Area (sq.km)	Area (%)	Area (sq.km)	Area (%)
1	Evergreen forest	919.3	45.8	822.1	40.96
2	Deciduous forest	504.2	25.12	160.4	7.99
3	Scrub forest/Grasslands	149.5	7.45	34.9	1.74
4	Forest Plantations	110.2	5.49	110.2	5.49
5	Agriculture	120.4	6	184.7	9.2
6	Horticulture	92.1	4.59	587.9	29.29
7	Built up	4.4	0.22	11.2	0.56
8	Water	29.9	1.49	44.6	2.22
9	Others	75.3	3.75	51.2	2.55

5.9 Eco-hydrological assessment of Mahadayi Catchment from 1972-2018

Hydrological parameters such as rainfall, runoff, interception, infiltration, groundwater recharge, baseflow, pipe flow etc., were quantified in the catchment monthly, as explained in detail below.

Gross rainfall was calculated based on catchment area and rainfall. The catchment mainly receives rainfall from May to October. The monthly variations in the rainfall are as shown in the Figure 5.89 reveal that the forested regions of catchment, especially VSST015, sub-basin, receive the highest rainfall i.e., in the Ghats, contributing to higher rainfall volume in the sub-basin in July varying from 525 Mm^{3}to 1150 Mm^3.

The intercepted rainfall, i.e., the portion of rainfall which doesn't reach the earth's surface is contributing to about 15- 30% based on the literature studies [10], [41], [44] is considered for the hydrological assessment. The monthly interception variations in the catchment is as shown in Figure 5.91, which reveals that the regions with high forest cover, especially VSS015 have high interception rates. VSS015 has higher interception rates varying from 20.11 Mm^3 (May) to 237.43 Mm^3 (July). The remaining basins VSS016, VSS019 where there is forest cover lesser than that of VSS015, experience interception rates up to 85.28 Mm^3. The overall assessment of interception analysis indicates that the interception volume decreased about 35.08 % from 1612.09 Mm3 (1972) to 1046.56 Mm3(2018) due to changes in the landscape driven by anthropogenic activities.

The monthly runoff variations are depicted in Figure 5.82, which explains that the regions with higher forest cover have less runoff over plain lands. The runoff variations from 1972 to 2018 show that there is about 34.83% increment in the overland flows (surface runoff) in the monsoons from 1138.15 Mm^3 (1972) to 1534.59 Mm^3 (2018) in this region. The landscape changes are the major drivers for the increment in these overland flows. This percentage change reveals that the recharging of the soil is decreased drastically, leading to lesser infiltration rates, groundwater resources.

Groundwater recharge accounts for about 1827.96 Mm^3 in the year 2018 (Table 5.26). Water is stored in the vadose zone, or the sub-surface zone moves laterally in the post-monsoons with cessation of rain. The vadose water has decreased to about 23.45 % from 1972 to 2018 from 1236.77 Mm^3 to 946.80 Mm^3 because of landscape changes in decreasing forest cover in the catchment.

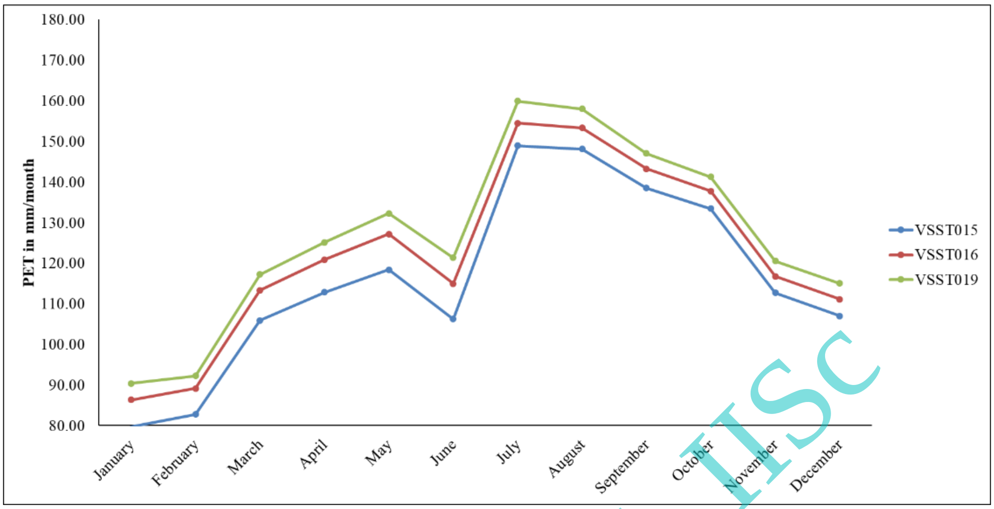


Figure 5.88: Potential evapotranspiration

Evapotranspiration in the catchment depends on the land's use characteristics, extra-terrestrial solar radiation, variations in temperature, precipitation, etc. As shown in Figure 5.88, potential evapotranspiration varies from 83 mm/month to 160 mm/month from non-monsoons to monsoons. Based on the various land use categories, the actual evapotranspiration is calculated based on the evapotranspiration coefficient. Net evaporation was calculated as the difference between actual evapotranspiration and the interception, emphasizing that the intercepted water accounts for evaporation during monsoon.

Similarly, the evaporation from the crops, i.e., agriculture and horticulture, are considered based on the different phases of the growth. Actual evapotranspiration accounts for about 937.92Mm^3 (1972) and 620.71Mm^3 (2018), as shown in Table 5.29 **and below** Table 5.30. The large-scale destruction of forest regions has decreased the evaporation rates.

Agriculture demand or the crop water requirement was calculated based on the crops grown in the catchment considering its crop pattern, an area under each crop, water requirement for various growth phases which were collated as explained in **Chapter 4**. Monthly variations in the agriculture water requirement reveal that the basins VSS016 and VSS019 catchments dominated with agriculture and horticulture activities require a higher quantum of water. The area under agriculture and horticulture has increased from 1972 to 2018 by about 41.04 %, with an increase in the water requirement for agriculture by about one and a half folds from 113.5813 Mm3 (1972) 1483.15 Mm^3 (2018) as shown in Table 5.29 and **Table 5.30**Table 5.30.

Domestic water requirement was calculated based on the population in catchment interpolated for the basins from the taluks data obtained from the census of India for the years 2001 and 2011, projected geometrically to 2018. The domestic water requirement has increased from 18.24 Mm^3 (1972) to 22.08 Mm^3 (2018) about 21.05% as shown in the Table 5.29 and Table 5.30 in the catchment, especially in the regions of Bicholim and Panaji.

Ecological water requirement was calculated based on literature studies[10], [12], [17], [35], [41], [42], [44]. The Tenant method was adopted in the current study [10], accounting for about 20-30% of mean annual runoff. Similarly, the National green tribunal states that about 15-20% must be maintained for the ecological sustenance based on the locality and region-specific. The region's ecological water requirement has 27.96 Mm^3(2018), as shown in the Table 5.29 and Table 5.30.

The eco-hydrological footprint is computed by considering all the eco-hydrological parameters, as explained in the next section 5.10.

Figure 5.89: Monthly rainfall variations in Mandovi catchmennt

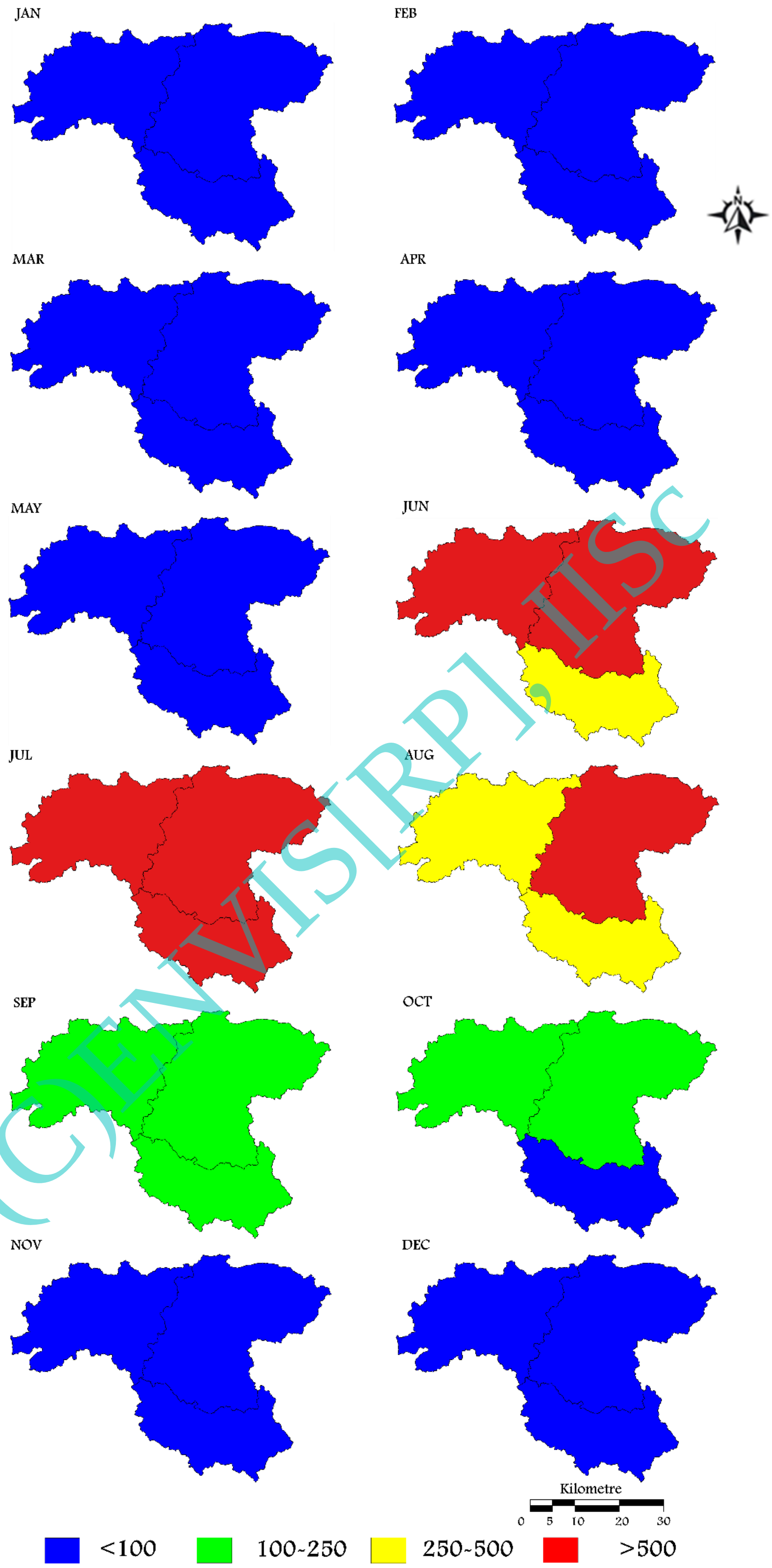


Figure 5.90: Gross Rainfall (in Mm^3) - Mahadayi catchment

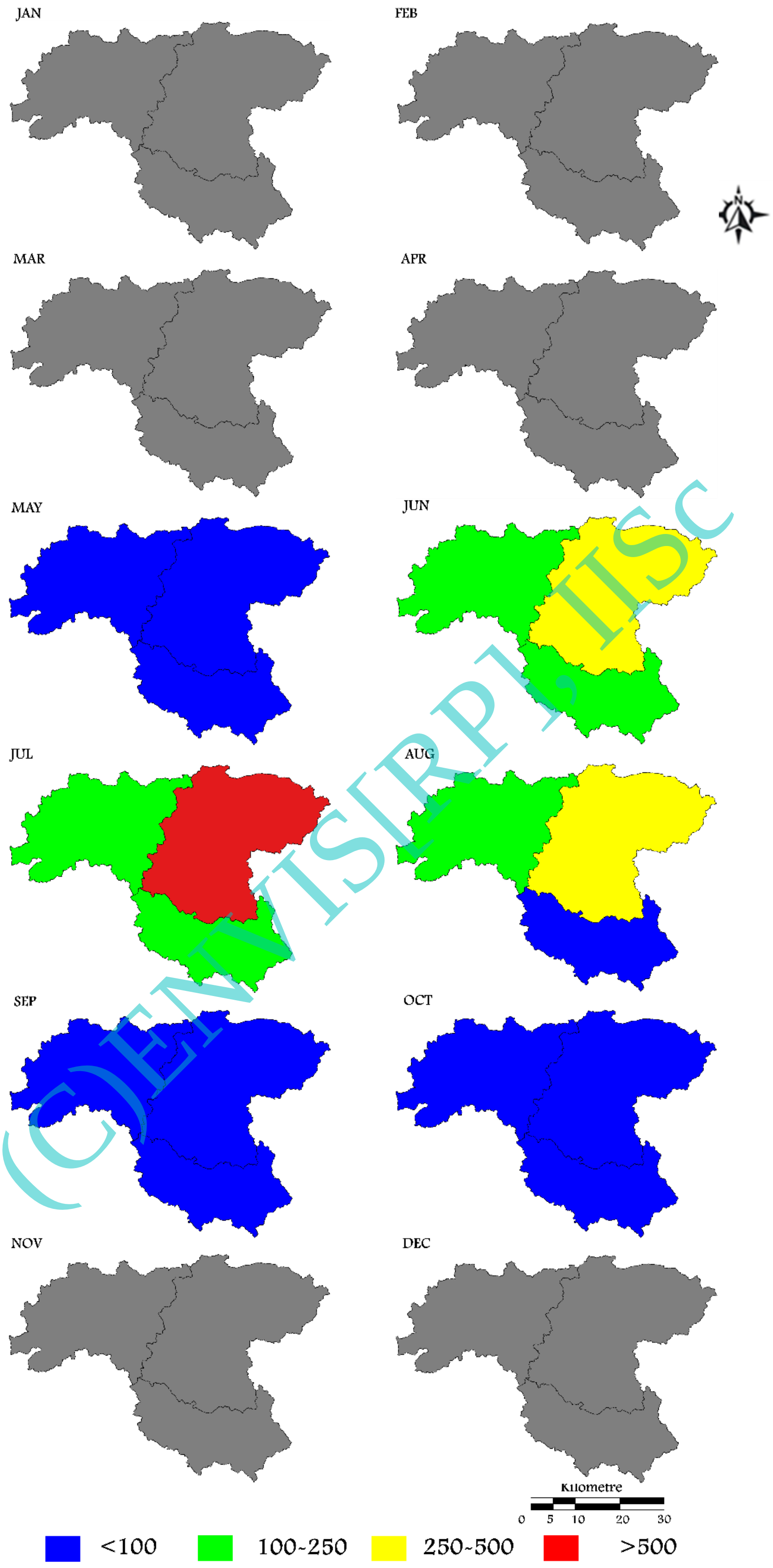


Figure 5.91: Interception (in Mm3)-Mahadayi catchment

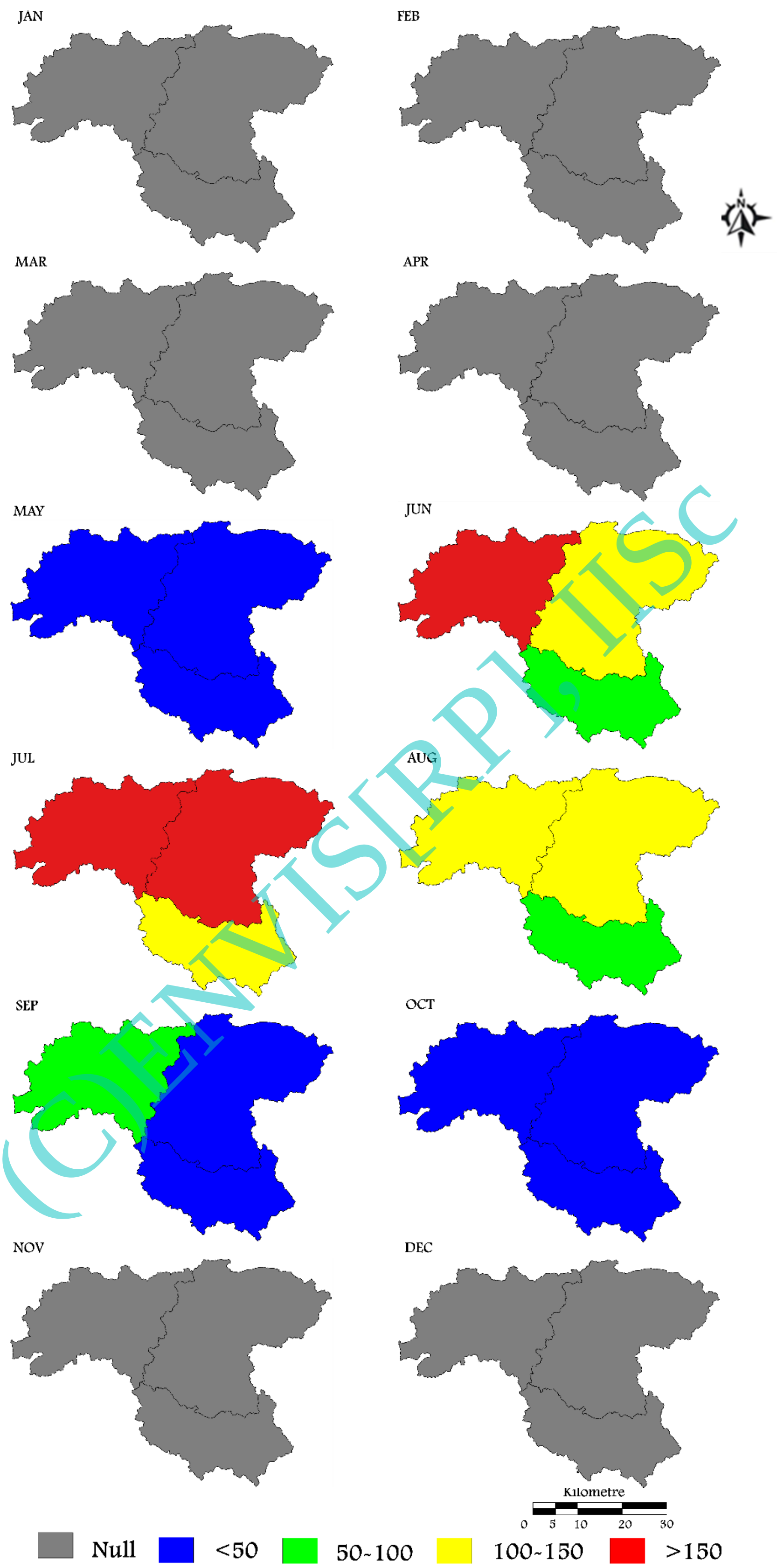


Figure 5.92: Runoff (in Mm^3)-Mahadayi catchment

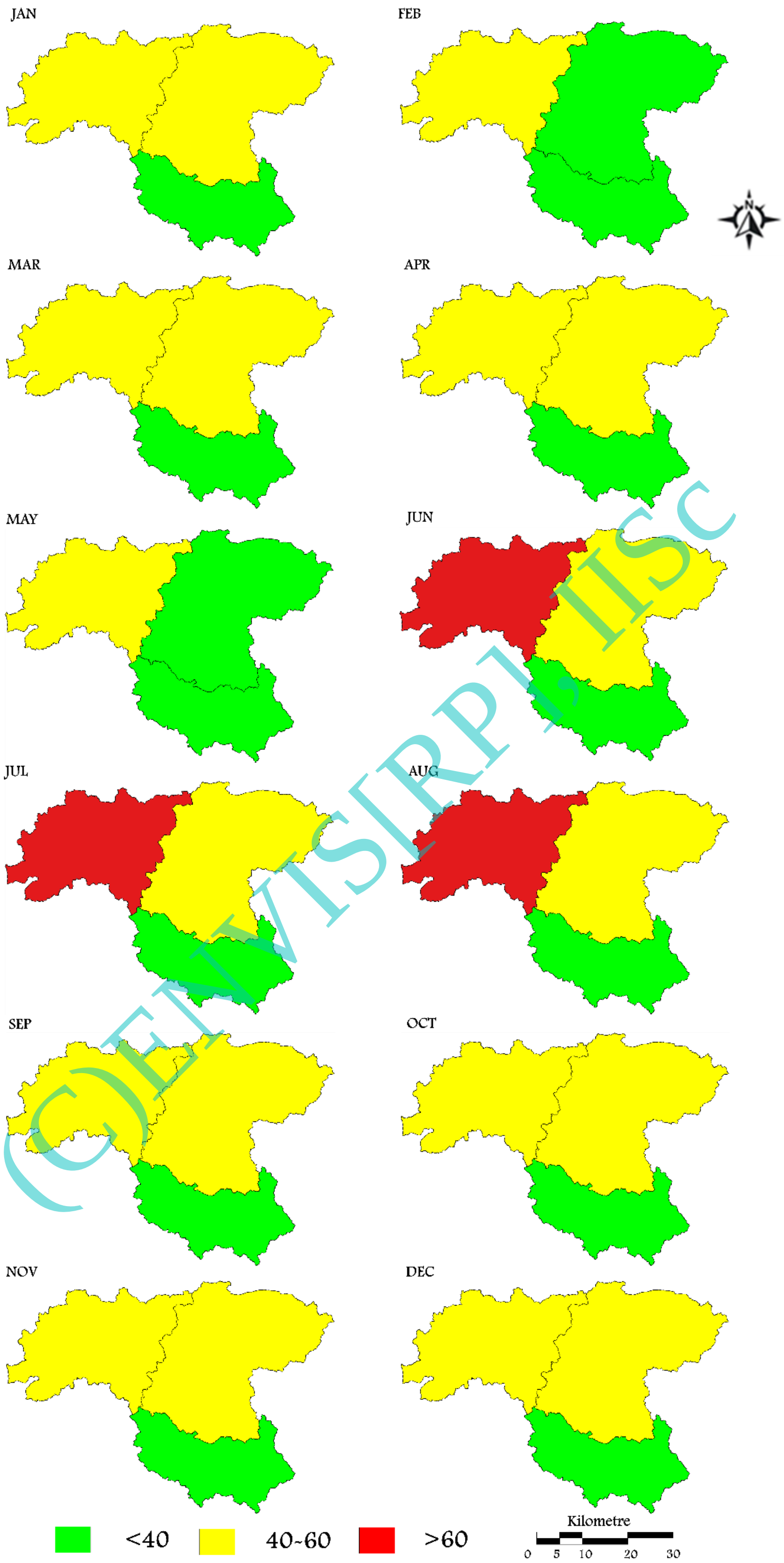


Figure 5.93: Crop water demand(in Mm^3) - Mahadayi catchment

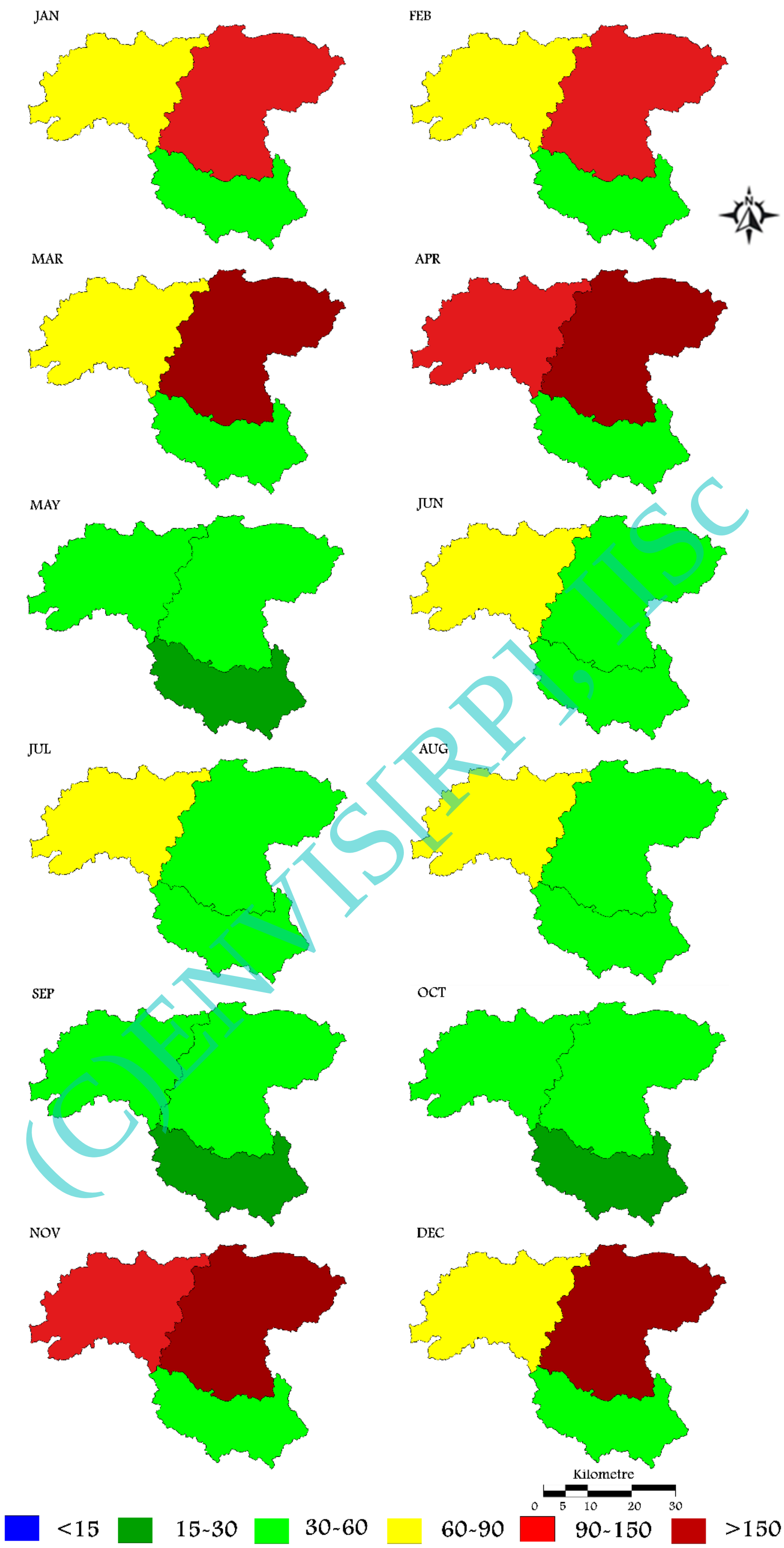


Figure 5.94: Total demand(in Mm^3)-Mahadayi catchment

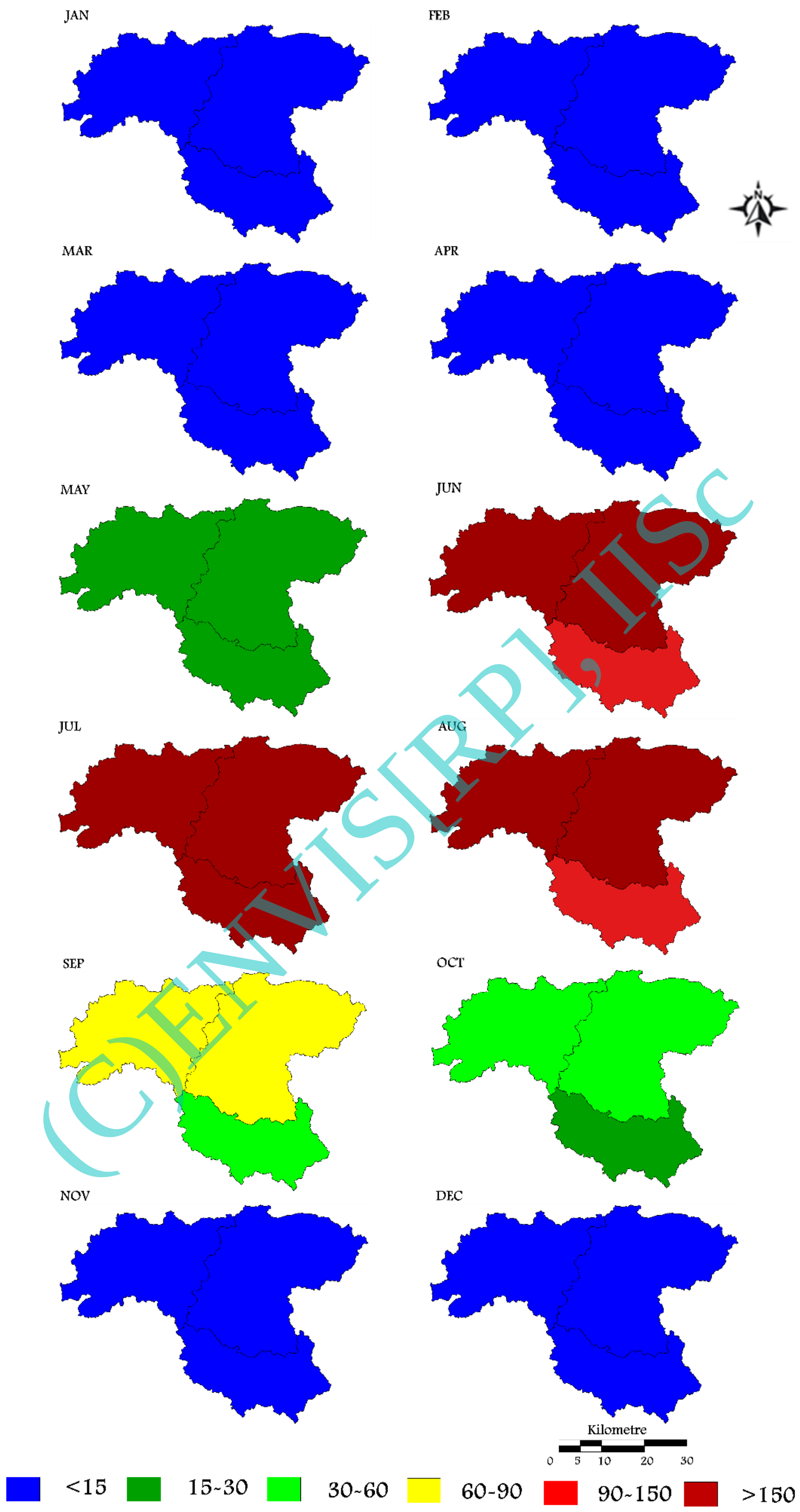


Figure 5.95: Water available (in Mm^3)- Mahadayi catchment

Table 5.29: Eco-hydrological assessment in Mahadayi catchment (in Mm3) -1972

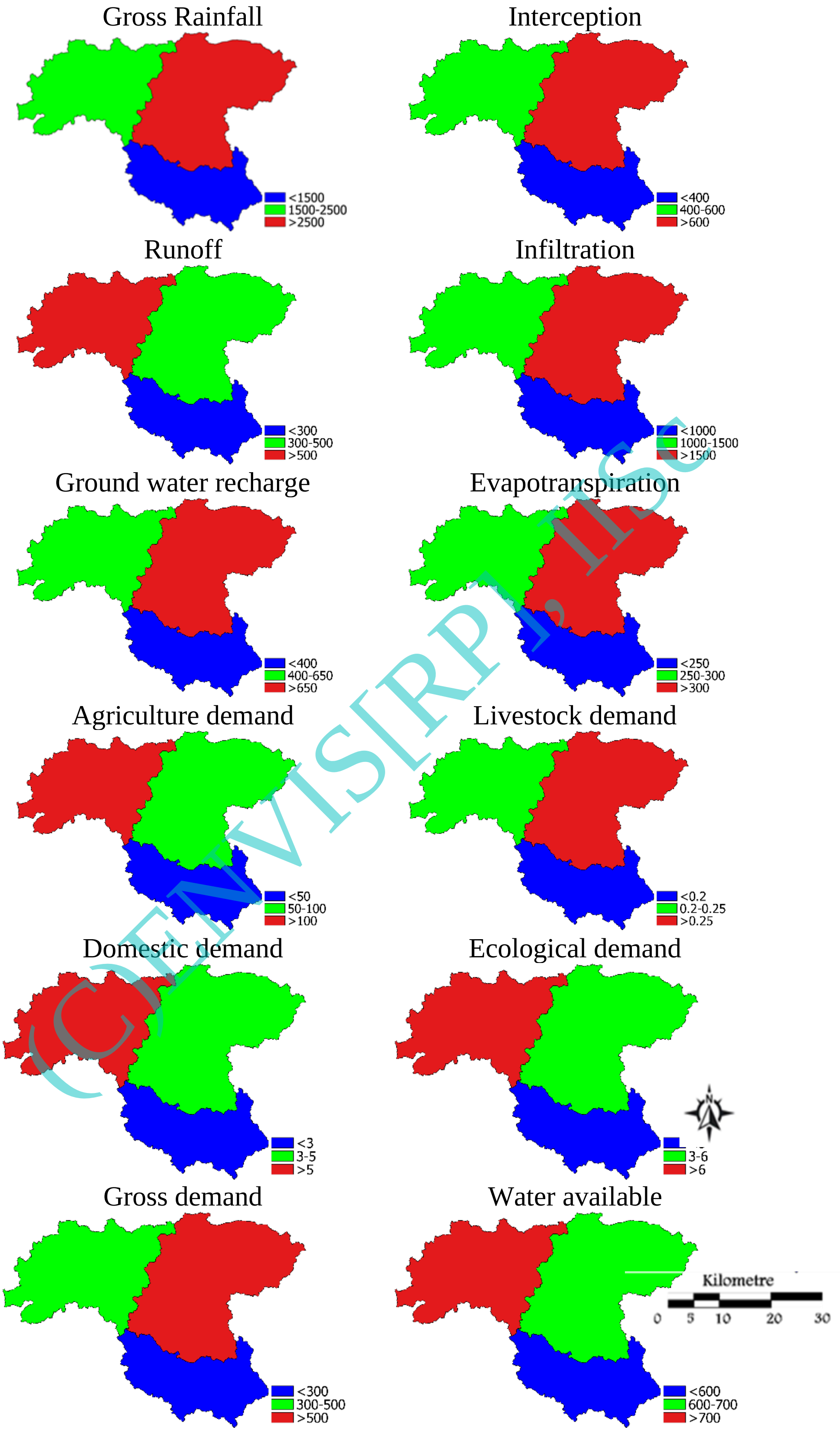
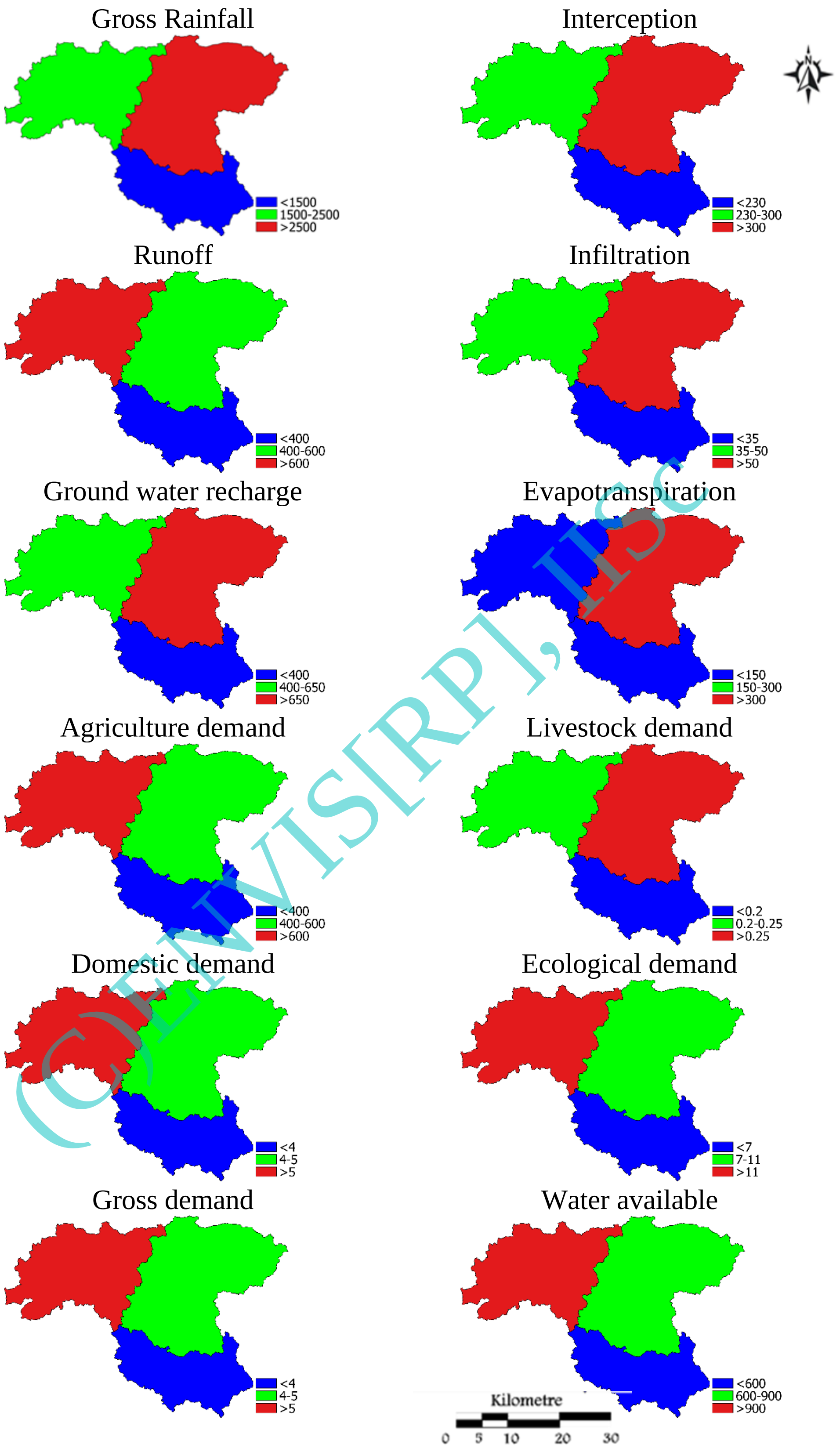
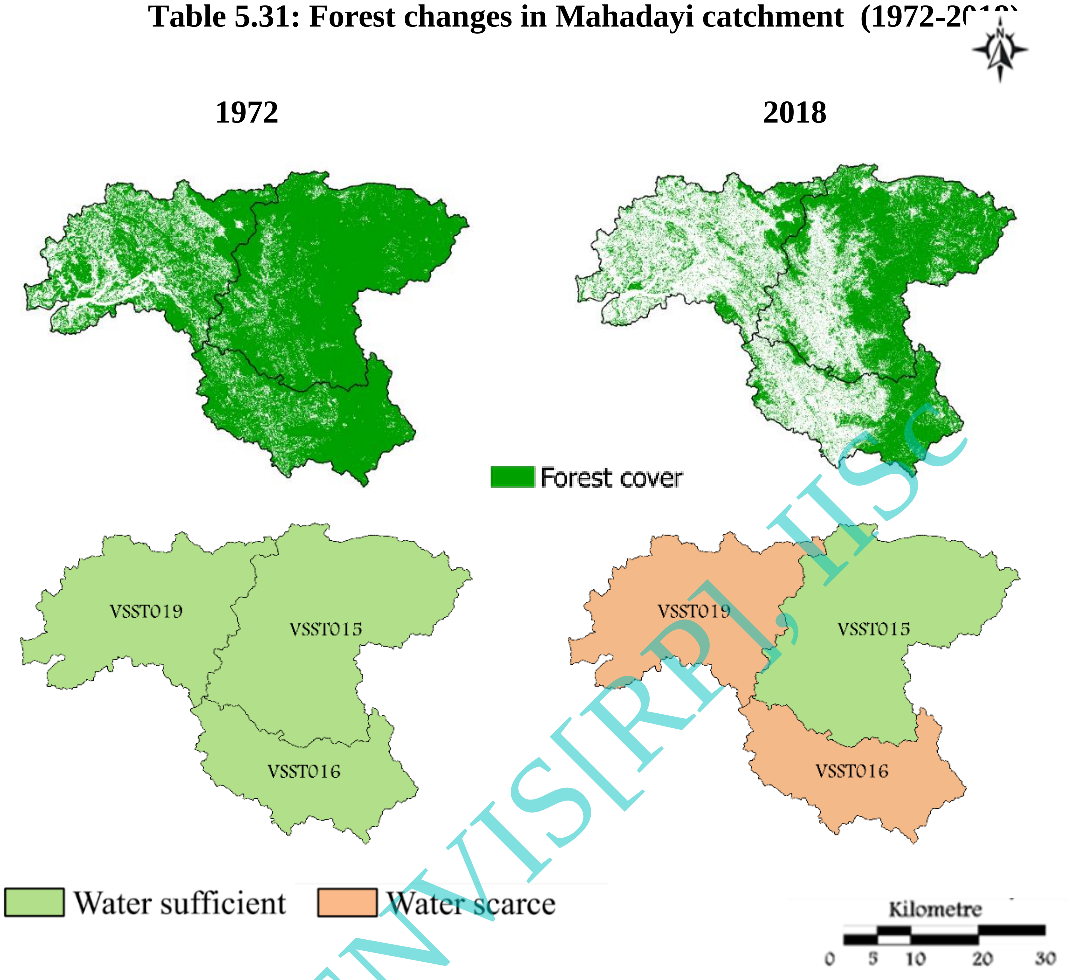


Table 5.30: Eco-hydrological assessment in Mahadayi catchment (in Mm3) -2018


Gross Rainfall
<1500
1500-2500
>2500
Interception
<230
230-300
>300
Runoff
<400
400-600
>600
Infiltration
<35
35-50
>50
Ground water recharge
<400
400-650
>650
Evapotranspiration
<150
150-300
>300
Agriculture demand
<400
400-600
>600
Livestock demand
<0.2
0.2-0.25
>0.25
Domestic demand
<4
4-5
>5
Ecological demand
<7
7-11
>11
Gross demand
<4
4-5
>5
Water available
<600
600-900
>900
Kilometre
0 5 10 20 30

5.10 Eco-hydrological footprint of Mahadayi Catchment from 1972-2018

Table 5.31: Forest changes in Mahadayi catchment (1972-2018)



Basin Id	1972	2018	% decrement of forest (1972-2018)
VSS015	93.98	66.57	29.17
VSS016	89.00	49.91	43.92
VSS019	62.80	30.01	52.22

Temporal analysis carried out for the catchment reveals the large-scale changes in the forest, as shown in Table 5.31. Sub-catchments VSST015, which is part of Western Ghats due to forest cover, retains water for all 12 months, leading to sufficient conditions. Sub-catchments VSS016 and VSS019 i.e. the regions of Panaji, Bicholim have undergone intense urbanization from 1972 to 2018 leading to water scarce conditions about 1 to 3 months' shortage in the catchment. This analysis carried out in the establishment of eco-hydrological footprint revealed the importance of forest in retaining the catchment with sufficient water conditions required to meet the ecological and societal needs.

Hydrological assessment reveals that forest with native vegetation helps maintain the streamflow, water holding capacities (groundwater recharges and vadose water), groundwater discharges (base flows), which plays a pivotal role in catering the ecological and societal requirements.

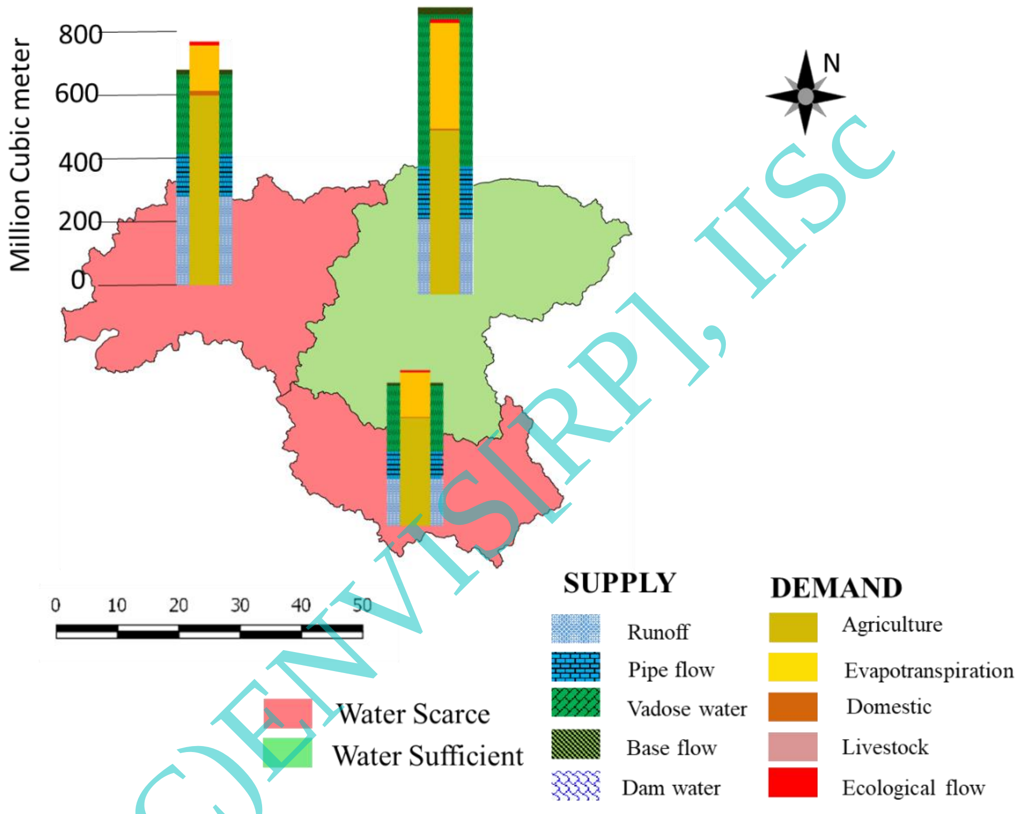


Figure 5.96: Eco-hydrological footprint (Mahadayi catchment)

Conclusion

Landscapes in the catchments of Ghataprabha, Malaprabha, Mandovi have witnessed alterations from 1972 to 2018, which is evident from the decline of forest cover by about 39.45% in Ghataprabha, 33.35% in Malaprabha, and 35.31% in Mandovi. The structural changes of the landscape in the catchment have disturbed the natural hydrologic regime. In this study, assessment of Eco-Hydrological footprint considered the requirement of water for forests, ecological, domestic, livestock, and agriculture requirements. The green water requirements that are the evapotranspiration requirements are being met by the percolated water in the vadose zone, as surface and subsurface flows function.

Eco-hydrological footprint established in the catchment emphasizes the role of forest in infiltration and evapotranspiration capabilities. The sub-catchments dominated with forest cover provided sufficient water in catering to the societal and ecological requirements for all the 12 months over other land use categories. The environmental linkages with landscape dynamics are strengthened with this study and provides an invaluable insight to understand the need for integrated approaches in the river basin management to overcome the poor water efficiency by preserving the forest cover.

The present concern is to focus on the sustenance of the remaining forest for water and food security, which needs to be accounted for in the river basin management.

BIBLIOGRAPHY

[1] "Food and Agriculture Organization (FAO)," Rome., 2000.

[2] Brij gopal, *Environmental flows, An introduction for water resources managers*. 2013.

[3] New Zealand Ministry for the Environment, "Draft guidelines for the Selection of Methods to Determine Ecological Flows and Water Levels," 2008.

[4] M. Dyson, G. Bergkamp, and J. Scanlon, "Flow: The Essesntials of Environmental Flows," 2003.

[5] T. C. Annear *et al.*, "Instream Flows for Riverine Resource."

[6] Ministry of Water Resources INDIA, "National Water Policy 2012," 2012.

[7] B. Karthick, K. Divakar, Mesta, and T. V. Ramachandra, "Influence of land-use changes on stream ecology," 2006.

[8] lilesand, Kiefer, and Chipman, *Remote sensing and image interpretation*. .

[9] E. F. Lambin, H. J. Geist, and E. Lepers, "Dynamics of Land-Use and Land-Cover Change in Tropical Regions."

[10] T. V. Ramachandra, S. Vinay, S. Bharath, and A. Shashishankar, "Eco-hydrological footprint of a river basin in western ghats," *Yale J. Biol. Med.*, vol. 91, no. 4, pp. 431–444, 2018.

[11] A. Das Gupta, "Implication of environmental flows in river basin management," *Phys. Chem. Earth*, vol. 33, no. 5, pp. 298–303, 2008.

[12] S. Vinay, H. A. Bharath, S. Chandran, and T. V Ramachandra, "Linkages between Catchment Landscape Dynamics and the Natural Flow Regime," 2016.

[13] T. W, *Watershed management*. .

[14] T. V. Ramachandra, S. Vinay, R. Bhargavi, and H. A. Bharath, "Integrated Watershed Management For Water Food Security in Kolar and Chikballapur districts, Karnataka," 2017.

[15] "The importance of environment flow," *IUCN WWF*.

[16] H M RAGHUNATH, *Hydrology*. .

[17] J. D. Tonkin, S. C. Jähnig, and P. Haase, "The rise of riverine flow-ecology and environmental flow research," *Environ. Process.*, vol. 1, no. 3, pp. 323–330, 2014.

[18] H. J. Finkel, "Hydrology," *Semiarid Soil Water Conserv.*, pp. 5–26, 2018.

[19] H. Gu, Z. Yu, C. Yang, Q. Ju, B. Lu, and C. Liang, "Hydrological assessment of

TRMM rainfall data over Yangtze River Basin," *Water Sci. Eng.*, vol. 3, no. 4, pp. 418–430, 2010.

[20] "RESEARCH ON ACCURACY ASSESSMENT OF URBAN RAINFALL SPATIAL INTERPOLATION FROM GAUGES DATA School of Geomatics and Urban Spatial Information of Beijing University of Civil Engineering and Architecture , Beijing , China Key Laboratory for Urban Geomatics of ," pp. 3121–3124, 2014.

[21] T. Davie, *Fundamentals of hydrology*. 2017.

[22] M. R. Y. Putty and R. Prasad, "Runoff processes in headwater catchments — an experimental study in Western Ghats , South India," vol. 235, pp. 63–71, 2000.

[23] J. Wang, X., Cao, Y., Hong, Y., & Zhou, B. (2012, "Effects of forest on stream water quality in southeast China. In World Automation Congress (WAC), 2012 (pp. 1-4). IEEE."

[24] R. H. Hawkins, "Asymptotic Determination of Runoff Curve Numbers from Data," *J. Irrig. Drain. Eng.*, vol. 119, no. 2, pp. 334–345, Mar. 1993.

[25] A. B. Lakhote, D. B. V. Khode, and E. N. Z. Baisware, "Analysis of Rainfall Runoff for Agricultural Watershed Area," *IOSR J. Environ. Sci. Toxicol. Food Technol.*, vol. 8, no. 5, pp. 58–65, 2014.

[26] P. Natarajan, S. V. Kottiswaran, A. Balasubramanian, and B. Palanikumaran, "Groundwater Recharge Estimation Using Comparison of Methods in Sirumugai Area of Coimbatore, Tamil Nadu, India," *Int. J. Curr. Microbiol. Appl. Sci.*, vol. 7, no. 06, pp. 1433–1440, 2018.

[27] M. Ali, S. Mubarak, A. Islam, and P. Biswas, "Comparative Evaluation of Various Empirical Methods for Estimating Groundwater Recharge," *Arch. Curr. Res. Int.*, vol. 11, no. 1, pp. 1–10, 2017.

[28] P. G. Deshbhandari and C. Krishnaiah, "Comparative Analysis of Empirical Models Derived Groundwater Recharge Estimation in Venkatapura," vol. IV, no. June, pp. 7–10, 2017.

[29] A. Berti, G. Tardivo, A. Chiaudani, F. Rech, and M. Borin, "Assessing reference evapotranspiration by the Hargreaves method in north-eastern Italy," *Agric. Water Manag.*, 2014.

[30] I. Drainage, S. Eng, N. Kb, and S. Av, "Irrigation & Drainage Systems Engineering Study on Water Requirement of Selected Crops under Tarikere Command Area using

CROPWAT," vol. 5, no. 1, pp. 5–8, 2016.

[31] H. A. Bharath, S. Bharath, and D. Sanna Durgappa, "Empirical patterns of the influence of Spatial Resolution of Remote Sensing Data on Landscape Metrics," vol. 2, no. 3, pp. 767–775, 2012.

[32] T. V. Ramachandra and S. Bharath, "Geoinformatics based Valuation of Forest Landscape Dynamics in Central Western Ghats, India," *J. Remote Sens. GIS*, 2018.

[33] "SWAT." .

[34] A. V. J. Perumal, M. A. Maun, and S. P. Ecology, "Ecophysiological Response of Dune Species to Experimental Burial under Field and Controlled Conditions response of dune species to experimental Ecophysiological and controlled conditions burial under field," vol. 184, no. 1, pp. 89–104, 2011.

[35] W. A. Monk, P. J. Wood, D. M. Hannah, and D. A. Wilson, "Selection of river flow indices for the assessment of hydroecological change," *River Res. Appl.*, vol. 23, no. 1, pp. 113–122, 2007.

[36] H. Mei, Yangxiaoyan, Liuyuan, and Duhuan, "The research progress of ecological water requirement in China and abroad," *Procedia Environ. Sci.*, vol. 2, pp. 1904–1911, 2010.

[37] X. Fuju, Z. Mingxi, and Z. Hong, "Research on Ecological Environmental Carrying Capacity in Yellow River Delta," *Energy Procedia*, vol. 5, pp. 1784–1790, 2011.

[38] F. Yang, Z. Xia, L. Yu, and L. Guo, "Calculation and analysis of the instream ecological flow for the Irtysh River," *Procedia Eng.*, vol. 28, no. 2011, pp. 438–441, 2012.

[39] A. Dubey, D. Kant, O. Singh, and R. P. Pandey, "A Comparative Study of Environmental Flow Requirement Approaches Using Hydrological Index Methods," *J. Indian Water Resour. Soc.*, vol. 33, no. 3, pp. 20–27, 2013.

[40] S. Vinay, S. Bharath, H. A. Bharath, and T. V. Ramachandra, "Hydrologic model with landscape dynamics for drought monitoring," in *Joint International Workshop of ISPRS VIII/1 and WG IV/4 on Geospatial Data for Disaster and Risk Reduction*, 2013.

[41] T. V. Ramachandra, N. Nagar, S. Vinay, and H. A. Bharath, "Modelling hydrologic regime of Lakshmanatirtha watershed, Cauvery river," *2014 IEEE Glob. Humanit. Technol. Conf. - South Asia Satell. GHTC-SAS 2014*, pp. 64–71, 2014.

[42] A. Butt, R. Shabbir, S. S. Ahmad, and N. Aziz, "Land use change mapping and

analysis using Remote Sensing and GIS: A case study of Simly watershed, Islamabad, Pakistan," *Egypt. J. Remote Sens. Sp. Sci.*, vol. 18, no. 2, pp. 251–259, 2015.

[43] S. Adhikari, S. M. Shrestha, R. Singh, S. Upadhaya, and J. R. Stapp, "Land Use Change at Sub-Watershed Level," *J. Waste Water Treat. Anal.*, vol. 7, no. 3, pp. 3–7, 2016.

[44] T. V. Ramachandra, S. Vinay, and H. A. Bharath, "Environmental Flow Assessment in a Lotic Ecosystem of Central Western Ghats, India," *J. Waste Water Treat. Anal.*, vol. 7, no. 3, pp. 1–14, 2016.

[45] S. J. Zeiger and J. A. Hubbart, "Quantifying relationships between watershed characteristics and hydroecological indices of Missouri streams," *Sci. Total Environ.*, vol. 654, pp. 1305–1315, 2019.

[46] "Shodganga."

[47] S. E. Fick and R. J. Hijmans, "Worldclim 2: New 1-km spatial resolution climate surfaces for global land areas," *International Journal of Climatology*, 2017. [Online]. Available: http://worldclim.org/version2.

[48] "Office of the Registrar General & Census Commissioner, India," 2019. [Online]. Available: http://censusindia.gov.in/.

[49] "Soil map of India," 2019. [Online]. Available: https://esdac.jrc.ec.europa.eu/.

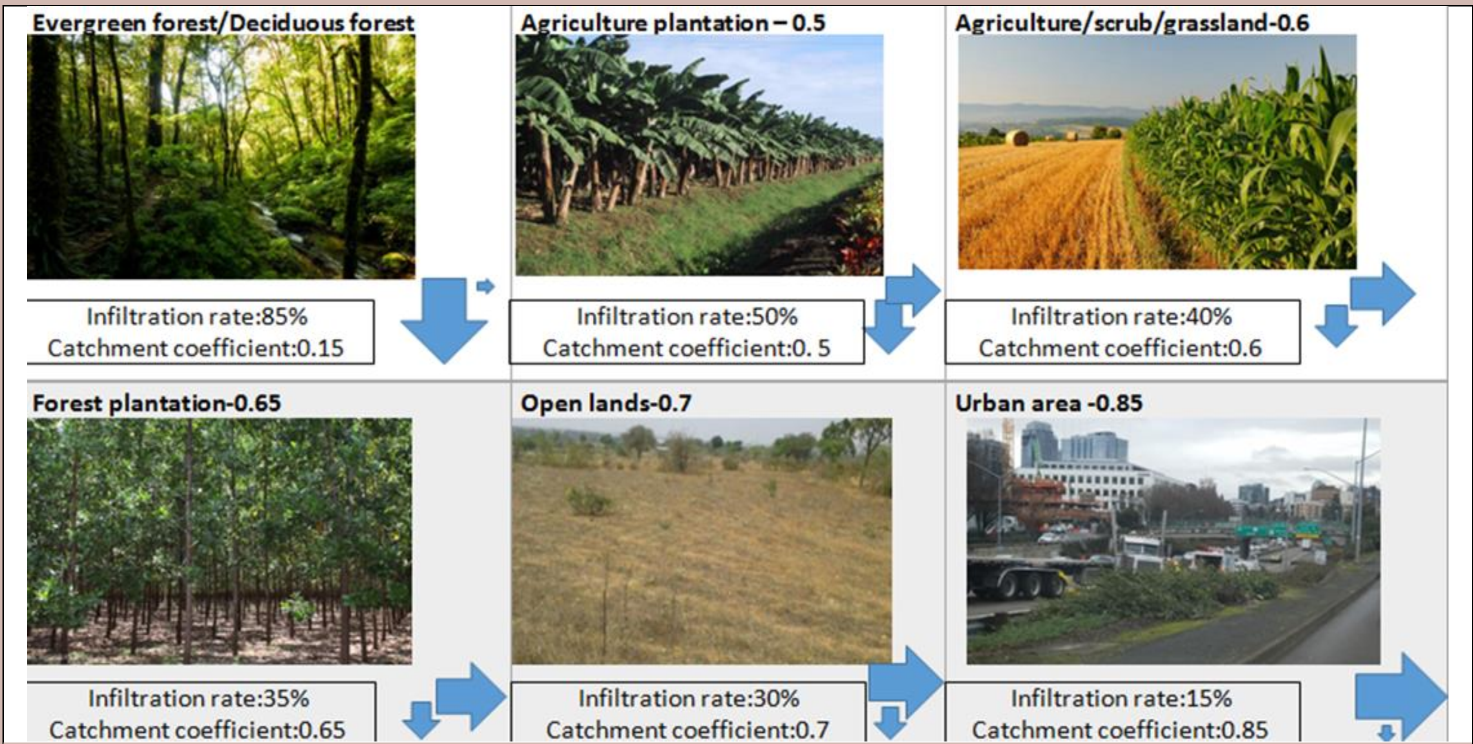
[50] "Central Ground Water Board (CGWB)," 2018. [Online]. Available: http://cgwb.gov.in/.

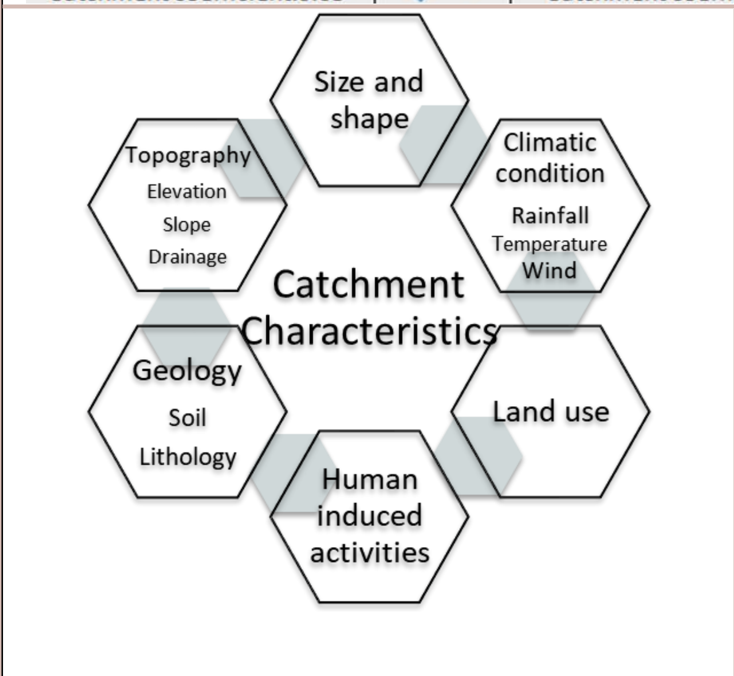
[51] T. V Ramachandra, S. Vinay, S. Bharath, and H. A. Bharath, *Profile of Rivers in Karnataka*,. ENVIS Technical Report 129, Sahyadri Conservation Series 71, 2017.

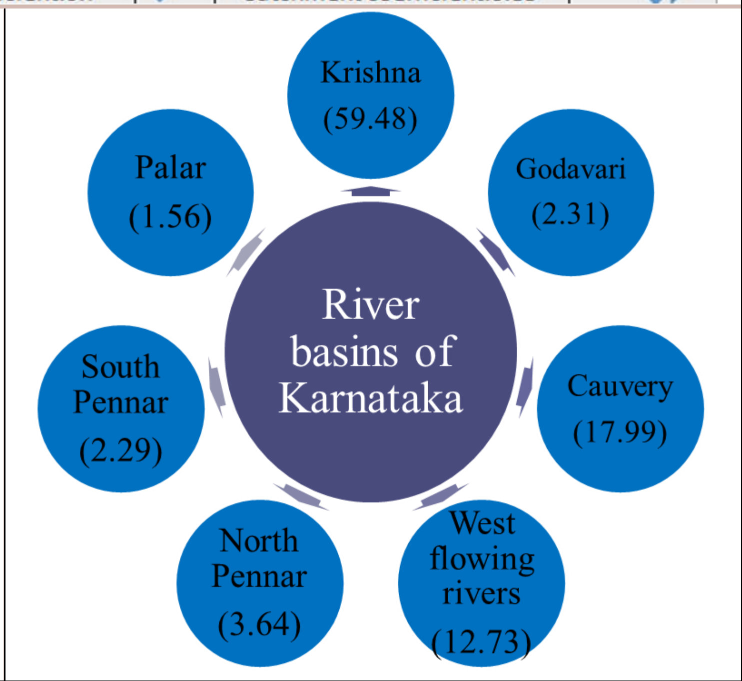
[52] "Land Processes Distributed Active Archive Center (LP DAAC) at the USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota."

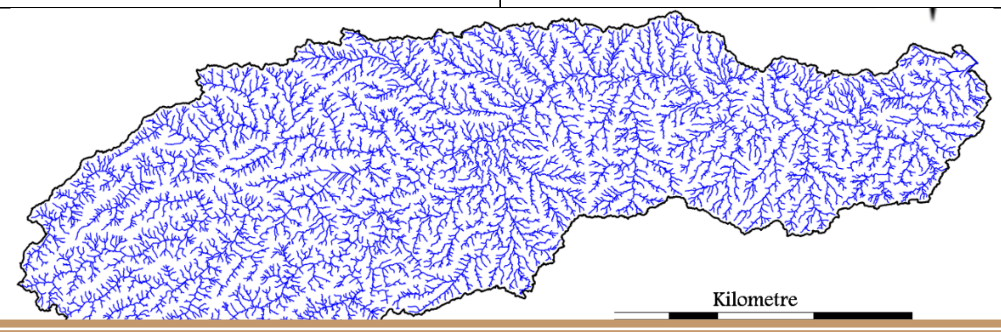
[53] "National Food security mission." [Online]. Available: https://nfsm.gov.in/nfmis/rpt/calenderreport.aspx.

[54] "Raithamitra." [Online]. Available: http://raitamitra.kar.nic.in/KAN/index.asp.









ENERGY AND WETLANDS RESEARCH GROUP
SAHYADRI: ENVIRONMENTAL INFORMATION SYSTEM (ENVIS)
CENTRE FOR ECOLOGICAL SCIENCES
NEW BIOSCIENCE BUILDING, III FLOOR, E-WING, LAB: TE15
Indian Institute of Science, Telephone : 91-80-22933099/22933503(Ext:107)
Fax : 91-80-23601428/23600085/23600683[CES-TVR]
Email : tvr@iisc.ac.in, energy.ces@iisc.ac.in
Web: http://ces.iisc.ernet.in/energy, http://ces.iisc.ernet.in/biodiversity
Open Source GIS: http://ces.iisc.ernet.in/grass