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Forestry Interventions and Groundwater Recharge, Sediment Control and Carbon Sequestration in the Krishna River Basin

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Abstract

It is a known fact that human activities have a significant impact on global rivers, making the task of rehabilitating them to their former natural state or a more semi-natural state quite challenging. The ongoing initiative called "Rejuvenation of Krishna River through Forestry Interventions" aims to contribute to the overall river rejuvenation program in the country. In this context, the effects of forestry interventions on the Krishna River will be evaluated based on water quantity, water quality, and the potential for carbon sequestration through plantation efforts. To assess the outcomes of this study, various methodologies such as Soil Conservation Service Curve Number (SCS-CN), Central Ground Water Board (CGWB) and Intergovernmental Panel on Climate Change (IPCC) have been utilized to estimate water savings, reduction in sedimentation, and carbon sequestration potential within the Krishna basin. The projected results indicate that the implementation of forestry plantations and soil and moisture conservation measures in the Krishna River rejuvenation program could lead to significant improvements. Specifically, the interventions are expected to enhance water recharge by 400.49 million cubic meters per year, reduce sedimentation load by 869.22 cubic meters per year, and increase carbon sequestration by 3.91 lakh metric tonnes per year or 14.34 lakh metric tonnes of CO_2 equivalent. By incorporating forestry interventions into the Krishna riverscape, it is anticipated that the quality and quantity of water flowing through the river will be positively impacted. These interventions will enhance water infiltration, mitigate soil erosion, and contribute to an improved vegetation cover, thereby conserving biodiversity. Moreover, they offer additional intangible benefits such as addressing climate change concerns through enhanced carbon sequestration potential along the entire stretch of riverine areas.

Keywords

Forestry Interventions, Krishna River Basin, Sediment Control, Water Recharge, Carbon Sequestration

1. Introduction

The Krishna basin is characterized by significant variations, particularly in terms of precipitation, evapotranspiration, water supply, and cropping patterns, as highlighted by Biggs et al. (2007). Research studies indicate that future climate change scenarios may further exacerbate hydrological extreme events in the basin (Nikam et al., 2018). The fertile nature of the basin has led to a shift from subsistence farming to intensive farming, driven by improved irrigation facilities and a change in cropping patterns favouring high-value crops. However, this transition has gradually resulted in the accumulation of salinity in the command areas and the loss of fertile soil. The intensive farming practices in the region also demand increased water usage, leading to escalated groundwater extraction. Consequently, the depletion of groundwater resources has resulted in reduced streamflow, leading to the degradation of mangrove vegetation in the Lower Krishna Basin (Survase, 2014; Supriya, 2015). Moreover, the presence of several urban areas along the banks of the Krishna River and its tributaries has resulted in rapid development and industrialization. Unfortunately, improper waste management practices in these urban areas have led to water pollution and the indiscriminate dumping of waste along the riverbanks (Pullaiah, 2012; Hemant et al., 2018).

Furthermore, the Krishna basin has been identified as an “active hotspot of frequent drought occurrences,” with a significant portion of the basin exhibiting medium-to-high vulnerability to drought. Studies have documented a notable increase in the number and intensity of hot days within the Krishna Basin, accompanied by extreme high temperatures during dry periods, while observing a scarcity of cold temperatures during the winter months (Bobba et al., 1997; Deshpande et al., 2016). Krishna is a prominent east flowing river of the Peninsular India, which sustains diverse ecosystems in four states of Maharashtra, Karnataka, Telangana and Andhra Pradesh. The river originates in wet evergreen forests of Western Ghats at an elevation of 1337 m near Mahabaleshwar in Maharashtra State (Ramachandra et al., 2017) and flows in arid and scrub lands of Deccan plateau before joining Bay of Bengal with the formation of mangrove delta at the mouth. Apart from forested areas, the water flows through vast expanse of agricultural lands with diverse cropping patterns and through densely populated urban/peri-urban areas. Krishna River and its tributaries form an important riverine system which is a lifeline for four major states of India; however, these rivers are highly stressed due to over exploitation and pollution. It involves both extremities such as fragile biodiversity rich mountain ranges of Western Ghats, which receives the highest rainfall in the world and most arid regions of the Deccan plateau of India. Restoration of such diverse ecosystems is a challenging task.

Restoring degraded waterways and ensuring their ecological integrity is a complex and challenging endeavor. However, restoration efforts should prioritize maximizing natural processes while addressing current human priorities. Over the past few decades, there has been a growing integration of hydrological, geomorphological, and biological research, leading to a better understanding of dynamic river systems. It is a well-known fact that human activities heavily influence rivers worldwide, making the task of rehabilitating a river to its former or semi-natural state quite challenging (Acevedo et al., 2014). Rehabilitation projects commonly aim to enhance the naturalness of rivers, with "naturalness" becoming a crucial aspect of the restoration ethos (Nienhuis et al., 2002). Skidmore and Wheaton (2022) highlight the importance of considering riverscapes as critical natural infrastructure, which can contribute to ecosystem-based adaptation, improve resilience to climate change, and restore river ecosystem health. The concept of "riverscape," particularly in a developing country like India, holds significant value due to the strong linkages major rivers have with civilization, culture, and prosperity. The riverscape approach seeks to describe the broad-scale physical, biological, and aesthetic characteristics of rivers, examining spatio-temporal patterns and processes that connect rivers, their banks, and riparian areas within a fluvial system. This approach provides insights into the complex interactions between disturbance regimes, spatial heterogeneity, and biodiversity (Singh et al., 2023).

Forests, aquifers, soils, lakes, and wetlands all play vital roles in water management. Wetlands and soils filter water, lakes and wetlands store water, rivers provide conveyance and transportation, floodplains and wetlands mitigate flood peaks downstream, while mangroves, coral reefs, and barrier islands protect coastlines from storms and inundation. Sustainable forest management is crucial for effective water management and can offer nature-based solutions to various water-related challenges. Protecting and restoring natural vegetation yields numerous benefits, as natural communities have evolved to sustain water effectively without human intervention. Local observations are valuable in identifying effective strategies for specific locations (Carey, 2020). Forests also play a significant role in mitigating and adapting to climate change. They act as sinks, reservoirs, and sources of carbon. Healthy and expanding forests sequester and store more carbon than any other terrestrial ecosystem (FSI, 2019). Trees and forests influence hydrological cycles by modifying the release of water into the atmosphere, affecting soil moisture, and improving soil infiltration and groundwater recharge (Springgay et al., 2019). Changes in land use related to forests, such as deforestation, reforestation, and afforestation, can impact water supplies locally and in distant areas (Jones et al., 2022). For example, deforestation in one region leading to reduced evapotranspiration may result in decreased rainfall in downwind areas (Ellison et al., 2017). Furthermore, climate change and increased occurrence of extreme weather events disrupt water cycles and pose threats to the stability of water flows (IPCC, 2019).

The Institute of Wood Science and Technology (IWST) in Bengaluru, in collaboration with the Ministry of Environment, Forest and Climate Change (MoEF & CC), has prepared a comprehensive "Detailed Project Report" (DPR) titled "Rejuvenation of Krishna River through Forestry Interventions." This project aims to address the restoration of the Krishna River in the four stakeholder states of Maharashtra, Karnataka, Telangana, and Andhra Pradesh. The riverscape approach was adopted for this project, which encompasses a 5 km buffer on either side of the Krishna riverbank within the four states. Additionally, a 2 km buffer was included along the banks of various tributaries of the Krishna River. A total of 13 tributaries have been selected for inclusion in the project, namely Bhima, Koyna, Panchganga, Dudhganga, Ghataprabha, Malaprabha, Tungabhadra, Dindi, Musi, Halia, Paleru, Munneru, and Peddavagu. The designated riverscape covers an area of 34977.47 square kilometres, allowing for planning, assessment, and management of proposed forestry interventions. The project's methodology involves a consultative process, scientific analysis utilizing remote sensing and GIS technologies for geospatial assessment, modelling, and site prioritization in order to rejuvenate the Krishna River (**Table 1**), (IWST, 2022), (**Figure 1**).

Within the delineated riverscape area of the Krishna River, forestry interventions were planned across three landscapes: natural (forests), agriculture (agroforestry), and urban areas, with corresponding conservation activities in each landscape. Conservation interventions include soil and moisture conservation (SMC), wetland management, and riparian wildlife management throughout the river's course. The selection of tree species, shrubs, and medicinal plants for planting in each landscape is based on factors such as biogeographic zone, land use, soil type, and prevalent forest types within the riverscape. Forest type information is particularly important for identifying suitable sites for forestry interventions, focusing on areas with sparse forest cover or those falling within

Table 1. Proposed area in Krishna riverscape.

State	Krishna Basin area (km^2)	Area in riverscape (km^2)	Percent area in riverscape
Maharashtra	69425.00	8393.98	12.09
Karnataka	113271.00	12845.32	11.34
Telangana	39665.56	8130.34	15.32
Andhra Pradesh	36586.44	5607.83	14.13
Total	**258948.00**	**34977.47**	**13.51**

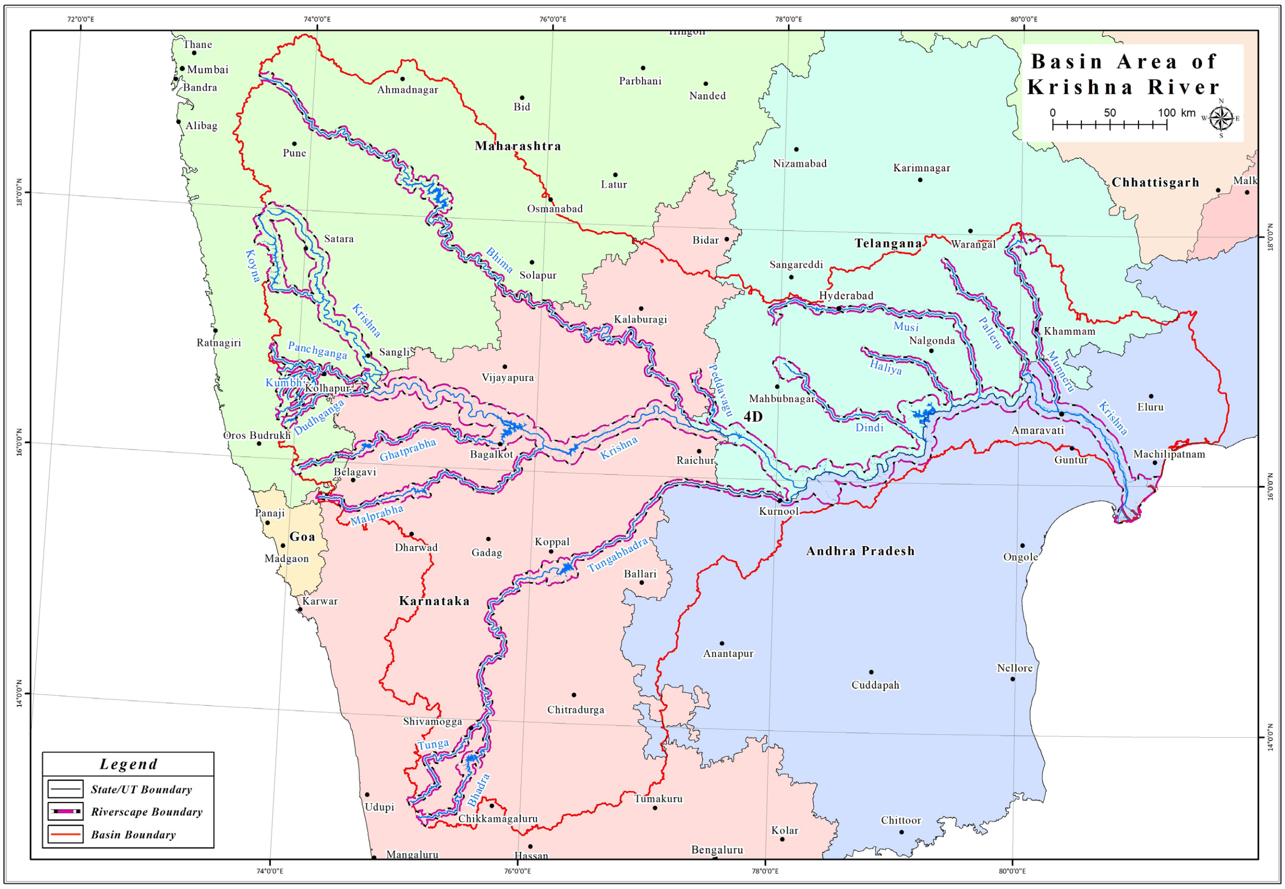


Figure 1. Location map of Krishna riverscape/study area.

scrub and riverine habitats along the river banks. Vegetation type information is also considered when suggesting appropriate sites, taking into account areas with limited forest cover or those within scrub and grassland habitats (Champion & Seth, 1968) (**Figure 2**).

A diverse range of native tree species, grasses, medicinal plants, and fruit trees are proposed for planting within the riverscape area across the states of Maharashtra, Karnataka, Telangana, and Andhra Pradesh. The selection of species aims to enhance the ecological composition of the region. Given the soil erosion activities observed in the Krishna basin (**Figure 3**), the proposed SMC activities include measures such as checkdam, contour trenches, forest/farm ponds, percolation tanks, and gully plugging. These activities are tailored to address the specific needs of hilly regions and plains within the four stakeholder states (IWST, 2022). The locations for forestry interventions within the Krishna basin are illustrated in **Figure 4**.

The implementation of forestry interventions in the Krishna River basin is expected to contribute significantly to achieving several key objectives, including ensuring uninterrupted and unpolluted water flow in the river, reducing sedimentation load, and enhancing carbon sequestration potential in the basin. The primary focus of the present work is to assess the impact of these forestry interventions

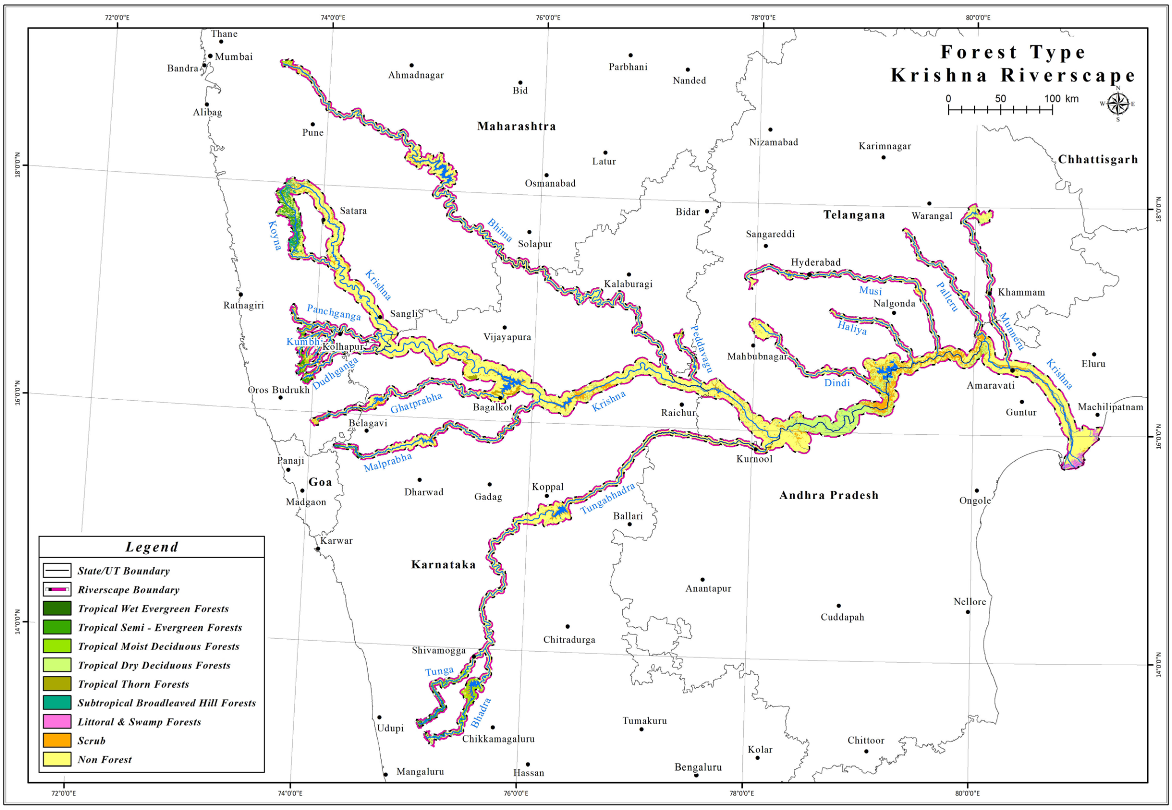


Figure 2. Forest types in Krishna riverscape.

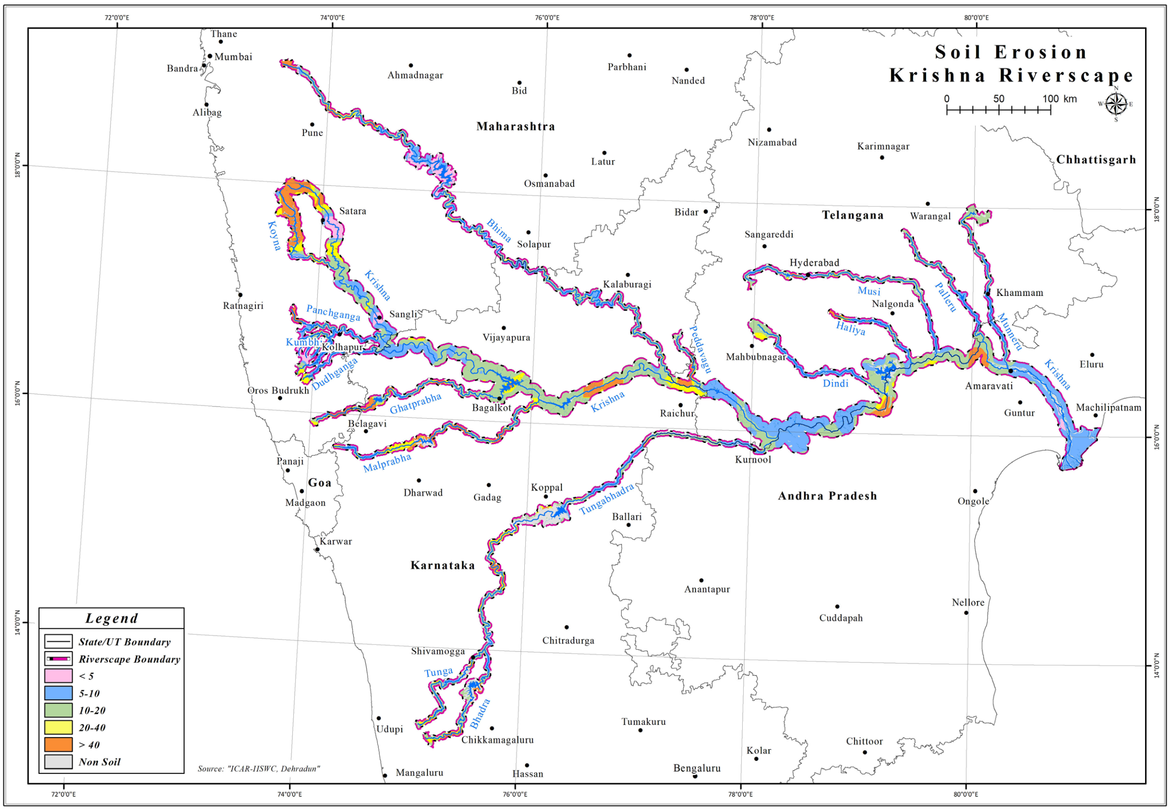
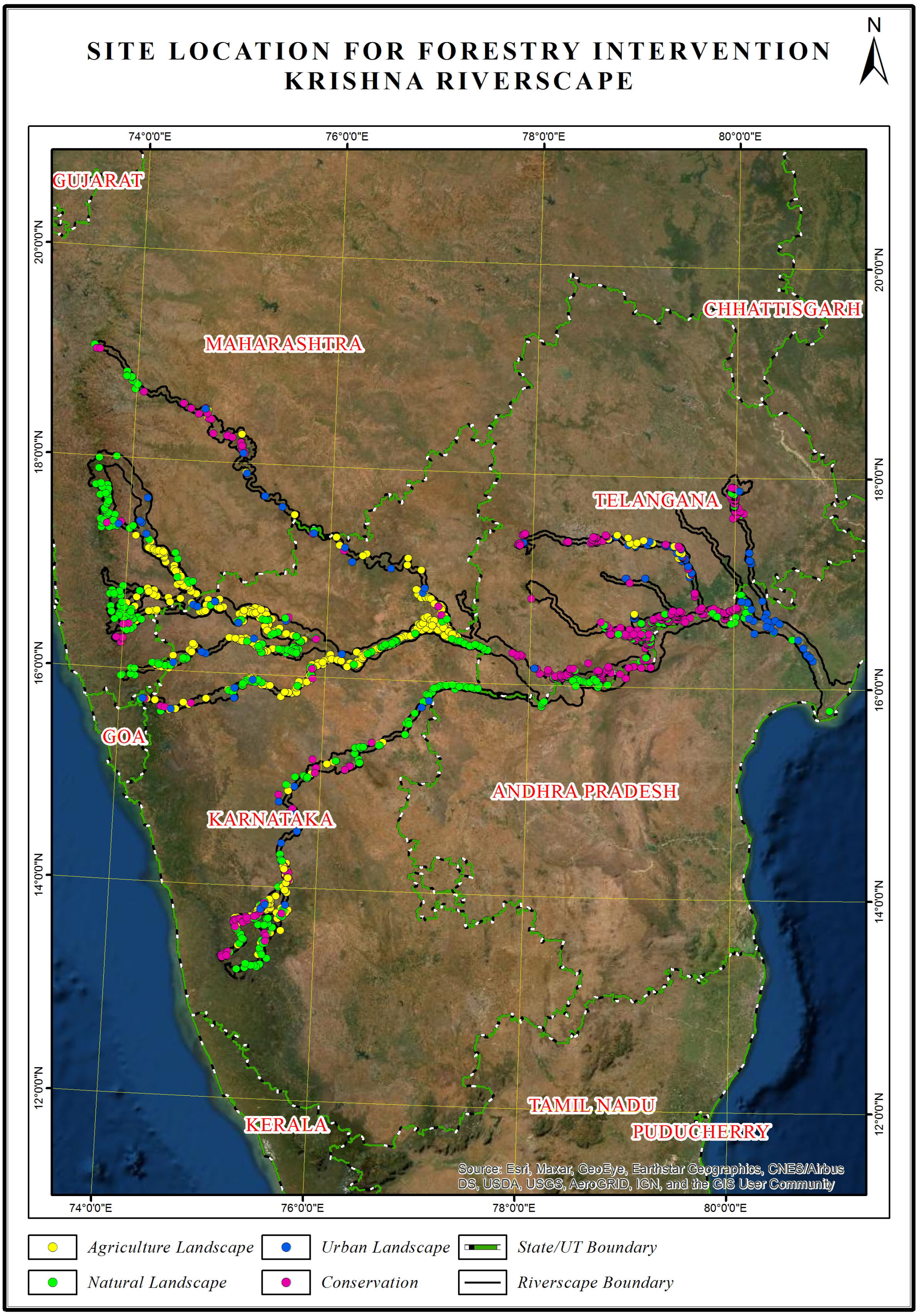


Figure 3. Soil erosion in Krishna riverscape.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 4. Sites of forestry interventions in Krishna riverscape.

on three critical aspects: groundwater recharge, sediment control, and carbon sequestration. By strategically implementing forestry interventions, there is an anticipation of increased groundwater recharge, which can help replenish the water table and contribute to sustainable water resources in the Krishna River basin. Additionally, these interventions aim to mitigate sedimentation by implementing measures such as afforestation, soil conservation, and moisture retention techniques. By minimizing soil erosion and promoting healthy vegetation cover, the interventions can reduce sedimentation load and enhance the overall health of the river system.

Furthermore, the forestry interventions are expected to have a positive impact on carbon sequestration in the basin. Afforestation activities, combined with the preservation and restoration of natural vegetation, can contribute to the absorption and storage of carbon dioxide from the atmosphere. This carbon sequestration potential can help mitigate the impacts of climate change and contribute to the overall ecological integrity of the Krishna River basin. Through systematic assessment and monitoring, the present work aims to evaluate the specific effects of these forestry interventions on groundwater recharge, sediment control, and carbon sequestration in the Krishna River basin. The findings of this study will provide valuable insights and inform future strategies for the rejuvenation and sustainable management of the Krishna River.

2. Material and Methods

In the field of water management, nature-based solutions involve the utilization of ecosystem management techniques to replicate or optimize natural processes, such as vegetation, soils, wetlands, water bodies, and even groundwater aquifers, to ensure the provision and regulation of water resources. The proposed work for the rejuvenation of the Krishna River includes various measures such as protection of natural areas, habitat management, afforestation, catchment area treatment, soil and moisture conservation, restoration of riparian forest buffers, bioremediation, improvement of livelihoods for forest-dependent communities and dwellers, and the promotion of regulated tourism and awareness activities for alternate income generation.

The environmental outcomes of these forestry interventions in the Krishna River basin will be assessed based on water quantity, water quality, and carbon sequestration.

1) The first component of the assessment will involve a conservative estimation of the benefits of the proposed forest plantations and soil and moisture conservation works in terms of green water, which refers to the water stored in the soil and available for plant use. The Soil Conservation Service Curve Number method (SCS-CN) and the methodology of the Central Ground Water Board (CGWB) (GEC, 2015; Trimble, 1999) will be employed to estimate the green water benefits and groundwater potential in the Krishna basin, respectively.

2) The second component of the assessment will focus on quantifying the reduction of sedimentation load in the Krishna basin resulting from the forestry interventions and soil and moisture conservation measures (Central Water Commission, 2019). Sedimentation refers to the process of erosion and transport

of sediment, which is subsequently deposited in water bodies.

3) Lastly, carbon sequestration will be calculated using the methodology outlined by the Intergovernmental Panel on Climate Change (IPCC, 1997). This will involve estimating the carbon sequestration potential of the forested areas as well as non-forest areas within the Krishna basin.

By evaluating these aspects, the environmental impact of the forestry interventions in terms of water quantity, water quality, sedimentation load reduction, and carbon sequestration will be assessed. This comprehensive assessment will provide valuable insights into the effectiveness and potential benefits of the proposed interventions in rejuvenating the Krishna River and its surrounding ecosystem.

2.1. Water Quantity Benefit Assessment

Component 1: *Forestry Plantations*

The first part of the proposed forestry interventions in the Krishna River basin is focused on establishing forest plantations. The objective is to increase the vegetation cover and promote the ecological integrity of the basin. The plantation area and associated quantitative benefits are outlined below:

Plantation Area

The table provided (**Table 2**) contains information on the total plantation area in the Krishna basin riverscape, which includes the buffer zones along the river banks and tributaries.

Green Water Benefits

The Soil Conservation Service Curve Number (SCS-CN) method is employed to estimate the green water benefits of the forest plantations. This method takes into account factors such as soil type, land use, and vegetation cover to determine the water storage and availability for plant use in the basin.

Component 2: *Soil and Moisture Conservation* (*SMC*) *Measures*

The second part of the proposed forestry interventions focuses on implementing soil and moisture conservation measures in the Krishna basin riverscape. These measures aim to reduce soil erosion, improve water retention, and enhance overall water management. The quantitative assessment of SMC activities includes the following aspects:

Table 2. Proposed forestry activities in the Krishna riverscape.

State	Riverscape area (ha)	Plantation area (ha)	SMC works (ha)	Rainfall (mm)
Maharashtra	839398.00	31934.31	1360.68	859*
Karnataka	1284532.00	69168.48	10740.10	
Telangana	813034.00	46018.24	1858.44	
Andhra Pradesh	560783.00	34233.70	437.00	
Total	**3497747.00**	**181354.74**	**14396.22**	

*(Central Water Commission, 2014).

SMC Activities

The table provided (**Table 2**) should contain information on the specific SMC activities planned in the Krishna basin riverscape area. This may include chekdam, contour trenches, forest/farm ponds, percolation tanks, gully plugging, and other relevant measures.

Groundwater Potential: The Central Ground Water Board (CGWB) methodology will be utilized to assess the groundwater potential resulting from the SMC activities. This assessment helps in understanding the impact of the measures on groundwater recharge and availability.

Rainfall Data

Table 2 should also include information on rainfall patterns in the Krishna basin region. This data is crucial for understanding the hydrological dynamics and the overall effectiveness of the proposed forestry interventions. By quantitatively assessing the forestry plantations and SMC activities, including the green water benefits and groundwater potential, the environmental benefits of these interventions in the Krishna River basin can be better understood. These assessments will provide valuable insights into the water quantity aspects of the rejuvenation efforts and help guide future management strategies.

The quantitative benefits of the activities proposed in the basin could be assessed in the following sections:

2.1.1. Water Augmentation through Plantation Activities

Conceptual model for assessment: *Water Balance Model*

Water balance is based on the law of conservation of mass, which states that any change in the water content of a given soil volume during a specified period, must equal the difference between the amount of water added to the soil volume and the amount of water withdrawn from it. It helps to quantify the relationships between precipitation, surface and groundwater runoff, evaporation, transpiration, and aquifer drafts and provides a framework for future planning of sustainable exploitation of the available water resource (Kneis, 2015).

The water balance of a forest basin is crucial for understanding the dynamics of water availability and usage. It involves calculating the input, output, and storage changes of water within a specific area. A comprehensive water balance model (**Figure 5**) typically includes four sub-modelling systems that describe different aspects of the hydrological cycle:

1) *Atmospheric Water Balance Sub-system*

This sub-system focuses on the input and output of water in the atmosphere. It considers factors such as precipitation, evaporation, and transpiration from vegetation. Precipitation is the primary source of water input, while evaporation and transpiration contribute to water loss from the system.

2) *Surface Water Balance Sub-system*

This sub-system deals with the movement of water on the land surface. It accounts for factors such as surface runoff, infiltration, and storage changes in lakes, ponds, and other water bodies. Surface runoff occurs when the soil is saturated, and excess water flows over the land surface.

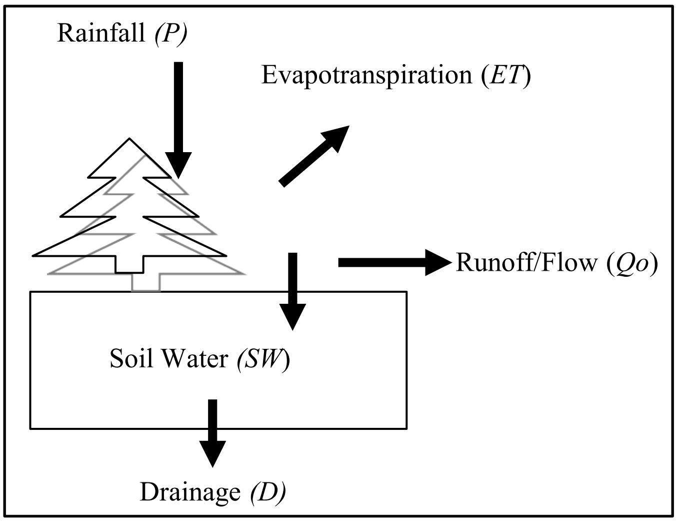


Figure 5. Water balance model.

3) *Soil Water Balance Sub-system*

This sub-system focuses on water movement within the soil profile. It considers processes such as infiltration, percolation, and storage changes in the soil. Infiltration refers to the entry of water into the soil, while percolation refers to water movement downward through the soil layers.

4) *Groundwater Balance Sub-system*

This sub-system deals with the movement of water within the groundwater aquifer. It considers factors such as groundwater recharge, discharge, and storage changes in the aquifer. Groundwater recharge occurs when water from precipitation or surface runoff infiltrates into the ground and replenishes the aquifer.

By modelling each of these sub-systems separately, the water balance of a forest basin can be analysed comprehensively. This allows for a better understanding of the interactions between different components of the hydrological cycle and provides insights into the sustainable management of water resources in the area.

The general water balance equation is given in Equation (1) as follows:

$$G + P = Q_{dsro} + Q_b + ET + \Delta S_g \quad (1)$$

where, P = *rainfall;* G = *glacial inflow;* Q_{dsro} = *direct surface runoff;* Q_b = *base flow;* $E_t = ET$ = *evapo-transpiration;* ΔS_g = *change in groundwater storage* (*in soil or the bedrock/ground water*).

Assumptions:

1) Inflows from precipitation and glacial inflows would remain the same for both scenarios.

2) Evapo-transpiration (*ET*) is the sum of evaporation and plant transpiration from the surface to the atmosphere. Evapo-transpiration is an integral part of the water cycle. However, it is excluded from the calculations showcasing how forestry interventions can reduce surface runoff and improve recharge for under-

standing benefits. The forest also provides ecological functions such as carbon storage, nutrient cycling, water and air purification, soil protection, microclimatic benefits, and habitat maintenance. In addition, it is also important to note that the ET values in the forests are much higher than that of other land uses.

3) From the hydrogeological point of view, it is observed that the groundwater occurs in confined (restricted) setting in joints, cracks, fissures, and fractures, moving to deeper levels in the weathered zones. In addition, the changes in groundwater storage (ΔS_g) are considered zero for computational purposes.

Changes in surface runoff (Without FI Q_{dsro} − With FI Q_{dsro}) = Changes in base flow (With FI Q_b − Without FI Q_b)

The Soil Conservation Service Curve Number (SCS-CN) model will estimate the surface water outflow from the catchment area. The SCS-CN model is based on the single parameter Curve Number (CN), which depends on the land use, land cover, soil type, and the antecedent moisture conditions prevailing in the catchment. The direct surface runoff has been estimated using the SCS-CN model given in Equation (2) and (3).

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad \text{for} \quad P > I_a \text{; and} \quad Q = 0 \quad \text{for} \quad P \le I_a \tag{2}$$

$$S = \frac{25400}{CN} - 254 \tag{3}$$

where, P = rainfall; Q = direct surface runoff (mm); S = potential retention (mm); CN = curve number; I_a = initial abstraction.

Step 1: *Annual rainfall* (*P*)

The Krishna basin has a tropical climate. The climate is dominated by the southwest monsoon, which provides most of the precipitation for the basin. High flow in the rivers occurs during the months of August-November and the lean flow season is from April to May. The annual rainfall varies from 800 to 2200 mm in the Krishna Basin. According to the India-WRIS database the average annual rainfall in the Krishna basin for the period of 1969 to 2004 is 859 mm (Central Water Commission, 2014) (**Table 2**), (Equation (4)).

$$P = (P_1 + P_2 + P_3 + \cdots + P_n)/n \tag{4}$$

Step 2: *Assessing Curve Number* (*CN*)

CN value for soils having high infiltration rates and for more than 58 mm precipitation under the conditions of Antecedent Moisture Conditions (AMC-III) is referred from Hawkins et al. (2002). The soil moisture affects runoff before a precipitation event; the antecedent moisture condition (AMC) provides different conditions for estimating the runoff. Considering the interventions were implemented in the riverscape area, we have considered the AMC III condition for estimating the runoff, which provides higher CN and potential runoff values considering the high soil moisture in the Riverscape areas.

Step 3: *Calculation of Potential Retention* (*S*) (*mm*)

It is defined as the potential maximum retention after runoff begins. "*S*" lumps all variation in the runoff response because of land use, soils, soil moisture, rainfall pattern, duration, or intensity, plus any other variation into one variable.

Step 4: *Initial Abstraction* (I_a)

The initial abstraction consists mainly of interception, infiltration during the early parts of the storm, and surface depression storage. The initial abstraction (I_a) is some fraction of the potential maximum retention (S) wherein λ = 0.2 is adopted as a standard value for general soils (Equation (5)).

$$I_a = \lambda S \tag{5}$$

Step 5: *Direct Surface Runoff* (*DSRO*)

Direct surface runoff is the rain that runs off during the rain event as overland flow or in the vegetation cover above a soil (Equation (6)).

$$Q = \frac{\left(P - I_a\right)^2}{P - I_a + S} \quad \text{for} \quad P > I_a \tag{6}$$

Step 6: *Changes in Base Flow*

The base flow consists of water that infiltrates into the soil and travels laterally downslope through upper soil layers and groundwater flow that infiltrates and travels through the aquifer. The changes in the base flow caused by plantation activity can also be called "Green Water". Green water is the amount of rainfall intercepted by the vegetation or enters the soil and is picked up by plants and evapo-transpiration back into the atmosphere (Equation (7)) using parameter values.

$$\begin{aligned} \text{Total base flow}\left(\text{Green Water}\right) &= \text{Area with Forestry Interventions } \left(\text{FI}\right) \\ &\quad - \text{Area with FI}\left(\text{With FI}Q_b - \text{Without FI } Q_b\right) \end{aligned} \tag{7}$$

2.1.2. Water Augmentation through SMC Measures

Nature has provided enormous inter-connected reservoirs underneath and SMC structure's arrested rain water to recharge groundwater. Estimating groundwater recharge is essential to measure the effectiveness of water conservation measures. In the recharge assessment framework, the estimation of groundwater recharge due to Soil Moisture Conservation (SMC) works in the Krishna basin will be done using the Ground Water Resource Estimation Committee (GEC, 2015) methodology. The methodology provides a simple assessment framework for estimating groundwater recharge from water conservation structures.

Step 1: *Estimating Gross Storage*

The gross storage of water in the study area is calculated using the following equations: Gross Storage = Storage Capacity × Number of fillings (8) Storage Capacity = AWSA × H × Efficiency × Number of fillings (9) Where:

- AWSA refers to the storage potential created through excavation.
- H represents the height of the water conservation structures.
- Efficiency denotes the storage efficiency of the structures.
- Number of fillings refers to the number of times the structures are filled dur-

ing the rainfall season.

Several conservative assumptions are made during this estimation:

- The proposed SMC work areas are considered as water spread areas.
- 50% of the SMC activities' area is assumed to be the average water spread area.
- Gross storage is estimated assuming a 1-meter height for nalas (small channels) and check dams.
- The efficiency is taken as 50% for earthen structures, considering leakages and other factors according to GEC norms.
- It is assumed that the structures are located in the riverscape area, and annual fillings are considered to be 10, taking into account 30 to 50 rainy days and surface runoff from adjoining areas in the Krishna River basin.

Step 2: *Recharge due to Water Conservation Structures* (*RWCS*)

The recharge factor (RF) suggested by GEC (2015) is used to estimate the recharge due to water conservation structures in the Krishna riverscape. The recharge factor is multiplied by the gross storage calculated in Step 1 to determine the total recharge amount. Therefore, the equation for estimating the recharge due to water conservation structures is as follows:

$$\text{RWCS} = \text{GS} \times \text{RF} \tag{10}$$

where:

RWCS represents the recharge due to water conservation structures. RF denotes the recharge factor.

GS refers to the gross storage calculated in Step 1.

By employing these calculations, the total recharge amount resulting from the proposed SMC activities in the Krishna basin can be estimated.

2.2. Water Quality Improvement due to Forestry and SMC Interventions

In the long term, forest catchments play a crucial role in influencing water quality by mitigating the impacts of rainfall variability and seasonal climate variations. One of the key factors affected by forest catchments is sediment yield from a given basin. Degraded lands and unstable soils can lead to heavy sedimentation during rainstorms, resulting in increased sediment yield from river basins. However, forest catchments have a significant effect in reducing sediment yield under various conditions (Conroy, 2001).

For this study, only the sedimentation parameter is considered due to data availability and its relevance to the project activities (Rao, 2012). By rehabilitating forest watersheds, the rate at which sediments are delivered to a reservoir can be significantly reduced. To estimate sediment yields from the basin, standard extrapolation techniques will be employed using previous measurements (Trimble, 1999). Legacy data on the silt rate of major/minor irrigation and hydroelectric projects has been used to provide a realistic estimate of sediment yields in the basin (Central Water Commission, 2015). **Figure 6** provides a

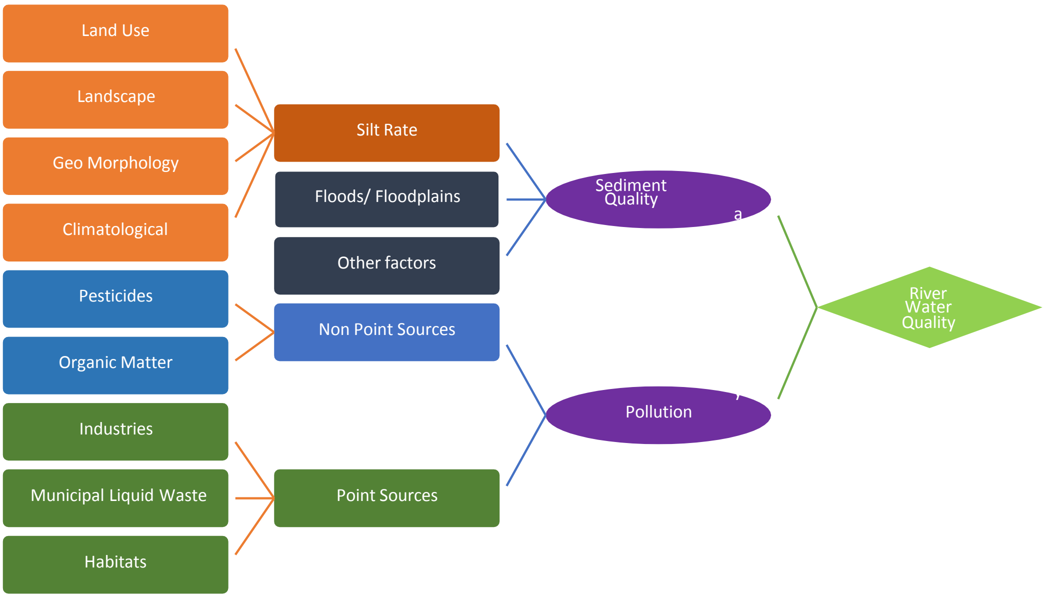


Figure 6. Activities in river basin, which influences water quality.

schematic representation of the main influences on water quality within a river basin, illustrating the complex interactions between various factors (Sandström, 1998; Owens, 2008).

Step 1: *Treatment Area*

The selected area for riverscape management under the proposed project in the Krishna River basin is 34,977.47 km^2 (34,97,747.00 ha), which is a part of the larger basin covering 2,58,948.00 km^2 (2,58,94,800.00 ha) (**Table 1** and **Table 2**).

Step 2: *Sediment Factor*

Assessing sediment inflow in rivers is a complex task due to variations in sediment content based on flow and season. It involves complex sediment modeling and requires significant time and resources for measurement. Additionally, there are inherent uncertainties associated with the results. However, reliable assessments of sedimentation can be made based on legacy data available at the project locations, following the guidelines provided by the Central Water Commission (CWC, 2019) (**Table 3**).

Step 3: *Trap Efficiency*

The efficiency of sediment trapping by forestry interventions and SMC activities can vary based on factors such as sediment gradation and maintenance of structures. For this study, a conservative estimate of 90% efficiency is considered.

Step 4: *Sediment Reduction*

The sediment reduction in the Krishna basin due to forestry and SMC interventions can be calculated using Equation (11) (Trimble, 1999):

$$\text{Sediment load} = \text{Catchment area} \times \text{Sediment factor} \times \text{Trap Efficiency} \quad (11)$$

where:

Catchment area: The area of the catchment where the interventions are implemented.

Table 3. Average silt rate in Krishna Sub-basins.

State	Major Reservoir	Observed Sediment Rate (000.Cum/km^2/year)
Maharashtra	Bendsura Reservoir	0.695
Karnataka	Tungabhadra Reservoir(s)	0.697
Telangana	Nagarjuna Sagar Dam	0.301
Andhra Pradesh	Srisailam Reservoir	0.360

Sediment factor: The sediment factor determined based on sedimentation legacy data or other reliable sources. Trap Efficiency: The estimated efficiency of sediment trapping, assumed to be 90% in this case.

By multiplying the catchment area by the sediment factor and the trap efficiency, the sediment load reduction can be estimated.

2.3. Carbon Sequestration due to Forestry Plantations

To calculate carbon sequestration in the Krishna River basin, two different methodologies are employed based on the land cover types.

Forest Area:

For the forest area, the carbon sequestration potential is calculated using the methodology provided in the revised 1996 IPCC guidelines (IPCC, 1997). This methodology takes into account factors such as biomass density, growth rates, and carbon content to estimate the carbon sequestration potential of forests.

Non-Forest Area:

For non-forest areas, specifically the Tree Outside Forests (TOF) category, the carbon sequestration potential is calculated using the data from the Indian State of Forest Report (ISFR), 2019. The ISFR provides information on the carbon stock in trees outside forest areas, including landscapes such as natural, agricultural, and urban areas.

In the proposed project, a total riverscape area of 181354.73 hectares is earmarked for afforestation in three categories of landscapes: natural, agriculture, and urban, along the banks of the Krishna River and its tributaries. The carbon sequestration potential of this afforested area will be calculated using the respective methodologies mentioned above.

3. Results

The results on water recharge and sedimentation decrease in the Krishna basin due to plantation and SMC activities are as follows:

3.1. Water Quantity Benefit Assessment

In the present study, the water quantity improvement resulting from plantation activities and SMC measures in the Krishna basin is as follows:

3.1.1. Water Augmentation through Plantation Activities

The surface runoff in the absence of forestry intervention was measured to be

774 mm, while with forestry interventions, it reduced to 573 mm. This indicates a 26% reduction in surface runoff compared to the river basin without any intervention (Table 4). The presence of forestry activities acted as a barrier to the flow of runoff, allowing more time for water infiltration and storage in the soil profile, ultimately leading to groundwater recharge (Table 5). The estimated water recharge due to forestry interventions in the Krishna basin is approximately 364.50 million cubic meters (MCM), with the highest recharge of 139.00 MCM occurring in Karnataka state (Table 6). These estimates highlight the significant contribution of forestry interventions in enhancing water recharge and availability in the basin.

3.1.2. Water Augmentation through SMC Measures

In the proposed SMC measures for the Krishna River basin, various states were involved, and the storage potential varied across these states. Karnataka had the maximum storage potential, while Andhra Pradesh had the minimum storage potential. The groundwater recharge also followed a similar trend, proportionate to the treated area under the project in each state. The estimated groundwater recharge due to the proposed conservation structures is expected to be 35.99 million cubic meters (MCM) for the study area under consideration (Table 7). This indicates the potential impact of the conservation measures in enhancing groundwater recharge and overall water availability in the Krishna River basin.

Under this study, it is expected that the forestry interventions in the Krishna River basin will contribute to a total water recharge of 400.49 million cubic meters (MCM). This includes 365.50 MCM of water recharge through plantation

Table 4. Parameter values to estimate green water in Krishna basin.

Parameters*	With forestry interventions (FI)	Without forestry interventions (FI)
Curve number (CN) (mm)	76	45
Potential retention (mm)	310.40	75.87
Initial abstraction (mm)	62.00	15.14
Direct surface runoff (mm)	573.00	774.00

*Parameter values deduced from SCN Curve values.

Table 5. Gross storage by SMC works in Krishna basin.

State	SMC works area (ha)	Average water spread area (ha)	Efficiency	Number of fillings	Gross storage (000 cub mt)
Maharashtra	1360.68	680.34	50%	10	34017.00
Karnataka	10740.10	5370.05	50%	10	268502.50
Telangana	1858.44	929.22	50%	10	46461.00
Andhra Pradesh	437.00	218.5	50%	10	10925.00
Total	**14396.22**	**7198.11**			**359905.50**

Table 6. Estimated green water after forestry interventions in Krishna basin.

State	Riverscape area (ha)	Plantation area (ha)	Green water (MCM)
Maharashtra	839398.00	31934.31	64.20
Karnataka	1284532.00	69168.48	139.00
Telangana	813034.00	46018.24	92.50
Andhra Pradesh	560783.00	34233.70	68.80
Total	**34,97,747.00**	**181354.74**	**364.50**
Total base flow (Green water)	Area with Forestry Interventions (FI) − Area with FI (With FI Q_b − Without FI Q_b) = 181354.74 (774 mm − 573 mm)/1000 = 36452.30274 = **364.50 MCM**		

Table 7. Ground water recharge in Krishna basin due to SMC interventions.

State	Gross storage (000 cub mt)	Recharge factor (%) GEC 2015	Recharge due to water conservation (MCM)
Maharashtra	34017.00	10	3.40
Karnataka	268502.50	10	26.85
Telangana	46461.00	10	4.65
Andhra Pradesh	10925.0	10	1.09
Total	**359905.50**		**35.99**

activities and an additional 35.99 MCM of water recharge through SMC measures. These interventions are anticipated to have a significant positive impact on the water resources of the Krishna River basin, enhancing water availability and sustainability.

3.2. Water Quality Improvement due to Forestry and SMC Interventions

The implementation of proposed forestry interventions in the Krishna River basin is expected to have a significant impact on reducing sedimentation rates and improving water quality. Sedimentation rate is a crucial parameter that affects the overall water quality of a river system, and the loss of tree cover and land use changes have increased sedimentation processes in many Indian basins, including the Krishna basin. Based on the sedimentation factor suggested by Central Water Commission (2015), trap efficiency, and the respective intervention areas, the sedimentation rate reduction due to the proposed interventions is estimated. Annually, it is projected that the forestry interventions will lead to a reduction of 869.22 thousand cubic meters of sedimentation in the Krishna basin. This reduction in sedimentation has multiple benefits, including increased reservoir capacity along the Krishna riverscape and the conservation of topsoil fertility and productivity by reducing erosion. The sedimentation rates vary among the states, with Karnataka having the highest sedimentation rate and Andhra Pradesh having the lowest. These rates are proportionate to the areas treated under the study, highlighting the effectiveness of the interventions in reducing sedimentation and preserving the quality of water resources in the Krishna River basin (**Table 8**).

The forestry interventions, including plantations and soil and moisture conservation measures, are anticipated to have substantial positive impacts on water resources in the Krishna River basin. These interventions are expected to increase water recharge by 400.49 million cubic meters per year (MCM/yr) and reduce the sedimentation load by 869.22 cubic meters per year (m^3/yr). The increased water recharge of 400.49 MCM/yr signifies the additional volume of water that will be available for groundwater replenishment and sustenance. This improvement in water recharge is crucial for maintaining adequate water availability, especially during dry periods and lean flow seasons.

On the other hand, the reduction in sedimentation load by 869.22 m^3/yr indicates the amount of sediment that will be prevented from entering the water bodies within the Krishna basin. This reduction helps in maintaining water quality, preserving the storage capacity of reservoirs, and mitigating the adverse effects of sedimentation on aquatic ecosystems. Overall, these forestry interventions play a vital role in enhancing water resources sustainability by increasing water recharge and minimizing sedimentation in the Krishna River basin.

3.3. Carbon Sequestration due to Forestry Plantations

The proposed forestry interventions in the Krishna River basin have a significant carbon sequestration potential, both in forest areas and non-forest areas. In forest areas, the estimated carbon sequestration potential of the interventions is 113160.14 metric tonnes carbon per year, which is equivalent to 414924.27 metric tonnes of CO_2 equivalent per year. This means that the forests established through these interventions will be able to absorb and store this amount of carbon dioxide from the atmosphere annually, helping to mitigate climate change. In non-forest areas, including agricultural and urban areas, the estimated carbon sequestration potential of the interventions is even higher. It is calculated to be 277816.91 metric tonnes carbon per year, equivalent to 1018671.27 metric tonnes of CO_2 equivalent per year. This indicates that the trees planted in these areas will contribute significantly to carbon sequestration and help offset carbon emissions. The total carbon sequestration potential of the proposed forestry interventions, considering both forest and non-forest areas, is the sum of these two values, amounting to a total of 390977.05 metric tonnes carbon per year or 1433595.54 metric tonnes CO_2 equivalent per year (**Table 9** and **Table 10**). This substantial carbon sequestration potential highlights the importance of these forestry interventions in mitigating greenhouse gas emissions and combating climate change in the Krishna River basin.

The forestry interventions in the forest area of the Krishna River basin are expected to have a moderate productivity, with an average capture of 3.64 metric tonnes of carbon per hectare per year. This translates to 13.35 metric tonnes of CO_2 equivalent per hectare per year. It is important to note that it may take 10 to

Table 8. Estimated sedimentation rate for the Krishna basin post proposed interventions.

State	*Sedimentation factor (000 m^3/sq. km/yr)	Trap efficiency	Intervention area (sq. km)	Sedimentation rate (cubic m/yr.)
Maharashtra	0.695	90	319.34	199.75
Karnataka	0.697	90	691.68	433.89
Telangana	0.301	90	460.18	124.66
Andhra	0.360	90	342.34	110.92

*Source: Central Water Commission, 2015.

Table 9. The state wise carbon stock and its CO_2 equivalent in forest areas.

State	Area (ha)	Mean wood density (D)	Biomass expansion factor (F)	Estimated Carbon stock (Metric tonnes)	Total Carbon stock (Metric tonnes)	Total CO_2 equivalent (Metric tonnes)
Maharashtra	9985.31	0.70	1.58	3.33	33219.61	121806.34
Karnataka	15662.76	0.79	1.59	3.78	59179.37	216993.00
Telangana	1809.77	0.79	1.59	3.78	6837.94	25072.68
Andhra Pradesh	3685.00	0.79	1.59	3.78	13923.22	51052.25
Total	**31142.84**	-	-	-	**113160.14**	**414924.27**

Table 10. The state wise carbon stock and its CO_2 equivalent in non-forest areas.

State	Area (ha)	MAI of Carbon sequestered	Estimated Carbon stock (Metric tonnes)	Total Carbon stock (Metric tonnes)	Total CO_2 equivalent (Metric tonnes)
Maharashtra	21949.00	73.98	1.85	40594.68	148848.50
Karnataka	53505.72	73.98	1.85	98958.93	362852.35
Telangana	44208.48	73.98	1.85	81763.58	299802.53
Andhra Pradesh	30548.70	73.98	1.85	56499.82	207167.89
Total	**15211.90**	-	-	**277816.91**	**1018671.27**

15 years for these plantations to reach their maximum productivity. Considering the entire project area, the forestry interventions have the potential to sequester 3.91 lakh metric tonnes of carbon per year, which is equivalent to 14.34 lakh metric tonnes of CO_2 equivalent per year. This estimation takes into account the cumulative carbon sequestration over time. To estimate the carbon sequestration over a longer time period, a Logistic Function (Sigmoid Growth Curve) model has been used. According to this model, the projected CO_2 sequestration after 10 years is 7.16 million tonnes, and after 20 years it would be 14.23 million tonnes. This highlights the long-term potential of the forestry interventions in capturing and storing carbon dioxide from the atmosphere. These estimates demonstrate the significant contribution of the forestry interventions in the Krishna River basin towards addressing the adverse impacts of climate change by sequestering carbon and reducing greenhouse gas emissions.

4. Discussion

The forestry interventions in the Krishna River basin have multiple benefits that positively impact water resources and the environment. By implementing plantations and soil and moisture conservation activities, water recharge is increased by 400.49 million cubic meters per year, which helps in maintaining perennial rivers, mitigating floods, and addressing drought conditions. Additionally, these interventions contribute to reducing sedimentation in the basin, with a decrease of 869.22 cubic meters per year. This helps in preserving the capacity of reservoirs, conserving soil fertility, and preventing soil erosion, which is crucial for sustaining agricultural productivity and preventing degradation. Furthermore, the forestry interventions play a significant role in addressing climate change. They contribute to carbon sequestration, with an estimated annual sequestration of 3.91 lakh metric tonnes of carbon or 14.34 lakh metric tonnes of CO_2 equivalent. Forests and trees have the ability to increase precipitation, promote water infiltration, and maintain soil moisture levels, which ultimately contribute to mitigating the adverse impacts of climate change. Overall, the forestry interventions in the Krishna River basin provide a holistic approach to water resource management, environmental conservation, and climate change mitigation.

4.1. Water Recharge

Forests and plantations play a crucial role in sustaining water resources and protecting water quality through various measures such as afforestation, contour bunding, land levelling, creation of farm ponds, and checking dams. These interventions aim to control surface water flow and direct it underground. By absorbing rainwater, dispersing surface runoff, and purifying pollutants, forests contribute to the production of clean water in rivers (Jones et al., 2022). Scientific studies have highlighted the impact of land use changes, such as deforestation, reforestation, and afforestation, on water supplies. Deforestation, for example, can lead to reduced evapotranspiration and subsequent changes in rainfall patterns in downwind areas (Ellison et al., 2017). Researchers have emphasized the important role of trees and forests in the hydrologic cycle, particularly in enhancing soil infiltration and groundwater recharge (Springgay et al., 2019). The concept of "nature for water" recognizes the role of terrestrial ecosystems in increasing water yields and improving water quality. Real-world examples, like the Lange Erlen Forest in Switzerland, demonstrate the use of forests to filter water and recharge groundwater.

Tree and land management practices, including species selection, land-use practices, grazing, and pruning, also influence water availability. Pruning, for instance, reduces transpiration, while moderate tree cover on degraded lands can enhance groundwater recharge, especially in dry tropical regions. The extent of tree cover and its benefits depend on various factors, such as soil characteristics, terrain, rainfall patterns, land use practices, and vegetation types. In conclusion, forests have a significant impact on water resources, playing a vital role in sustaining water availability, improving water quality, and promoting groundwater recharge. The implementation of forestry interventions, along with appropriate land management practices, can contribute to addressing water-related challenges and ensuring the long-term sustainability of water systems (Ilstedt et al., 2016).

In Peru's Pacific Coast water basin, where an estimated two-thirds of historical tree cover has been lost (WRI, 2017), integration of green and grey infrastructure could reduce Lima's dry-season deficit by 90 percent, and this would be more cost-effective than implementing grey infrastructure alone (Gammie & de Bievre, 2015). Ouyang et al. (2019) demonstrated that forest land slightly increased water recharge from land surface into the groundwater as compared to that of the agriculture land in subtropical watershed of the lower Mississippi River alluvial valley. Wu et al. (2015) concludes that there was a significant positive relationship between forestation and water yield in the upstream area of the Heihe River basin during 1980-2010. The annual water yield increased by 1.2 mm when the forest cover increased by 1%. A study in Ganga basin has shown to increase water recharge and decrease sedimentation load by 231.011 MCM yr^{-1} and 1119.6 cubic myr^{-1} or 395.20 tons yr^{-1}, respectively, in basin due to forestry plantations and soil and moisture conservation interventions (Singh et al., 2023b). Singh et al. (1984) observed that an oak (*Quercus leucotrichophora*) forest remains most useful for soil development, protection of nutrients, water retention and the life of connected springs of watershed in western Himalayas.

Enriching the basins with trees/shrubs increases the forest cover and the forests filter and regulate the flow ofwater, in large part due to their leafy canopy that intercepts rainfall, slowing its fall to the ground and the forest floor, which acts like an enormous sponge, typically absorbing up to certain depth of precipitation before gradually releasing it to natural channels and recharging ground water.The landscapes with some tree cover can sometimes capture several times more water than otherwise comparable treeless landscapes. In treeless areas only some 10 mm of rain per year replenishes groundwater, but close to trees, groundwater recharge increases dramatically due to improved soil infiltration capacity and preferential flow; i.e., the flow of infiltrating water through macropores such as the channels created by roots and soil fauna (Bargues Tobella et al., 2014).

4.2. Sedimentation Reduction

Forests' most significant contribution to water for all living things is in maintaining high water quality. They achieve this through minimizing soil erosion on site, thus reducing sediment in water bodies (wetlands, ponds and lakes, streams and rivers), and through trapping or filtering other water pollutants. Riparian forest buffers filter sediment from streams during heavy rain and flood; remove nitrogen and phosphorous leaching from adjacent land uses such as agriculture; provide stability to the bank (wood root systems); and reduce downstream flooding. Adapting agroforestry model in rural agricultural area contributes to prevention of soil erosion and water inflow. Symmank et al. (2020) showed that bioengineering techniques could be a feasible tool to enhance rivers' self-purification and contribute to mitigating climate change if conducted on a large scale. In the tropics, reforestation or tree planting in agriculture fields (agroforestry results in increased infiltration capacity (Ilstedt et al., 2007).

Conroy (2001) viewed that forest catchments have an important impact in reducing sediment yield from watersheds. Sediment monitoring in the Yangtze River and elsewhere shows evidence of reduced sediment loads after implementation of "Conversion of Cropland to Forest Programme" (CCFP) or "Grain-for-Green" and positively affecting drinking-water quality (Zhou et al., 2017; Mo, 2007). Ali et al. (2017) had studied the impact of SMC measures like (staggered contour trenching) for several watersheds in Chambal River basin of Rajasthan region, and it was observed that by constructing 417 trenches per ha the runoff (86.1%) and soil loss were reduced significantly. The result also suggested that the surface runoff have reduced 1.8mm with every 1% increase in the forest cover.

Pandey et al. (1983) assessed overland flow, and soil and nutrient loss for four sites under original forest cover, and for four sites affected by soil deposition, landslide or cultivation in the Kumaon Himalaya during the 1981 and 1982 monsoon seasons and concluded that soil loss was positively related with overland flow, both being greater for non-forested compared to forested sites. The study conducted by Sun et al. (2018) for Guangdong Province of China, suggest that the vegetation have a significant impact on controlling surface runoff, soil erosion and sediment load in the study area. The study carried out by Narain et al. (1997) for western Himalayan valley region of India suggest that agroforestry-based plantation of eucalyptus and Leucaena in steeper slopes prone to heavy erosion reduced the soil erosion due to the barrier effect of vegetation. Wang et al. (2016) observed that large scale vegetation restoration projects have reduced soil erosion from 1990 onwardsin Yellow River in China. Singh et al. (1984) observed that an oak (*Quercus leucotrichophora*) forest remains most useful for soil development, protection of nutrients, water retention and the life of connected springs of watershed in western Himalayas. By trapping the sediment, it will ultimately reduce the sediment load in river water and also improve the quality of river water. Hence, by adopting the proposed forestry interventions, it is expected to reduce the erosion and trap sediments in Krishna basin in the country.

4.3. Carbon Sequestration due to Forestry Plantations

Forestry has been widely acknowledged as a valuable approach to reduce CO_2 emissions and enhance carbon sinks. Forests play a crucial role in the carbon cycle by actively absorbing carbon dioxide (CO_2) from the atmosphere and storing it within their biomass, including wood, leaves, and roots. This makes forestry one of the most effective and scalable methods available today for carbon sequestration (Pukkala, 2017).

When it comes to carbon sequestration, forests act as significant carbon sinks, helping to mitigate greenhouse gas (GHG) emissions. In India, a tropical country with diverse forest types, it is challenging to identify a single forest type that is optimal for carbon sequestration (Kaul et al., 2010). The carbon stock in a given area depends on various factors such as tree species, spacing, age class distribution, soil characteristics, and climatic conditions (Pussinen et al., 2002). Therefore, forestry interventions for carbon sequestration often involve a combination of different species, including both natural forests and plantation species.

Research by Ravindranath and Murthy (2021) demonstrated the relevance of tree planting activities, such as drought proofing implemented under the Mahatma Gandhi National Rural Employment Guarantee.

Scheme (MGNREGS) in India, in achieving the Nationally Determined Contributions (NDCs) carbon sink target. It is projected that the cumulative carbon sink created by drought proofing activities will reach 56 $MtCO_2$ in 2020, 281 $MtCO_2$ in 2025, and 561 $MtCO_2$ in 2030.

5. Conclusion

In the program aimed at rejuvenating the Krishna River, forestry plantations and soil and moisture conservation measures have been devised to achieve multiple benefits. These interventions are expected to have positive impacts on water resources by increasing water recharge, reducing sedimentation load, and enhancing carbon sequestration. Specifically, the interventions are projected to result in an annual increase in water recharge by 400.49 million cubic meters (MCM), a decrease in sedimentation load by 869.22 cubic meters per year, and a carbon sequestration potential of 3.91 lakh metric tonnes of carbon per year (equivalent to 14.34 lakh metric tonnes of CO_2 per year) in the Krishna basin. It is important to note that these outcomes vary among states within the basin, reflecting the specific characteristics and areas targeted by the project. The role of trees and forests in improving hydrologic cycles, promoting soil infiltration, facilitating groundwater recharge, and sequestering carbon is likely driving these positive changes. Additionally, maintaining riparian vegetation along the riverbanks is crucial for preserving water quality and creating suitable habitat conditions for aquatic life. The findings of this study provide valuable insights for operational practices, such as forest plantations, aimed at restoring waterbodies and understanding the connections between forest structure, function, and streamflow.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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