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Impact of Forestry Interventions on Groundwater Recharge and Sediment Control in the Ganga River Basin

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Abstract

Water related services of natural infrastructure will help to combat the risk of water crisis, and nature-based solutions involve the management of ecosystems to mimic or optimize the natural processes for the provision and regulation of water. Forested areas provide environmental stability and supply a high proportion of the world's accessible freshwater for domestic, agricultural, industrial and ecological needs. The present work on "Forestry Interventions for Ganga" to rejuvenate the river is one of the steps toward the Ganga River rejuvenation programme in the country. The consequences of forestry interventions for Ganga will be determined on the basis of water quantity and water quality in the Ganga River. The study conservatively estimated the water savings and sedimentation reduction of the riverscape management in the Ganga basin using the Soil Conservation Service Curve Number (SCS-CN) & GEC, 2015 and Trimble, 1999 & CWC, 2019 methodologies, respectively. Forestry plantations and soil and moisture conservation measures devised in the programme to rejuvenate the Ganga River are expected to increase water recharge and decrease sedimentation load by 231.011 $\text{MCM}\cdot\text{yr}^{-1}$ and 1119.6 cubic $\text{m}\cdot\text{yr}^{-1}$ or 395.20 $\text{tons}\cdot\text{yr}^{-1}$, respectively, in delineated riverscape area of 83,946 km^2 in Ganga basin due to these interventions. The role of trees and forests in improving hydrologic cycles, soil infiltration and ground water recharge in Ganga basin seems to be the reason for this change. Forest plantations and other bioengineering techniques can help to keep rivers perennial, increase precipitation, prevent soil erosion and mitigate floods, drought & climate change. The bioengineering techniques could be a feasible tool to enhance rivers' self-purification as well as to make river perennial. The results will give momentum to the National Mission of Clean Ganga (NMCG) and its *Namami Gange* programme including other important rivers in the country and provide inputs in understanding the linkages among forest structure, function, and streamflow.

Keywords

Bioengineering Measures, Ganga River Basin, Sediment Control, Water Harvesting

1. Introduction

The Ganga River is the lifeline to billions of Indians and it is a precious commodity that nurtures the Indian agricultural system (Misra, 2013). The Ganga River is one of the prime rivers of India, and it flows eastward through the Gangetic plains of Northern India toward Bangladesh. The river, after originating in the state of Uttarakhand, flows across the states of Uttar Pradesh, Bihar, Jharkhand and West Bengal before merging into the sea. The river, from its origin to end, represents three biogeographic zones: 1) the Himalayas, 2) the Gangetic plains, and 3) the coastal including deltaic region. Unfortunately, the ecological health of the Ganga River and some of its tributaries have deteriorated significantly (Dwivedi et al., 2018) due to high pollution loads, high levels of water abstraction for irrigation, municipal & industrial uses, and river modifications due to water resource infrastructures (CPCB, 2016). Hence, the conservation and management of natural resources (particularly soil and water) are important for sustainable agricultural yield and livelihood (Kar et al., 2022). In this regard, the Government of India has committed itself to an ambitious goal of rejuvenating the Ganga River. However, there are no "silver bullet" interventions that solve all the problems. All stakeholders must realize that water availability will be insufficient to meet the rising demands. And there are no "easy" technical solutions; therefore, a combination of different interventions is required to be adopted. The agricultural sector will have to adapt lower water requiring cultivation practices in terms of choice of crops, planting season, and water efficiency. Future socio-economic development and climate change are expected to deteriorate further the Ganga River basin's ecological and socio-economic values (Bons, 2018). The assessment of the e-flow also indicates that the Ganga River basin shows a severely altered compared to the pristine situation due to alterations of the flow regime and poor water quality (WWF, 2012).

Isolationist approaches to river management have constrained the development of new scientifically based comprehensive approaches for river development and management. Integrating hydrological, geomorphological, and biological research establishes a new understanding of the dynamic river systems. Forested areas provide environmental stability and supply a high proportion of the world's accessible freshwater for domestic, agricultural, industrial and ecological needs. Trees and forests play important roles in hydrologic cycles, such as by altering the release of water into the atmosphere, influencing soil moisture and improving soil infiltration and groundwater recharge (Springgay et al., 2019). Forest-related changes in land use such as deforestation, reforestation, and afforestation can affect nearby and distant water supplies (Jones et al., 2022). For example, a decrease in evapotranspiration following deforestation in one area may reduce rainfall in downwind areas (Ellison et al., 2017). In addition, climate change and an increase in extreme weather events disturb water cycles and threaten the stability of water flows (IPCC, 2019). The riverine landscape or "riverscape" approach of river management includes delineating treatment areas based on understanding the patterns and processes of the river and its banks/riparian areas within a fluvial system. It is also helpful in devising a management plan to rejuvenate rivers/streams (Zhou et al., 2014; Ward, 1998; Ward et al., 2002).

Harnessing water related services of natural infrastructure (forests, wetlands, floodplains) will help to combat the risk of water crisis. Nature can only continue to deliver its services where ecosystems are healthy and functioning well. Keeping these things in view, Forest Research Institute, Dehradun has prepared a "Detailed Project Report (DPR)" on "Forestry Interventions for Ganga" to rejuvenate the river in collaboration with the Ministry of Water Resources, River Development, and Ganga Rejuvenation (MoWR, RD & GR) and National Mission of Clean Ganga for the five stakeholder states viz. Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal. Riverscape approach was followed in the project and the selected area includes the entire catchment of Bhagirathi, Alaknanda and Ganga sub-basins in the state of Uttarakhand, being the origin place of river, and a 5 km buffer around either side of bank lines of Ganga in five stakeholder states. In addition, the riverscape also included a 2 km buffer on either side of different tributaries of the river Ganga except the river Yamuna and its tributaries. A total of 25 tributaries have been selected for the purpose in the five participating states, viz., Bhagirathi, Asi Ganga, Bal Ganga, Bhilangana, Nayar, Dhauliganga, Alaknanda, Mandakini, Nadakini, Pindar, Song, Sharda, Gomti, Ghaghra, Sone, Gandak, Kosi, Mayurakshi, Ajay, Gumani, Damodar, Bansloi, Mahananda, Dwarkeshwar and Kangsabati. A riverscape covering an area of 83,946 km^2 has been delineated for the purpose of planning, assessment, and management through proposed forestry interventions following consultative process and science-based methodology including remote sensing and GIS technologies for geo-spatial analysis, modelling and prioritization of sites to rejuvenate the Ganga River (**Table 1**, **Figure 1**) (FRI, 2016). Here riverscape is a mosaic of different land uses viz., natural ecosystems, rural and agricultural ecosystems and built-up urban environment including flood plain and is an ecologically sustained system developed during the last 30 years due to river meandering all along the river and tributaries.

In the riverscape area of Ganga River, forestry interventions are planned in three landscapes: i) Natural (forests), ii) Agriculture (agroforestry), and iii) Urban, along with conservation activities in each landscape. Conservation interventions include soil and moisture conservation (SMC), wetland management and riparian wildlife management all along the river. Species combinations of

Table 1. Proposed area in Ganga riverscape.

State	Geographical area (km²)	Area in riverscape (km²)	Percent area in riverscape
Uttarakhand	53,483	23,372	43.70
Uttar Pradesh	240,928	25,639	10.64
Bihar	94,163	12,964	13.77
Jharkhand	79,714	3529	4.43
West Bengal	88,752	18,442	20.77
Total	**557,040**	**83,946**	**15.07**

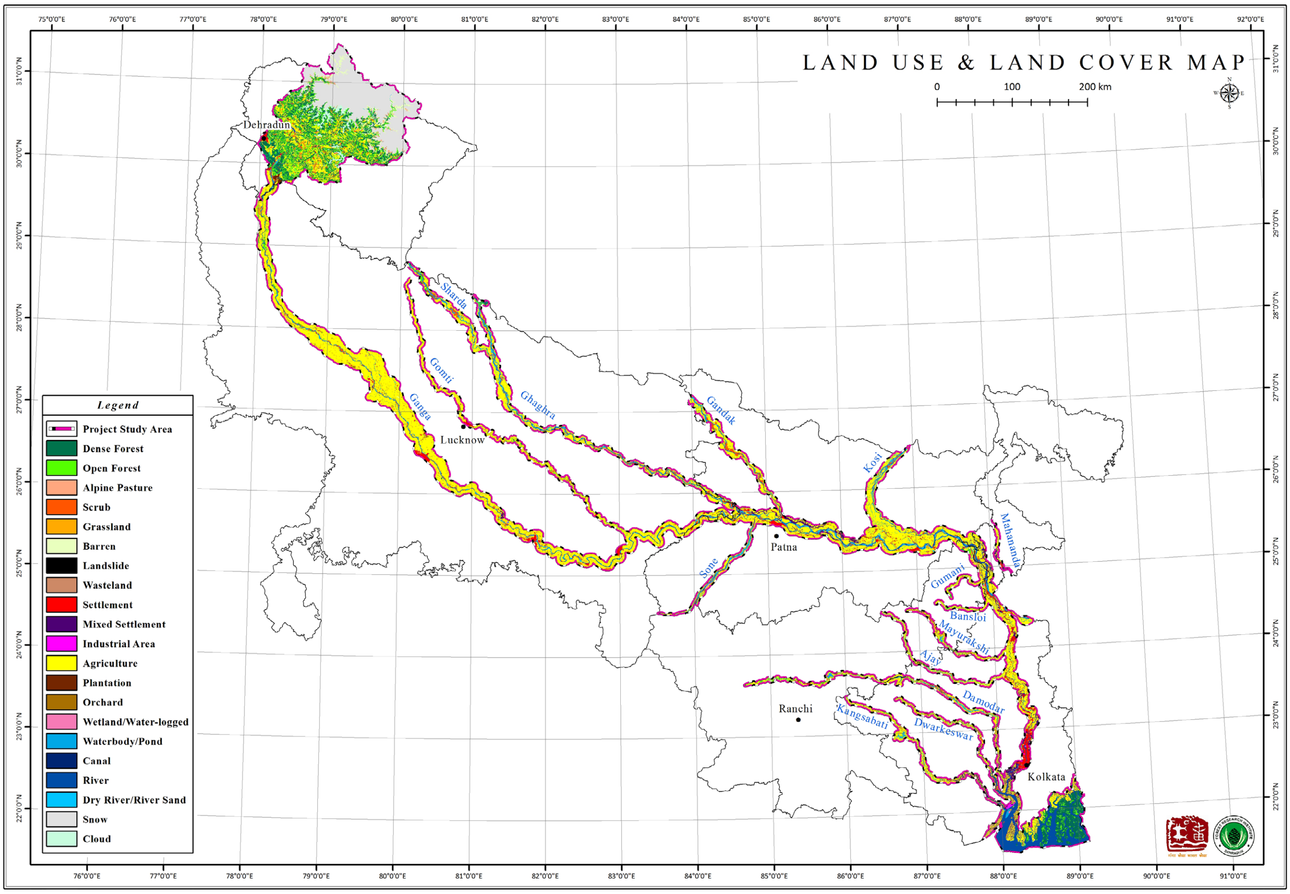

Figure 1. Location map of Ganga riverscape (Study area).

trees, shrubs and medicinal plants are proposed for plantings in each of the landscape and selection of species is based on the biogeographic zone, land use, soil, and forest type prevalent in the riverscape. For example, oak forests (*Quercus leucotrichophora*, *Q. floribunda*, *Q. semicarpifolia*) and pine forests in Uttarakhand Himalaya, Sal forests in the Shivalik's and Ganga plains, and mangrove forests in the Sundarbans (Champion & Seth, 1968), (**Figure 2**). There are as many as native species of trees, grasses, medicinal plants, fruit trees, etc. proposed for planting in riverscape area from alpine zone in Uttarakhand to mangrove

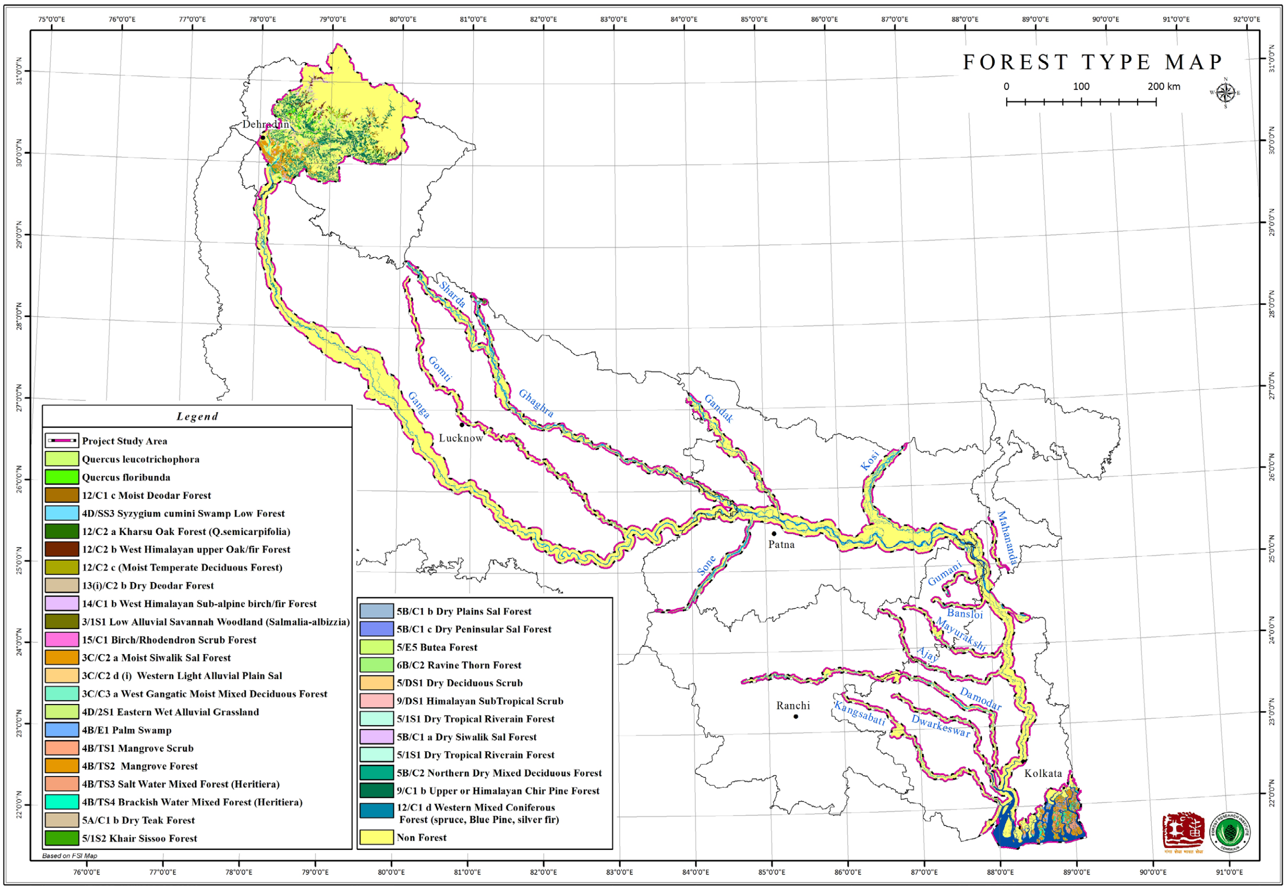

Figure 2. Forest types in Ganga riverscape (Study area).

ecosystem in West Bengal. Bioremediation and biofiltration interventions are also proposed in urban landscape in all five stakeholder states of the basin. Soil and moisture conservation (SMC) activities include i) vegetative measures for erosion control on stream slopes viz., brush layer, brush mattress, brush trench, filter strips; ii) streambank strengthening measures viz., riprap, cribs & gabions; and iii) flow obstruction and guiding structures viz., pile dikes, spur dikes retaining wall, revetment, wattling, etc. Forestry plantations and SMC activities broadly varied in five stakeholder states for the Himalayas and the Ganga plains (FRI, 2016).

Forestry interventions in Ganga riverscape are expected to increase the water recharge and decrease the sedimentation load in the river. The present work is devised to ascertain any impact of these interventions on groundwater recharge and sediment control in the Ganga River basin.

2. Material and Methods

Nature-based solutions are actions that protect, sustainably manage and restore natural and modified ecosystems in ways that effectively and adaptively address societal challenges and deliver benefits for human well-being and biodiversity (Cohen-Shacham et al., 2016). In water management, nature-based solutions involve the management of ecosystems to mimic or optimize the natural processes, such as vegetation, soils, wetlands, water bodies, and even groundwater aquifers, for the provision and regulation of water. The proposed work on "Forestry Interventions for Ganga" by way of protection, habitat management, afforestation, catchment treatment-soil and moisture conservation work, ecological restoration of vital riparian forest buffer, bioremediation, improved livelihood of forest dependent communities, etc. to rejuvenate the river is one of the crucial steps toward the Ganga River rejuvenation programme (Figure 3).

The environmental consequences of forestry interventions for Ganga will be determined based on water quantity and water quality in the river.

1) The first component will conservatively estimate the green water benefits of the proposed forest plantations and SMC works in the Ganga basin using the Soil Conservation Service Curve Number method (SCS-CN) and Groundwater Estimation Committee methodology of the Central Ground Water Board (CGWB), respectively.

2) The second component will quantify the reduction of sedimentation load in the Ganga basin from the forestry and SMC interventions.

2.1. Water Quantity Benefit Assessment

Under component 1, the proposed forestry interventions for the Ganga River basin have two major parts: i) Forestry plantations, and ii) SMC measure in the Ganga basin riverscape area. The proposed total riverscape area, plantation area, SMC activities and rainfall in the region are presented in Table 2.

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

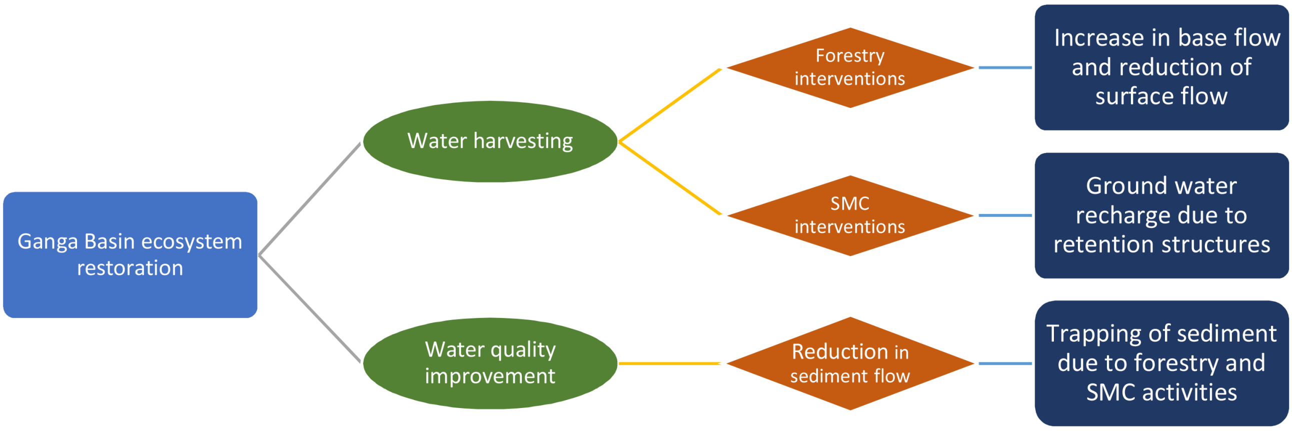

Figure 3. Flow chart showing a working procedure for the Ganga River basin restoration.

Table 2. Proposed forestry activities in the Ganga riverscape.

State	Rainfall (mm)	Riverscape area (sq. km)	Plantation area (sq. km)	SMC works (sq. km)
Uttarakhand	1176.00	23,372	468.89	79.67
Uttar Pradesh	909.80	25,639	131.96	10.17
Bihar	1036.90	12,964	256.67	20.00
Jharkhand	1097.10	3529	11.67	07.72
West Bengal	1144.90	18,442	268.82	86.00

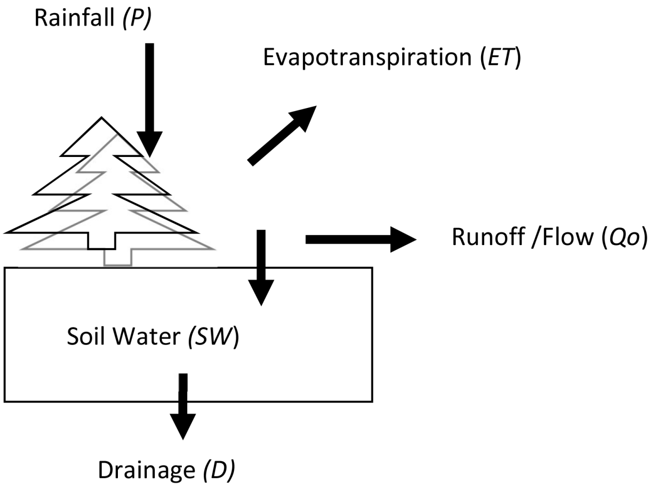

Figure 4. Water balance model.

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 can be determined by calculating the input, output, and storage changes of water. The significant water input is from precipitation, and the major output is runoff. A complete water balance model (**Figure 4**) may contain four sub-modelling systems describing the hydrologic cycle, namely, i) an atmospheric water balance sub-system, ii) a surface water balance sub-system, iii) a soil water balance sub-system, and iv) a groundwater balance sub-system. For the analysis purpose, each sub-system can be modelled separately.

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

$$G + P = Q_{dsro} + Q_b + ET + \Delta S_g \tag{1}$$

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) Evapotranspiration (ET) is the sum of evaporation and plant transpiration from the surface to the atmosphere. Evapotranspiration 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 understanding 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) settings 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 Equations (2) and (3).

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

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

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 Ganga basin has a tropical climate. The southwest monsoon dominates the climate, which provides most of the precipitation for the basin. High flow in the rivers occurs from July to September, and the lean flow season is from April to May. The annual rainfall varies from 600 to 1200 mm in the Ganga Basin. The average annual rainfall in the basin is estimated to be 1178 mm (IITM, 2016) (**Table 1**) (Equation (4)).

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

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 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 vegetation or enters the soil and is picked up by plants and evapotranspiration back into the atmosphere (Equation (7)).

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

2.1.2. Water Augmentation through SMC Measures

Estimating groundwater recharge is essential to measure the effectiveness of water conservation measures. However, a site-specific modeling approach to forecast groundwater recharge typically requires observed historical data to assist calibration. It is generally impossible to physically observe groundwater recharge activities spreading over large areas. However, the Ground Water Resource Estimation Committee (GEC, 2015) methodology provides a simple assessment framework for estimating groundwater recharge due to Soil Moisture Works (SMC). In the present study, this methodology will be employed to calculate groundwater recharge in Ganga basin from the proposed SMC activities, as given in **Table 2**.

Recharge assessment framework

Recharge due to water conservation structures is estimated based on Equation (8) as follows (GEC, 2015):

$$\text{RWCS} = \text{GS} \times \text{RF} \tag{8}$$

where, RWCS = Recharge due to water conservation structures, RF = Recharge factor, GS = Gross storage.

Step 1: *Estimating gross storage*

The gross storage of water in the study area is estimated using Equations (9) and (10) as follows:

$$\text{Gross Storage} = \text{Storage Capacity} \times \text{Number of fillings} \tag{9}$$

$$\text{Storage Capacity} = \text{AWSA} \times \text{H} \times \text{Efficiency} \times \text{Number of fillings} \tag{10}$$

where, AWSA = Storage potential created through excavation, H = Height, Efficiency means storage efficiency of the structures, Number of fillings = Number of fillings during the rainfall season.

Conservative assumptions:

- Proposed SMC works areas as water spread areas.
- 50% percent area of SMC activities is considered as average water spread area.
- Gross storage is estimated using 1 m height for the nalas and check dams.
- Efficiency = 50% for earthen structures as per GEC Norms; generally, check dams, nala bunds, contour channels, etc. can be taken as 50% of gross storage considering leakages and other factors.
- As the structures are located in the riverscape area, annual fillings are assumed to be 10, considering 30 to 50 rainy days and surface runoff from adjoining areas in the Ganga River basin.

Step 2: *Recharge due to water conservation structures* (*RWCS*)

The recharge factor required to estimate recharge due to water conservation structures in Ganga riverscape is considered as suggested by GEC (2015). The obtained recharge factor is multiplied by gross storage to estimate the total recharge amount.

2.2. Water Quality Improvement Due to Forestry and SMC Interventions

In the long term, one of the essential ways forest catchments can influence water quality is their effect on absorbing rainfall variability and seasonal climate variations. It is one of the critical factors influencing sediment yield from a given basin. If lands are degraded and soils are unstable, rainstorms can lead to heavy sedimentation from the river sheds. Under any given condition, forest catchments significantly reduce sediment yield from watersheds (Conroy, 2001).

Only the sedimentation parameter is considered for this study due to data availability and relevance to the project activities (Rao, 2012). The rehabilitation of some forest watersheds can dramatically reduce the rate at which sediments are delivered to a reservoir. These sediment yields will be calculated by standard extrapolation techniques from previous measurements (Trimble, 1999). The legacy data on the silt rate of major/minor irrigation/hydro-electric projects provides a realistic estimate for calculating the sediment yields from the basin (CWC, 2015). **Figure 5** shows a schematic representation of the main influences on water quality within a river basin (Owens, 2008).

Step 1: *Treatment Area*

As in component 1, component 2 also have the same proposed forestry interventions in the Ganga riverscape area for calculation purpose (**Table 1** and **Table 2**).

Step 2: *Sediment factor*

The evaluation of sediment inflow has always been complex because the sediment content varies considerably for the same river according to the flow and the season. In addition, it also requires complex sediment modelling based on the land use assumptions; besides requires enormous time and resources for measurement. Further, the results cannot be precise, and there would be associated uncertainties. However, based on the sedimentation legacy data at the project locations, the most reliable sedimentation assessments may be provided as per CWC (2019).

Step 3: *Trap efficiency*

The rate of sediment production in the catchment area and the actual rate of silting depends on many other factors, viz., gradation of silt, maintenance of structures, etc. Therefore, we conservatively estimate 90% efficiency of the forestry interventions.

Step 4: *Sediment reduction*

Sediment Reduction in the basin due to forestry and SMC Interventions is calculated using Equation (11) (Trimble, 1999).

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

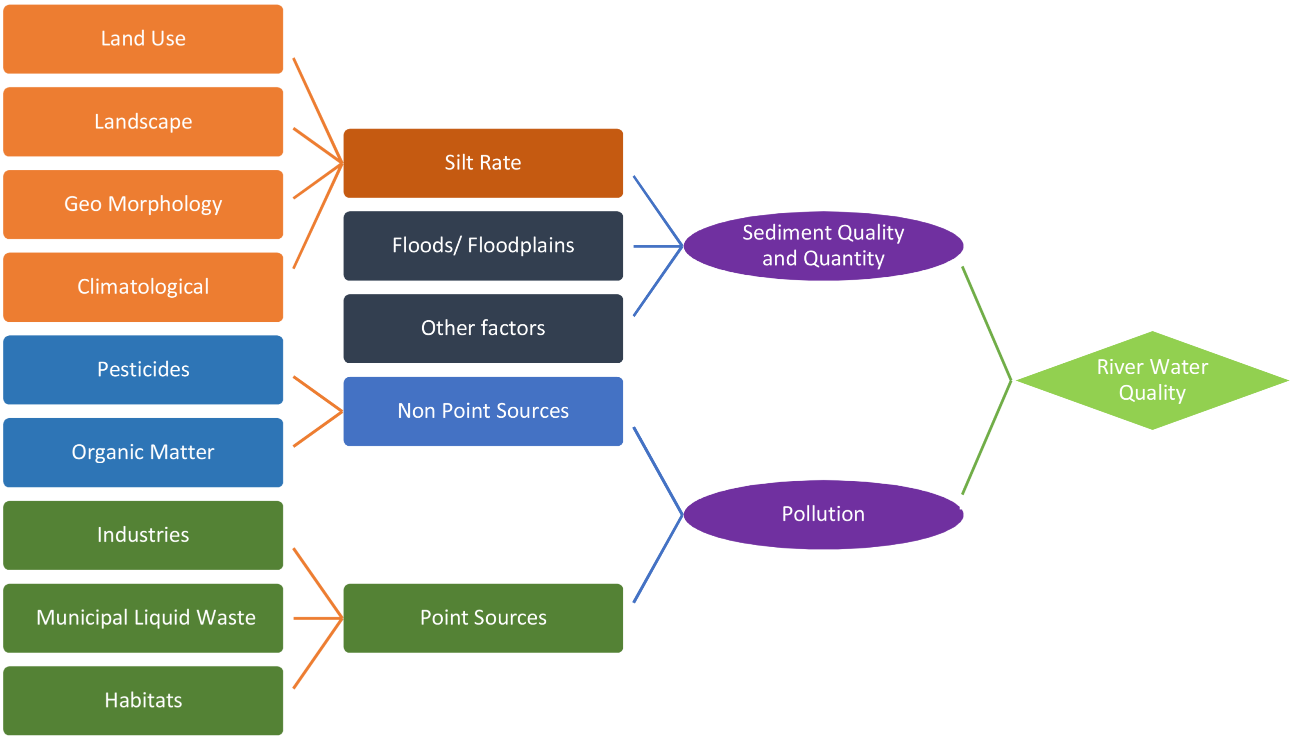

Figure 5. Activities in river basin, which influences water quality.

3. Results

The results on water recharge and sedimentation decrease in the Ganga basin due to plantation and SMC activities are discussed as follows.

3.1. Water Quantity Benefit Assessment

In the present study, the expected water quantity improvement in terms of recharge due to plantation activities and SMC measures is discussed as below.

3.1.1. Water Augmentation through Plantation Activities

The surface runoff due to absence of forestry intervention was 1092 mm, and in the presence of forestry interventions, it was 873 mm, thereby, the forestry interventions reduced the surface runoff by 20% in comparison to river basin without any intervention (Table 3). The forestry activities acted as a barrier to runoff flow and thereby increased the opportunity time for water infiltration and storage in the soil profile, which ultimately recharge the groundwater. In the present study, the water recharge due to forestry intervention was estimated to be around 231 million cubic meter (MCM) in Ganga basin.

3.1.2. Water Augmentation through SMC Measures

Several SMC measures were proposed to be carried out in five states under the Ganga River basin. It was observed that, maximum storage potential could be developed in West Bengal followed by Uttarakhand and least storage potential could be created in Jharkhand state. State wise ground water recharge varies and is proportioned to the area treated under the project. The amount of ground water recharge due to proposed conservation structures also followed the same trend as for storage potential. However, total recharge amount due to several conservation measures is expected to be 0.011 MCM for the study area under consideration (Table 4).

3.2. Water Quality Improvement Due to Forestry and SMC Interventions

Despite recognizing that trees can improve soil hydraulic conductivity and reduce

Table 3. Estimated green water after forestry interventions in Ganga riverscape.

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)	873.00	1092.00
Total base flow (Green water) (MCM)	Area with Forestry Interventions (FI) − Area with FI (With FI Q_b − Without FI Q_b) = 113,800.56 ha (812 mm − 609 mm)/1000 = 23,101.51638 = 231.00	

*Parameter values deduced from SCN Curve values.

overland water flow (Sandstrom, 1998), their contribution to groundwater recharge and water quality improvement is often understated. Overall, sedimentation rate is one of the most important parameters in the water quality of the river system. Due to rampant loss of tree cover and land use changes, sedimentation processes in reservoirs have increased in many basins of India, including the Ganga basin. Furthermore, climate change is also altering hydrological regimes, wherein prolonged dry spells, increased rainfall intensity, and decreased rainy days further accelerated this process.

Based on the sedimentation factor as suggested by CWC (2015), trap efficiency and respective intervention area, the sedimentation rate due to implementation of proposed interventions were estimated as given in **Table 5**. Among the states under study, the highest sedimentation rate (393.30 cubic m/yr) is expected in Uttarakhand and the lowest sedimentation rate (7.52 cubic m/yr) is expected in Jharkhand. State wise sedimentation rates vary and are proportioned to the area treated under the project. However, a total amount of 1119.56 cubic

Table 4. Gross storage of water in Ganga riverscape due to SMC interventions.

State	Storage potential created through excavation (Cubic Meter)	Number of fillings	Efficiency	Gross storage (m^3)	Recharge factor (%) based on soil conditions	Recharge due to water conservation structures (m^3)
Uttarakhand	7966.85	10	50%	39,834.25	10	3983.43
Uttar Pradesh	1016.53	10	50%	5082.65	16	813.22
Bihar	2000.00	10	50%	10,000.00	16	1600.00
Jharkhand	771.82	10	50%	3859.10	10	385.91
West Bengal	8600.00	10	50%	43,000.00	10	4300.00
Total Recharge in M^3						11,082.56
Total Recharge due to SMC in MCM						0.011
Water Savings due to Plantations in MCM						231.00
Overall Water Recharge due to Plantations and SMC in MCM						**231.011**

Table 5. Estimated sedimentation rate for the Ganga basin post proposed interventions.

State	*Sedimentation factor (000 m^3/sq km/yr)	Trap efficiency	Total intervention area (sq km)	Sedimentation rate (cubic m/yr.)	Sedimentation rate (tons/yr.)
Uttarakhand	0.932	90%	468.89	393.30	138.83
UP	2.96	90%	131.96	351.54	124.09
Bihar	0.802	90%	256.67	185.26	65.40
Jharkhand	0.716	90%	11.67	7.52	2.65
West Bengal	0.752	90%	268.82	181.94	64.22
	Total		**1138**	**1119.56**	**395.20**

*Source: CWC, 2015.

m/yr or 395.20 tons/yr of sediment is supposed to be trapped by the SMC activities and plantation activities, which otherwise would have lost from the basin or deposited in reservoirs or sea.

The plantations and soil and moisture conservation measures are expected to increase water recharge by 231.011 MCM·yr^{-1} and decrease the sedimentation load by 1119.6 cubic m·yr^{-1} or 395.20 tons·yr^{-1}, respectively, in delineated riverscape area of 83,946 km^2 in Ganga basin due to these forestry interventions.

4. Discussion

Increase in water recharge by 231.011 MCM·yr^{-1} and decrease the sedimentation load by 1119.6 cubic m·yr^{-1} or 395.20 tons·yr^{-1}, respectively, in Ganga basin by way of plantations and SMC activities may be attributed to forestry interventions and bioengineering techniques which help to keep rivers perennial, mitigate floods and drought. Forests and forestry have a substantial role in increasing precipitation, prevent soil erosion and help rain water seep into the soil as living and decaying roots make the soil porous by creating a network of well-connected, minuscule channels in the soil.

4.1. Water Recharge

Forest catchments have often been described as "sponges" storing rainwater and slowly releasing it to maintain groundwater and streams during dry periods (Hamilton & King, 1983). Forests are used as nature-based solutions for water-related natural hazards. Afforestation can play an integral role in sustaining water resources, protecting water quality, and more specifically can absorb rain water, disperse surface runoff, purify pollutants and produce clean water in rivers. Trees can help in collecting and filtering rainfall and releasing it slowly into streams and rivers, and are the most effective land cover for maintenance of water quality. This study supports the sponge theory, however, gathers no evidence against trade-off theory. Springgay et al. (2019) also advocated the important role of trees and forests in hydrologic cycles and in improving the soil infiltration and groundwater recharge. 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). Ilstedt et al. (2016) also found that moderate tree cover on degraded lands can increase groundwater recharge, and that tree planting and various tree management options can improve groundwater resources in dry tropics.

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) found 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%. In this way, present study supports sponge theory, however, gathers no facts against trade-off theory.

4.2. Sedimentation Reduction

Forests can help by filtering sediments and other pollutants from the water in the soil before it reaches a water source, such as a stream, lake or river. Conroy et al. (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). Maintaining riparian vegetation allows for multiple processes important to the formation, availability, and arrangement of instream habitats (Richardson et al., 2005) and to maintain water quality and instream habitat conditions, riparian-management standards are required e.g., adoption of buffers that maintain streamside vegetation (Richardson et al., 2012). Ali et al. (2017) 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.

By trapping the sediment, it will ultimately reduce the sediment load in river water and also improve the quality of river water. A study revealed that due to erosion, about 22.9% ± 29% of soil is lost to the oceans, 34.1% ± 12% is collected in the reservoirs, and the rest 43.0% ± 41% is relocated from the provenance (Sharda & Ojasvi, 2016). The study conducted by Sun et al. (2018) for Guangdong Province of China, suggest that the vegetations 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 onwards in Yellow River in China. Singh et al. (1984) observed that an oak (*Quercus leucoprichophora*) forest remains most useful for soil development, protection of nutrients, water retention and the life of connected springs of watershed in western Himalayas. Hence, by adopting the proposed forestry interventions, it is expected to reduce the erosion and trap sediments in Ganga River basin in the country.

5. Conclusion

The ecological health of the Ganga River and some of its tributaries have deteriorated significantly due to various anthropogenic reasons. Enhancing water provision services is a common target in forest restoration projects worldwide due to growing concerns over freshwater scarcity. Nature-based solutions are actions that protect, sustainably manage and restore natural and modified ecosystems in the world. Forestry plantations and soil and moisture conservation measures devised in the programme to rejuvenate the Ganga River are expected to increase water recharge and decrease the sedimentation load in the river by 231.011 $\mathrm{MCM \cdot yr^{-1}}$ and 1119.6 cubic $\mathrm{m \cdot yr^{-1}}$ or 395.20 $\mathrm{tons \cdot yr^{-1}}$, respectively, in delineated riverscape area of 83,946 $\mathrm{km^2}$ of Ganga basin. However, state wise ground water recharge and sedimentation rates vary and are proportioned to the area treated under the project. The role of trees and forests in improving hydrologic cycles, soil infiltration and groundwater recharge may be the reason for this change. Maintaining riparian vegetation is essential to maintain water quality and instream habitat conditions of rivers. These results may provide important information that supports operational practices, such as forest plantations to restore waterbodies and in understanding the linkages among forest structure, function, and streamflow. The results will give momentum to the National Mission of Clean Ganga (NMCG) and its *Namami Gange* programme including other important rivers.

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Conflicts of Interest

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

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