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Riverscape Approach and Forestry Interventions for Ganga River Rejuvenation

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Abstract

Rivers have been degraded globally due to various reasons over centuries and limiting their ecological health and value, including Ganga River in India. Riverscape approach can provide relevant information on riverine resources needed in river restoration programmes. We propose a conceptual riverscape model to rejuvenate the holy river Ganga in India through forestry interventions after due consideration of ecological processes, mosaic of landforms, communities and environment within the large landscape of Ganga basin. The select riverscape area includes the area of 5 km and 2 km on either side of the river Ganga and important tributaries, respectively, all along the rivers in five stakeholder states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal in the country. The width of the riverscape was taken from the maximum bank line in recent years on either side of river in the concerned state. However, all micro-watersheds in the hills of Uttarakhand state, being the origin place of river, have been included in riverscape area up to Haridwar. 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. Geospatial modelling and GIS data on land use pattern, soil erosion rates, slope of the topography, etc. were used to classify riverscape area into high, medium and low priority areas to implement forestry interventions in delineated riverscape. Thereafter, forestry interventions were planned and carried out in three identified landscapes viz., Natural (forests), Agriculture (agroforestry), and Urban along with conservation activities. Forestry interventions in delineated riverscape are expected to increase water recharge and decrease the sedimentation load in the Ganga River and its tributaries.

Keywords

Rivers, Landscape, Riverscape, Land Use, Ganga, Forestry Interventions.

1. Introduction

Rivers provide critically important nature contributions to human well-being, and play an important role in maintaining the structure, function, and integrity of landscapes in which the rivers reside (Zhou et al., 2013). The Ganga River has immense geographical, environmental, socio-economic, cultural and religious significance in India and beyond. Being a trans-boundary river, it traverses across five states of India and Bangladesh with a total stretch of 2525 km. The river forms one of the largest basins in the world, representing 26% of India's land mass and supporting about 43% of country's population. It is also a lifeline for millions of Indians who live along its course and depend on it for their daily needs. In spite of the religious and cultural pre-eminence of the river Ganga in the Indian ethos, fragmentation and degradation of the river continued down the ages and the river remained neglected for a long time.

Restoring the ecological integrity of degraded waterways is tough and complicated work but restoration work should emphasize maximizing natural process to meet current human priorities. Skidmore and Wheaton (2022) viewed that a strategic focus on riverscapes as critical natural infrastructure can serve ecosystem-based adaptation to improve resilience to climate change and restore river ecosystem health. Isolationist approaches to river management constrained the development of new scientifically based comprehensive approaches for river development and management. It is only in recent decades that hydrological, geomorphological and biological research have been integrated to establish a new understanding of the dynamic river systems. It is fact that all global rivers are heavily influenced by human activities and rehabilitating a river to its former or to a more semi-natural state is a challenging task (Acevedo et al., 2014). A common aim of rehabilitation projects is to make the river more natural, and "naturalness" has become an important element of the enhancement ethology (Nienhuis et al., 2002).

An increased understanding of fluvial ecosystems has led to a shift in conservation and restoration strategies of rivers. Functional perspectives of river restoration aim to regain the full suite of biogeochemical, ecological, and hydrogeomorphic processes that make up a healthy river (Palmer et al., 2014). In addition, dynamics of river behaviour play an important role in meandering, sediment transporting, scouring, etc. of river at bend, which solely depends on hydraulics properties such as horizontal and vertical stress, spatial and temporal variation of discharge (Chauhan et al., 2015). From an initial focus on enhancing fish habitat or river appearance, primarily through structural modification of channel form, restoration has expanded to incorporate a wide variety of management activities designed to enhance river process and form (Wohl et al., 2015). Different concepts have evolved and are in use from the perspective of planning, assessment, management, and conservation of a river or river ecosystem, viz., river basin, watershed, and riverscape management. The effectiveness of programs for environmental rehabilitation of aquatic ecosystems requires a tailored restoration approach that is based on sound scientific knowledge of processes and mechanisms and draws from the experience of previous successful interventions. 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).

Recognizing the significance as well as appreciating increasing national concern about environmental degradation of the Ganga River and its basin, the Government of India initiated the National Mission for clean Ganga (NMCG) to rejuvenate Ganga River. The Mission consolidates the existing ongoing efforts for Ganga rejuvenation and is putting in place a concrete action plan for the future. To achieve this, Ministry of Water resources, River Development, and Ganga Rejuvenation (MoWR, RD&GR), NMCG and its *Namami Gange* programme have decided to adopt a scientific approach to river basin management for Ganga rejuvenation. Keeping in view the multiple functions of forest ecosystems and their inter-connectedness with highly dynamic river ecosystems, NMCG has initiated a programme to rejuvenate the holy river Ganga through forestry interventions using riverscape approach in Ganga basin in collaboration with Forest Research Institute, Dehradun

2. Riverscape

The concept of "riverscape" (or river landscape) was proposed as early as in 1960s when Leopold and Marchand (1968) used the term to describe the broad-scale physical, biological and aesthetic nature of rivers. Landscape perspectives in riverine ecology have been undertaken increasingly in the last 30 years, leading aquatic ecologists to develop a diverse set of approaches for conceptualizing, mapping and understanding "riverscapes" (Torgersen et al., 2021). Incorporation of concepts from landscape ecology into understanding and managing riverine ecosystems has become widely known as riverscape ecology (Boisjolie et al., 2019). A riverscape perspective considers the ecological and social landscape of the river and its valley. The riverscape concept that treats rivers as spatially expanding longitudinal and lateral riverscape, rather than as sampling points, lines, or gradients, has been strongly advocated for application into the riverscape ecology and river ecology (Wang et al., 2014). Recent approaches to river management emphasize the riverine landscape or "riverscape" perspective as running waters are open ecosystems. Longitudinal changes from the river source to its mouth, vertical interactions (river bed/aquifer) and lateral exchange processes across the floodplains play a major role in alluvial river landscapes. The riverscape approach integrates rivers with their surrounding landscape and explains the broad-scale physical, biological and aesthetic nature of rivers and to describe spatio-temporal patterns and processes linking a river and its bank, or its riparian areas, within a fluvial system which ultimately provide an insight into the complex interactions between disturbance regimes, spatial heterogeneity, and biodiversity. In contrast to specific species focused management and evaluation, the current emphasis is on ecosystem management which focuses on key processes that enable river-floodplain systems to maintain, repair and regenerate themselves to a certain state.

Riverscapes are complex, interconnected ecosystems consisting of channels, banks, riparian zones, and floodplains (Resop et al., 2019). Rather, riverscape is a framework for understanding the rivers based on the principles of landscape ecology and its application requires information on the spatial distribution of organism scale habitat throughout the entire river system. Mapping of physical and biological characteristics of rivers and floodplains with high-resolution, spatially intensive techniques improves understanding of the causes and ecological consequences of spatial patterns at multiple scales (Torgersen et al., 2021). Riverscape approaches can provide relevant information on riverine resources needed by researchers and managers. For example, the spatial information about species distribution facilitates management decisions for making conservation strategies. In addition, riverscape approaches to mapping, sampling and modelling on physical, structural and functional heterogeneity help decision makers for effective riverine project implementation and monitoring. Riverscape encompass an area around and adjacent to the present channel where fluvial erosion, channel evolution and down-valley meander migration are most likely to occur. In fact, riverscapes are the part of the landscape that could be flood by their rivers and streams in natural regimes. By integrating water and land that is increasingly dominated by human activities, the riverscape approach can contribute to the sustainability of riverscape that highlights the importance of maintaining and improving ecosystem services in changing landscapes (Wu, 2013).

The rapidly evolving concept of "riverscape", particularly in a developing country like India, finds an important place as major rivers have strong linkages with civilization, culture and prosperity. The riverscape approach explains the broad-scale physical, biological and aesthetic nature of rivers and aims to describe spatio-temporal patterns and processes linking a river and its bank, or its riparian areas, within a fluvial system which ultimately provide an insight into the complex interactions between disturbance regimes, spatial heterogeneity, and biodiversity. Riverine landscape or "riverscape" approach of river management includes the delineation of treatment area based on the understanding of patterns and processes of the river and its banks/riparian areas (Ward, 1998; Ward et al., 2002). A key step in implementing a riverscape approach is to quantify the spatio-temporal pattern of the riverscape that encompasses upland systems surrounding the river. The species pool in riverine landscapes is derived from terrestrial and aquatic communities inhabiting diverse lotic, lentic, riparian, and groundwater habitats arrayed across spatio-temporal gradients. Further, river rejuvenation and management will not be sustainable unless key ecosystem services that rivers generate and influence are explicitly considered from the landscape sustainability perspective (Wiens, 2002; Montgomery & Wohl, 2003).

Riverscape scale studies seek to comprehensively assess biophysical processes throughout river systems, from estuary to headwaters, rather than in isolated segments or reaches. A riverscape approach is useful for characterizing and evaluating the distribution of specific riparian land-management standards across broad geographic extents of diverse land ownerships and land uses (Boisjolie et al., 2019). Though the riverscape concept has informed new ideas in ecological research (Falke et al., 2013; Pichon et al., 2016), its foundation in the broader field of landscape ecology also included social considerations of land-use policy and management (Wiens, 2002). As such river landscape is the interfaces between terrestrial and aquatic ecosystems and should be delineated considering ecological processes, mosaic of landforms, communities and environment within the large landscape.

We propose a conceptual riverscape model through forestry interventions for river rejuvenation programme for Ganga in India by understanding the structure & function of stream ecosystem, fluvial landforms, interaction between the rivers & floodplains, hydrologic, topographic and vegetation criterion. In this context, 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.

3. Forestry Interventions

Nature can only continue to deliver its services where ecosystems are healthy and functioning well. Nature-based solutions can often be used in conjunction with other types of interventions to address global societal challenges (IUCN, 2016). Forests, aquifers, soils, lakes and wetlands provide water storage, wetlands and soils filter water, rivers provide conveyance and transportation, floodplains and wetlands lower food peaks in downstream cities, while mangroves, coral reefs and barrier islands protect coasts against storms and inundation. Forest recycles and absorbs excess nutrients and decreases water pollution. 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). Acevedo et al. (2014) address the overall ecosystem and recognize that the restoration benefits transmitted throughout the river corridor are extensive and multi-trophic. Linkages between upstream land use and downstream habitat make assessments of riparian protection at a riverscape scale informative for conservation planning across management entities (Allan, 2004). 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.

The ecosystem approach seeks insight through inter-disciplinary researches at all stages of the planning, implementation and evaluation process. 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. "Forestry interventions" on a scientific basis are pertinent for river conservation, specifically to river rejuvenation and overall ecological integrity of river ecosystems. The availability and quality of water in the river have been increasingly threatened by overuse, misuse and pollution, and both are strongly influenced by the extent and condition of forests in the upstream and downstream areas. More so, climate change is also likely to alter the role of forests in regulating water flows and influencing the availability of water resources. 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., 2019). For example, a decrease in evapotranspiration following deforestation in one area may reduce rainfall in downwind areas (Ellison et al., 2017).

The present approach for river Ganga rejuvenation emphasizes appropriate forestry interventions 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 and forest dwellers, and alternate income generation activities through regulated tourism and awareness. The present work on "Forestry Interventions for Ganga" to rejuvenate the river is one of the crucial steps toward the Ganga River rejuvenation programme (**Figure 1**). It is envisaged that such concerted efforts and initiatives of forestry interventions for Ganga River will greatly facilitate the major goals to maintain clean (*Nirmal Dhara*) and continuous ecological (*Aviral Dhara*) flows of Namami Gange programme in the country. In this context, forestry interventions include afforestation/reforestation in different land uses and conservation activities like soil and moisture conservation (SMC), and management of wetlands and riparian wildlife all along the river.

4. Ganga Riverscape

The Ganga River, from its origin at Gaumukh in the Gangotri glacier at 3892 m altitude in the state of Uttarakhand to the mouth in the Bay of Bengal, represents three biogeographic zones: 1) the Himalayas, 2) the Gangetic plains, and 3) the coastal including deltaic region (CWC, 2008). The river is home to many threatened and sensitive ecosystems, viz, glaciers, alpine meadows, diverse upland forest, terai grasslands and swamps, riparian forests, mangroves, etc. along with a large variety of rare, endangered, and threatened faunal species that inhabit them.

4.1. Riverscape Area

The Ganga River and its tributaries are highly braided with large river islands due to high siltation rates and are prone to change course frequently. The river Ganga varies in its nature all through its length, having some stretches where vast floodplains exist and are annually flooded. Riverscape scale studies comprehensively assess the biophysical processes throughout river systems, from estuary to headwaters rather than in fragments. Accordingly, based on the global insight on the width of riparian corridors, nature of channel morphology & dynamics of Ganga River; an area called as "Ganga riverscape", which covers 83,946 km^2 area within five states (Uttarakhand, Uttar Pradesh, Bihar, Jharkhand and West Bengal), has been delineated throughout the length of Ganga River (2525 km) for the planning, assessment and further prescriptions to rejuvenate the river through forestry interventions (**Table 1**) (FRI, 2016).

The select riverscape area includes the area of 5 km and 2 km on either side of

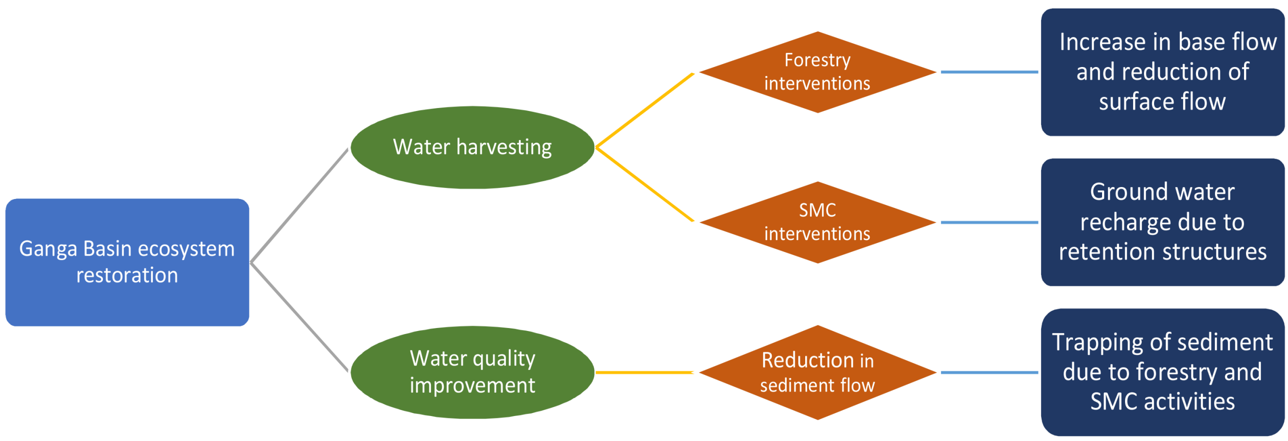

Figure 1. Flow chart showing a working procedure for the Ganga riverscape.

Table 1. Extent of Ganga riverscape.

State	Geographical Area (km^2)	Area in Riverscape (km^2)	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**

Ganga River and selected tributaries, respectively, in five stakeholder states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal in India (**Figure 2**). The width of the riverscape was taken from the maximum bank line on either side of river in recent years in the concerned state. However, being the origin place of Ganga river, all micro-watersheds in hills of Uttarakhand sate have been included in riverscape area up to Haridwar (**Figure 3**). A total of 25 tributaries (Bhagirathi, Asi Ganga, Bal Ganga, Bhilangana, Nayar, Dhauliganga, Alaknanda, Mandakini, Nandakini, Pindar and Song, Sharda, Ghagra, Gomti, Sone, Gandak, Kosi, Mayurakshi, Ajay, Damodar, Bansloi, Gumani, Mahananda, Darkeshwar and Kangsabati) except Yamuna have been included in the riverscape area in these five stakeholder states.

4.2. Riverscape Analysis

Image processing and GIS tools viz., ERDAS Imagine 2015, Geomedia Professional 2015, ArcGIS, etc. were used for riverscape analysis. Landsat TM, Landsat 8 and Landsat ETM datasets specific to the riverscape were downloaded from authoritative sources/sites. The time frame was selected keeping in view the pre and post monsoon seasons, maximum differentiation in various land cover features and the historical dates of maximum flooded area. The Landsat 8 satellite data (for the months of March and April 2015 and September to November 2014) and Landsat TM and ETM data (for the months of September to November, 1989, July to November 2010, November 2011) have been used for preparation of bank line map, land use land cover map of the riverscape. The historical review of floods in Ganga and its tributaries in last 30 years revealed that maximum flood spread in the river was in the year 1989 in West Bengal state; 2010 in Uttar Pradesh, Bihar and Jharkhand states; and 2013 in the state of Uttarakhand (FRI, 2016; Savita et al., 2018). In other words, riverscape here is the part of the landscape that could be developed due to flooding by their rivers and streams in natural regimes. After delineating the maximum bank line, buffer areas of 5 km ad 2 km were generated and analysis was carried out for creation of important spatial layers. Geospatial analysis and modelling were carried out using these spatial layers for recommending suitable sites for forest plantations sites. Ancillary data on soil types, soil erosion and forest cover were obtained from concerned national level agencies. 21 major land use and land cover type classes were delineated with distribution of area under corresponding classes for the entire riverscape in the five stake holder states—Uttarakhand, Uttar Pradesh, Bihar, Jharkhand and West Bengal. After that, GIS-assisted decision making process by way of geospatial analysis and modelling was used to prioritization of suitable areas for forestry interventions in Ganga riverscape. Different layers like land use pattern, soil erosion rates, and slope of the topography were generated within riverscape. Topographically, Uttarakhand state covers the region of high hills, while rest four states are mainly plain areas with agriculture dominance. So, based on the variation of topography and land use patterns; two processes

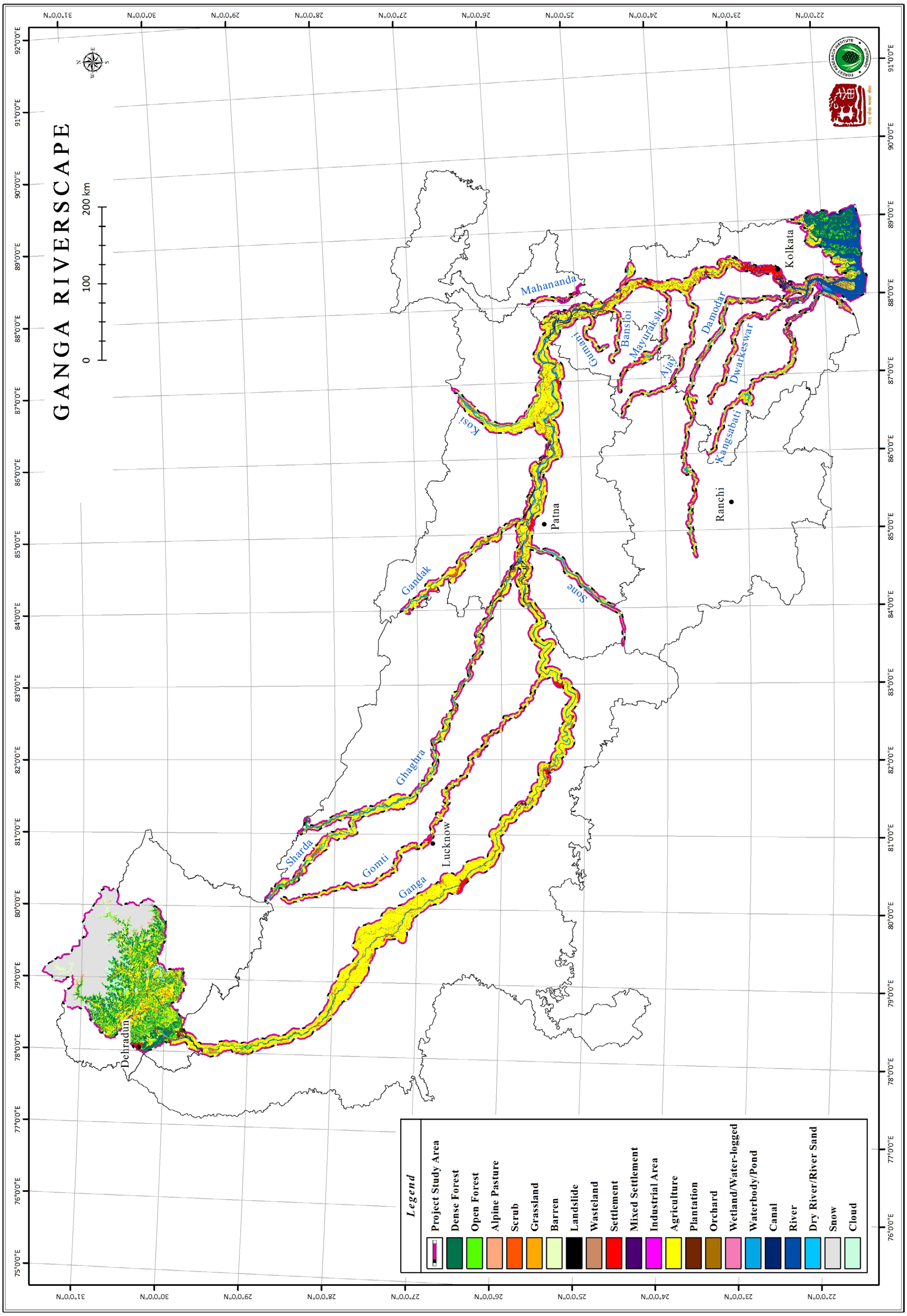

Figure 2. Ganga riverscape/Project study area.

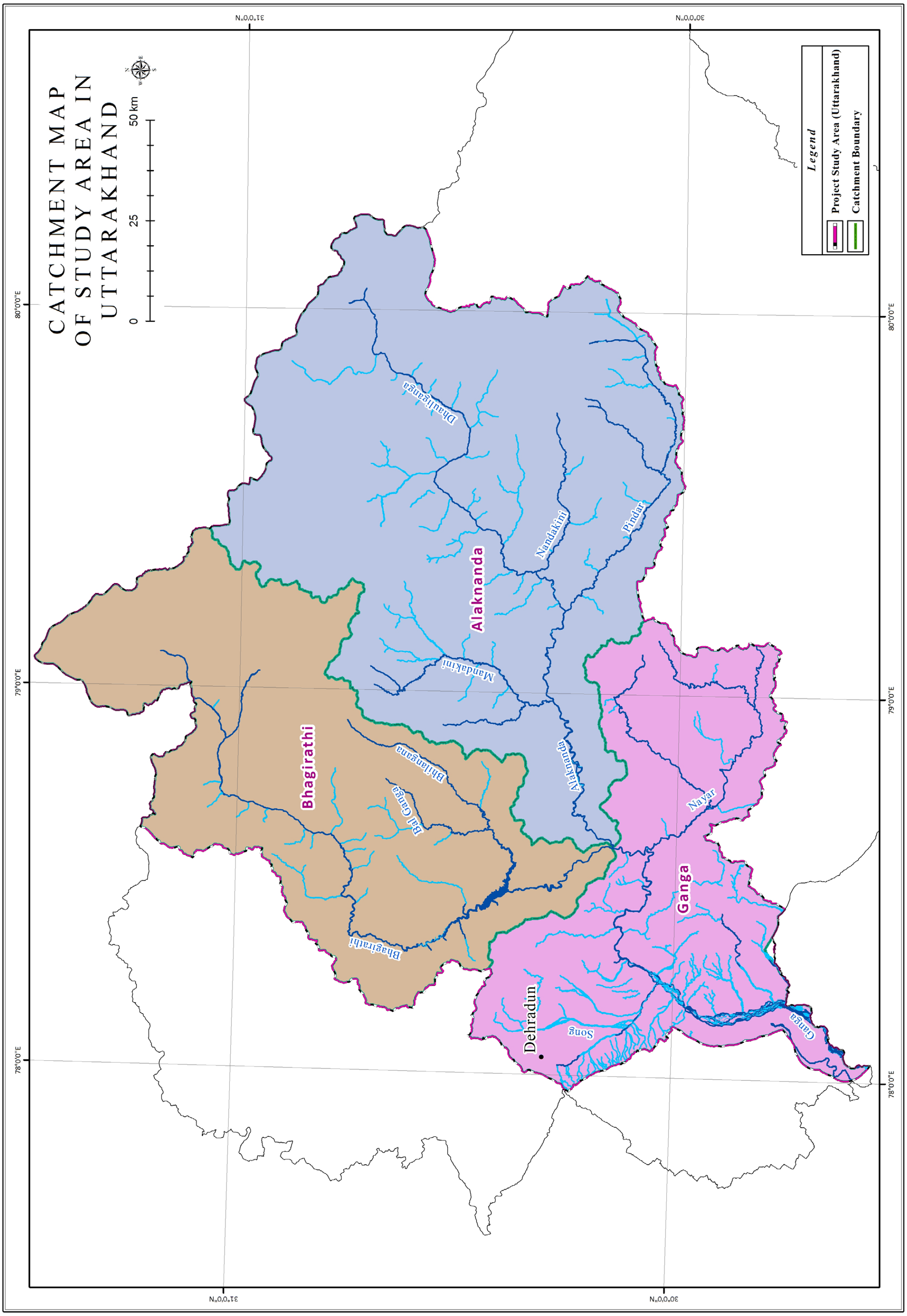

Figure 3. Riverscape/Project study area in Uttarakhand State.

were adopted to prioritize the suitable areas for forestry interventions in five stakeholder states. The geospatial layers of slope, soil erosion and forest density in the state of Uttarakhand, while, slope, soil erosion and land use in the state of Uttar Pradesh, Bihar, Jharkhand and West Bengal were used for the determination of priority areas in the riverscape. Accordingly, based on severity of feature, these combinations were then classified into 1) high, 2) medium and 3) low priority areas for further forestry interventions to be carried out (**Figure 4**).

4.3. Rationale of Riverscape Width

The Himalayan rivers (Indus, Brahmaputra and Ganga) are significantly different in magnitude of their flow in comparison to major world rivers owing to the fact of extremely high fragility of the Himalayan Mountain ecosystem, unstable geological formations, proneness to natural disasters, high biotic pressures etc. The width of river Ganga in high flood levels ranges from as low as 1 km to as high as 25 km. Thus, the river is highly braided with large river islands due to high siltation rates and is prone to change its course frequently. A similar situation exists in case of several of its tributaries originating in the high Himalayas and descending/flowing fast into the Ganga plain. The Ganga is mostly bounded by agricultural lands and large stretches of river Ganga in its plains are overburdened by numerous cities and large townships. Thus, most stretches are devoid of natural vegetation/forests in proximity to highly fluctuating river banks. It was decided that the river should have riparian corridors on both sides; a width of 5 km in the case of Ganga stem and 2 km in case of tributaries of the Ganga. The riverscape area covered as much of forest land, agriculture and revenue lands in rural and urban environments and community & village lands through the involvement of the communities themselves. Forestry interventions were planned and carried out in natural landscapes, agriculture landscapes, and the urban landscapes within the defined width of forest buffer (5 km—Ganga stem and 2 km—tributaries) on either side of the river banks while taking into account the high flood levels of recent times.

4.4. Calculating the Riverscape Width

Determining the width of riverscape of a river, from origin to mouth, depends on type of river, stream and catchment, resource functional value, intensity of adjacent land use, biotic pressure etc. Considerations also include the understanding of patterns and processes of the river & its banks/riparian areas within a fluvial system and quantification of the spatio-temporal pattern of the nearby area of the river. For example, upland streams with narrow valley width have smaller riparian zone but higher energy; while lowland streams have broader width with larger riparian zone but less energy and more prone to meandering. Realistically, there is no ideal riverscape width applicable to all circumstances and the necessary width varies considerably and depends on the specific geomorphic conditions of a particular river. River corridor widths are calculated to

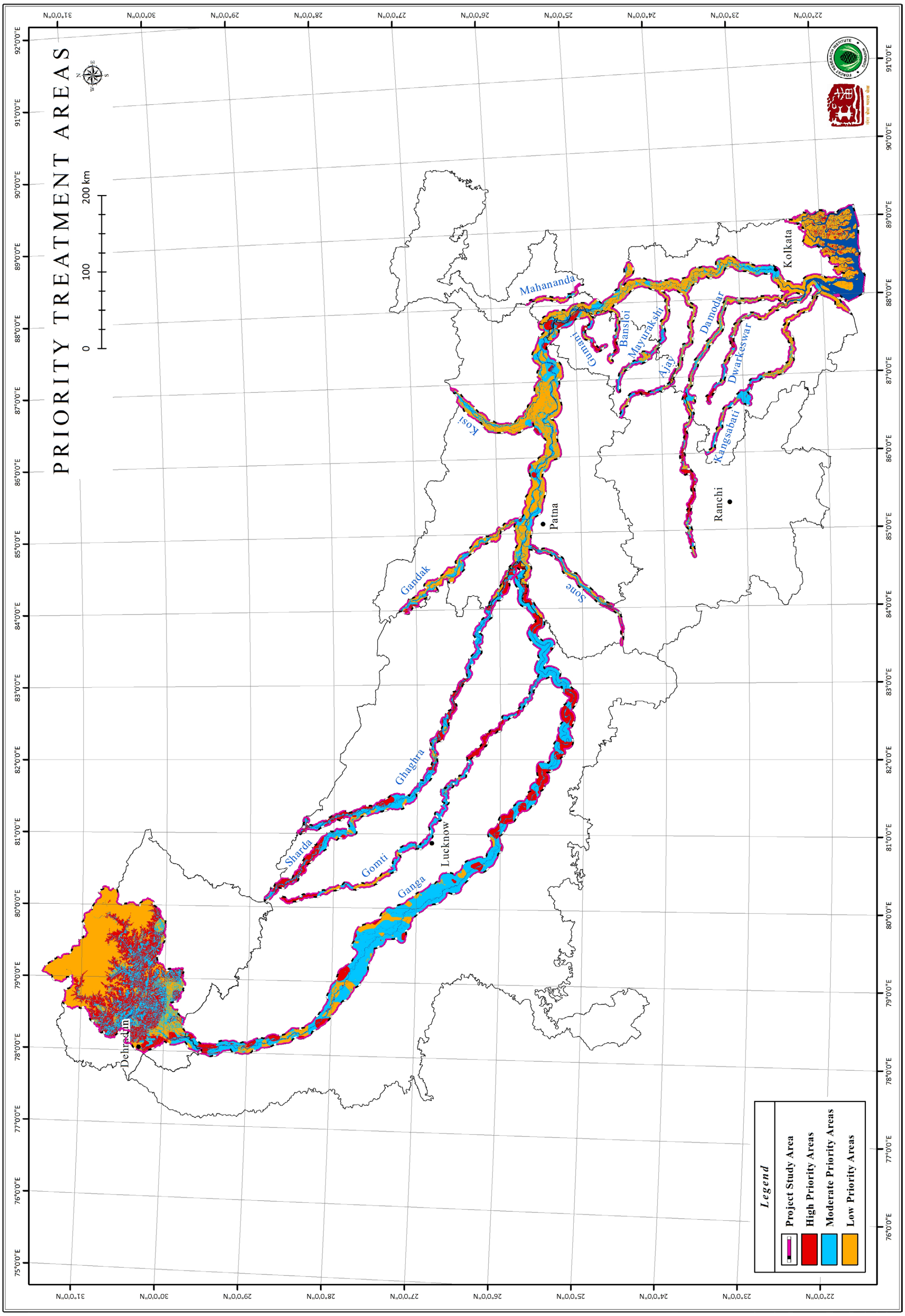

Figure 4. Priority treatment classes in Ganga riverscape.

represent the narrowest band of valley bottom and riparian land necessary to accommodate the least erosive channel and floodplain geometry (i.e., equilibrium conditions) that would be created and maintained naturally within a given valley setting. Though, the width of riverscape has varied from river to river and in deciding the width of riverscape in Indian River context, the Vermont Rivers Programme, which is responsible for protecting and restoring natural river and floodplain processes to enhance water quality, ecological health, and flood resilience of rivers in USA, has been used in deciding to have 5 km and 2 km width of riverscape for Ganga River and its tributaries, respectively.

According to this programme, a river corridor includes lands adjacent to and including the course of a river and the width of corridor is the lateral extent of the river meanders is known as meander belt width. The width is governed by valley forms, surficial geology and the length and slope requirements of the river channel (VT, 2004). This meander belt width would accommodate the meanders and maximize channel stability. Researchers have developed meander geometry formulas to relate channels dimensions with planform measurements. On the basis of data collected from 153 alluvial rivers around the world, Williams (1986) found that the relationship between channel width and the meander belt width is expressed by the formula B-3.7 W (Where B is the belt width and W is the channel width in feet for channels ranging from 5 to 13,000 ft wide) (**Figure 5**).

The formula resulted in a meander width ratio approximately equal to six (i.e., the belt width is equal to about 6 bank full channel widths). Corridors for gentle gradient rivers and streams (slope < 2%) in narrow to broad alluvial valleys are calculated and drawn to accommodate a meander belt width that is equal to 6 times the width of the river channel. Where rivers are assessed as being in equilibrium and the lateral extent of their meanders created a belt width that is at or near the "6 times channel width" relationship, then corridors are drawn as two roughly parallel lines following down the valley and capturing the extent of existing meanders. If the river slope and sinuosity have been modified, the corridor is drawn using 3 channel widths either side of a meander centre line or 6 channel widths out from the toe of the valley if the river is presently flowing less than 3 channel widths from the toe. Based on these studies, the followings are suggested for width of corridors for rivers and streams:

i) Steeper, confined to narrow valleys with less erodible boundaries where

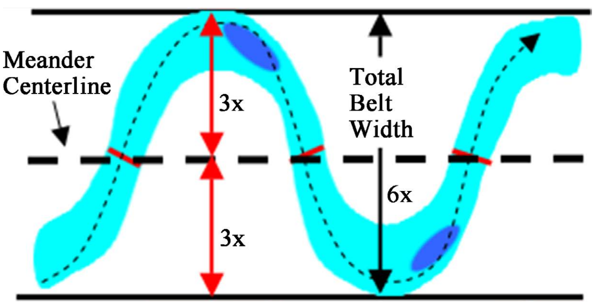

Figure 5. Idealized Representation of Riverscape/River Corridor (Source: Williams, 1986).

corridors of "1 to 4 times channel width" are recommended based on stream type and specific valley characteristics.

ii) Extremely sensitive stream types or landslide areas that may require corridors > 6 channel widths for adjusting river corridors by stream and valley type and accommodating human developments and infrastructure.

The determination of adequate) buffer sizes/width basically depend on i) resource functional value, ii) intensity of adjacent land use, iii) buffer characteristics, and iv) specific buffer functions required (Castelle et al., 1992). Realistically, there is no ideal riparian width applicable to all circumstances. The necessary width varies considerably based on the specific management goal (Mah et al., 2015). Moreover, implementing river corridor plans will require a long-term commitment to reducing fluvial erosion hazards and restoring the natural and recreational values of rivers.

In addition, the literature review identified three generic approaches to adjusting corridor/buffer width along river and streams. These included fixed-width, modified fixed-width and variable-width approaches. Each approach has several advantages and disadvantages. The modified fixed-width approach was initially used in the South African context but developed and matured as variable-width method due to integration of a range of variables in the Buffer-Zone Models to reflect the variability of both risks posed by developments and the inherent variability in climatic, buffer and water resource characteristics (Macfariane & Bredin, 2017; Lane, 1955). Based on these studies, fixed-width approach has been followed in river rejuvenation project on forestry inventions for Ganga River in India.

5. Forestry Activities in Riverscape Area

Reducing stormwater or agricultural runoff to streams and restoring riparian vegetation are essential implementation measures for recovering natural processes in many degraded streams. A study has shown that watershed-scale, out-of-channel management practices to restore urban streams can be quite successful: "measures of biodiversity in restored streams were 132% of those in unrestored urban streams, and indices of biotic condition, community structure, and nutrient cycling significantly improved" (Smucker & Detenbeck, 2014). Accordingly, in the riverscape area of Ganga River, forestry interventions are planned and carried out in three identified landscapes; 1) Natural (forests), 2) Agriculture (agroforestry), and 3) Urban, along with conservation activities in of each landscape in delineated riverscape area of Ganga River (**Figure 6**).

Conservation interventions include soil and moisture conservation (SMC), wetland management and riparian wildlife management all along the river. Species combinations of 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, forest type prevalent in the riverscape viz., oak forests (*Quercus leucotrichophora*, *Q. floribunda*, *Q. semicarpifolia*) and pine

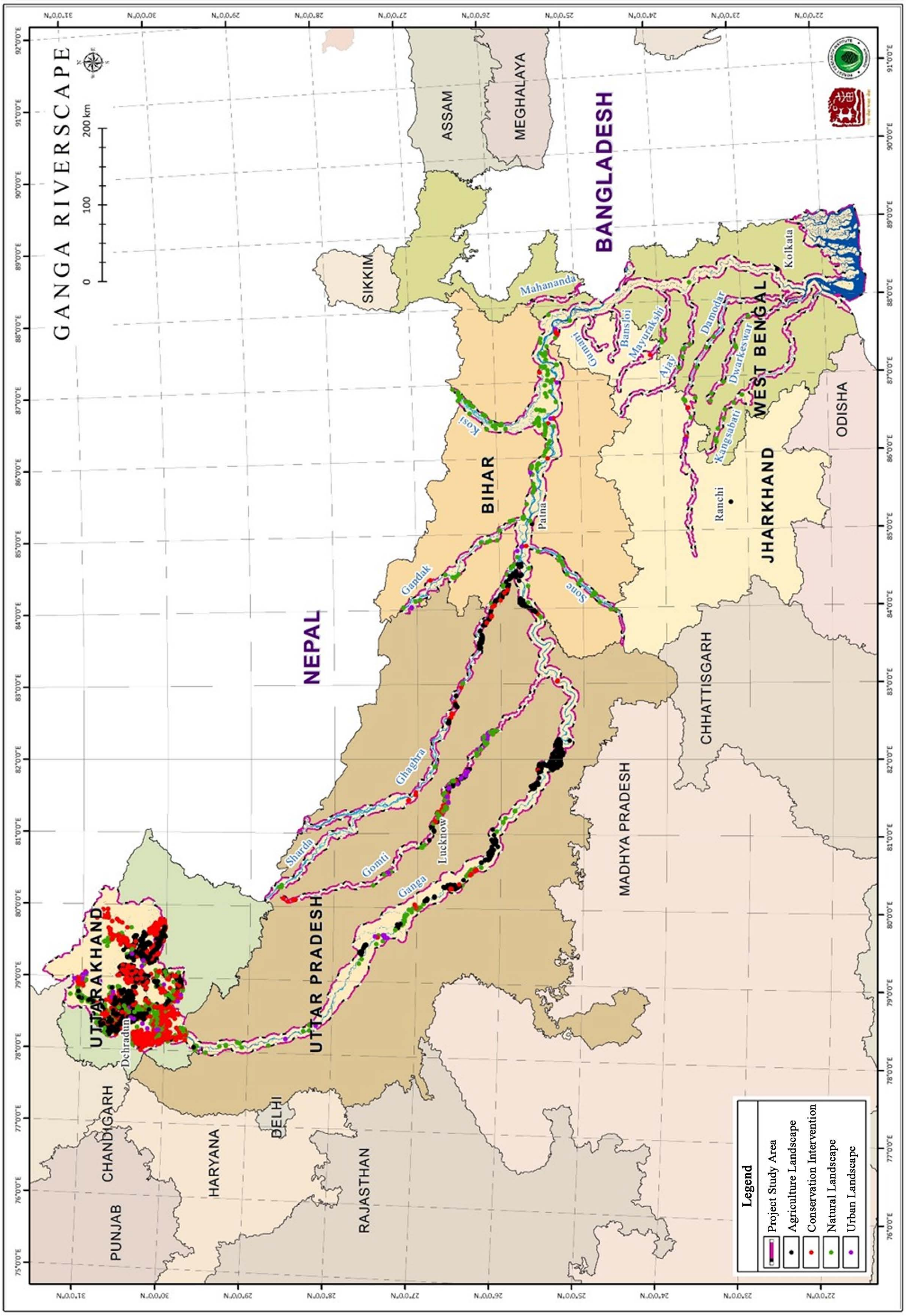

Figure 6. Forestry interventions in Ganga riverscape.

forests in Uttarakhand Himalaya, Sal forests in the Shivalik's and Ganga plains, and mangrove forests in the Sundarbans (Champion & Seth, 1968). There are as many as native species of trees, grasses, medicinal plants, fruit trees, etc. proposed and planted in riverscape area from alpine zone in Uttarakhand to mangrove ecosystem in West Bengal. Bioremediation and biofiltration interventions were also proposed in urban landscape in all five stakeholder states of the basin. Soil and moisture conservation (SMC) activities include 1) vegetative measures for erosion control on stream slopes viz., brush layer, brush mattress, brush trench, filter strips; 2) streambank strengthening measures viz., riprap, cribs & gabions; and 3) 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. The purpose of various plantations, especially in natural landscape is primarily protection, eco-restoration and conservation. The various plantations models and other treatment combinations from Himalayas to Sundarbans in five stakeholder states are given in Table 2.

Table 2. Treatment models for Ganga riverscape.

Natural Landscape	
State	**Treatment Model**
Uttarakhand	Alpine Meadows Conservation
	Sub-Alpine Conservation
	Temperate Conifer Forest
	Temperate Mixed Forest
	Temperate Broadleaved Forest
	Moist Temperate Broadleaved Forest
	Himalayan Chir Pine Forest
	Upper Sub-tropical Dry Deciduous Forest
	Lower Sub-tropical Dry Deciduous Forest
	Eradication of Invasive Species
	Plantation by Eco-task Force
Uttar Pradesh	Tree-Shrub-Medicinal Plant
	Grasses-Bamboo-Tree
	Grass-Shrub-Tree-Medicinal Plant
	Plantation by Eco-task Force
Bihar	Block Forest Plantation
	Bamboo Gabion Linear Mixed Species Plantation
	Iron Gabion Linear Mixed Species Plantation
	Linear Mixed Species Plantation Without Gabion

Continued

	Canal side Linear Mixed Species Plantation
	Riverside Linear Mixed Species Plantation
Jharkhand	Mixed Species Strip Plantation
West Bengal	Sal and Associate species
	Quick Growing Small Timber, Fuel and Fodder Plantation
	Restoration of Degraded Forests
	Multiple Shoot Cutting
	Riverbank Afforestation
	Mangrove Afforestation
	Eradication of Invasive Species and Restoration of Mangroves
	Agriculture landscape
Uttarakhand	Planting of Economic Trees in Hills
Uttar Pradesh, Bihar and Jharkhand	Planting of Economic Trees in Plains
West Bengal	Distribution of plants of fruit trees
	Urban Landscape
Uttarakhand and Uttar Pradesh	Bioremediation and Biofiltration
Uttarakhand, Uttar Pradesh, Bihar and West Bengal	Riverfront development
Uttarakhand, Uttar Pradesh, Bihar and West Bengal	Eco Park development
Uttarakhand, Uttar Pradesh, Jharkhand and West Bengal	Institutional and industrial estate plantation
Uttarakhand, Uttar Pradesh and West Bengal	Avenue plantation

Massive plantations of moisture loving species and bioengineering activities, as per treatment model suggested to different biogeographic zones and priority index of the riverscape area, have been done and are in vogue all along the Ganga River and its tributaries to restore the degraded landscape of river with the help concerned state forest departments. 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 producing clean water in rivers. The consequences of forestry interventions for Ganga River have been determined on the basis of water quantity and water quality in the Ganga River. A study in Ganga riverscape has shown to increase water recharge and decrease sedimentation load by 231.011 $MCM \cdot yr^{-1}$ and 1119.6 cubic $m \cdot yr^{-1}$ or 395.20 $tons \cdot yr^{-1}$, respectively, in delineated area of Ganga basin due to forestry plantations and soil and moisture conservation interventions (Singh et al., 2023). 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. The present riverscape methodology using forestry interventions to restore ecological integrity of Ganga River would definitely boost the National Mission of Clean Ganga (NMCG) and its *Namami Gange* programme of Ganga rejuvenation in the country.

6. Analytical Discussion

The ecological health of the Indian Rivers and tributaries has deteriorated significantly as a result of high pollution loads, high levels of water abstraction for irrigation, river modifications, etc. Climate change and an increase in extreme weather events are disturbing water cycles and threatening the stability of water flows (IPCC, 2019). Riverscape approaches are now becoming more essential to address explicit and more accurate concepts of stream ecology to explore new frontiers in river research and management with the assistance of advances in data collection and analysis. Riverscape approach has also been developed based on a perspective that conceptualized how streams and their biota are linked to landscapes longitudinally, laterally, vertically and temporally. Longitudinal changes from the river source to its mouth, vertical interactions (river bed/aquifer) and lateral exchange processes across the floodplains play a major role in alluvial river landscapes.

Forestry plantations and soil & water conservation measures in different landscapes proposed and executed in the delineated riverscapes of Indian rivers would definitely have long-lasting impacts in the direction of river rejuvenation programme of the country. Forests are used as nature-based solutions for water-related natural hazards. The hydro-geological conditions and groundwater regime in Indo-Ganga-Brahmaputra basin indicate the existence of large quantities of fresh groundwater at least down to 600 m or more below land surface. Bestowed with high rainfall and good recharge conditions, the groundwater gets replenished every year in these zones (Anon, 2009). However, in regions where groundwater use is greater than natural recharge rates, aquifers will be depleted over time and requires interventions. Rejuvenation of aquifers can play an important role in rejuvenation of rivers in the country; hence, the proposed artificial recharge/augmentation of natural movement of surface water into groundwater reservoir through suitable civil structures at specified points in delineated riverscape will increase the capacity of aquifers in the river basins in India.

7. Conclusion

The riverscape in this study 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. As forests and water have strong linkages, the forestry interventions in Ganga riverscape would certainly increase water recharge and decrease the sedimentation load in the river and tributaries. The main concluding remarks of the study are as follows:

- The riverscape approach integrates rivers with their surrounding landscape and explains the broad-scale physical, biological and aesthetic nature of rivers and aims to describe spatio-temporal patterns and processes linking a river and its bank, or its riparian areas, within a fluvial system which ultimately provide an insight into the complex interactions between disturbance regimes, spatial heterogeneity, and biodiversity.
- The conceptual riverscape model has been developed and proposed to rejuvenate this holy Ganga River in India through forestry interventions after considering ecological processes, mosaic of landforms, communities and environment within the large landscape of Ganga basin.
- The select riverscape area includes the area of 5 km and 2 km on either side of the river Ganga and selected tributaries, respectively, in five stakeholder states of Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal in the country. The width of the riverscape was taken from the maximum bank line on either side of river in recent years in the concerned state. However, being the origin place of river, all micro-watersheds in the hills of Uttarakhand state have been included in riverscape area up to Haridwar.
- Geospatial modelling and GIS data on land use pattern, soil erosion rates, slope of the topography, etc. were used to classify riverscape area into 1) high, 2) medium and 3) low priority areas to implement forestry interventions in delineated riverscape area. Thereafter these interventions were planned and carried out in three identified landscapes; 1) Natural (forests), 2) Agriculture (agroforestry), and 3) Urban, along with conservation activities in each of the landscape.
- The results of this study would have long-lasting impacts in the direction of river rejuvenation programme of the country.

8. Way Forward

The Government of India has committed itself to an ambitious goal of rejuvenating the all-major Rivers in the country. However, no “silver bullet” intervention solves the problem and all the stakeholders must realize that water availability will be insufficient to meet the rising demands. As such there are no “easy” technical solutions; therefore, a combination of different interventions is required to be adopted. A riverscape approach along with forestry interventions, as applied in the case of Ganga River, could be applicable in other river rejuvenation programmes of major rivers in India in the future and society will get innovative avenues to understand, conserve and restore riverine ecosystems in the country.

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Conflicts of Interest

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

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