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https://jisem-journal.com/ **Research Article**

Engineering Management of River Dredging for Flood Protection: An AI-Assisted Socio-Hydrodynamic Study of the Ghaghara-Saryu Basin, Uttar Pradesh, India

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ABSTRACT

Riverbank erosion remains a persistent and serious threat to rural communities and agricultural land in the Gangetic plains of India, where highly active alluvial rivers cause continuous lateral migration and bank failure during monsoon seasons. This study evaluates the effectiveness of sectoral dredging as a soft-engineering river training approach through two field interventions in Uttar Pradesh: the Ghaghara River at Village Sirauli Gung, District Barabanki, and the Saryu River at Village Bahadurpur, District Gonda. Pilot channels, referred to as cunettes, measuring 3.8 km and 3.9 km in length and 45 metres in width, were excavated to redirect the river's main current away from vulnerable concave banks. A hybrid bank stabilisation system combining Geotubes and Balli piling was deployed to induce siltation in abandoned reaches and reinforce the bank toe. Data acquisition integrated LiDAR surveys, high-resolution UAV photogrammetry, bathymetric mapping, and 2D hydrodynamic modelling using HEC-RAS to validate hydraulic performance and sediment transport behaviour. Discharge calculations based on Lacey's Regime Theory confirmed that the standard 45-metre cunette can convey approximately 472.63 m^3/s, while the widened 100-metre channel section achieved a capacity of approximately 1,458 m^3/s. Post-intervention numerical simulations and field observations confirmed a significant reduction in near-bank flow velocity to 0.8–1.2 m/s and boundary shear stress to below 15 N/m^2. Economic evaluation yielded Benefit-Cost Ratios of 1.41:1 for the Ghaghara reach and 1.35:1 for the Saryu reach. In total, 13.46 lakh cubic metres of dredged material were reused in situ for embankment reinforcement and land reclamation, consistent with the National Framework for Sediment Management-2022. The interventions secured the livelihoods of approximately 22,000 residents, protected 8,000 hectares of fertile agricultural land, and generated 15,288 temporary employment days for local communities. These findings present sectoral dredging as a scalable, cost-effective, and ecologically responsible model for flood risk reduction in dynamic braided river systems.

Keywords: River Training, Sectoral Dredging, Bank Erosion, Sediment Management, Geotubes, Ghaghara River, Saryu River, Flood Control

1. INTRODUCTION

Floods are one of the most damaging natural disasters in the world, and India is among the countries most affected by them. A large number of people living in low-lying and riverside areas face the risk of losing their homes, farmland, and livelihoods every year due to flooding. Studies show that a significant portion of the global flood-exposed population lives in poverty, which makes the damage even harder to recover from (Rentschler et al., 2022). In India, the situation is made worse by the intensity of the summer monsoon season, which brings heavy and sometimes extreme rainfall over a short period of time. Research has shown that flood-causing rainfall events are becoming more frequent and severe due to climate change, which is increasing the overall flood risk across Indian river basins (Vegad et al., 2024).

Within India, the state of Uttar Pradesh faces some of the most serious flood challenges. The rivers that flow through the Gangetic plains in this region carry very high amounts of sediment and experience large changes in water levels between seasons. These conditions make the rivers move constantly, shifting their banks and eroding farmland and settlements nearby. The Ghaghara and Saryu rivers are particularly active in this way. Both rivers are alluvial in nature, meaning their beds and banks are made of loose material that is easily moved by fast-flowing water. This makes them very difficult to manage and causes serious problems for the communities living along their banks (Arya & Singh, 2021). The Ghaghara River in particular has been studied for its strong flood and erosion behaviour in Uttar Pradesh, where it regularly threatens villages and agricultural land (Singh, 2024). Flash floods and rapid bank erosion in sub-continental river basins like these are driven by a combination of steep gradients, large sediment loads, and intense monsoon discharge (Garg, 2017; Khurana et al., 2024).

Traditionally, the response to these problems has been to build hard structures like concrete spurs, revetments, and embankments. While these methods can provide some short-term protection, they often push the hydraulic pressure further downstream, disturb the natural behaviour of the river, and require very high costs to maintain. Over time, researchers and engineers have recognised that these rigid approaches are not always the best solution for dynamic alluvial rivers. A growing body of work now supports the use of soft-engineering methods, including sectoral dredging, which works with the river rather than against it (Pakhale et al., 2023). The socioeconomic and environmental factors that drive flood vulnerability in India also suggest that communities need solutions that are cost-effective and sustainable in the long run (Garg, 2017; Sharma et al., 2025).

This study examines two dredging interventions carried out by the Irrigation and Water Resources Department, Government of Uttar Pradesh, at Village Sirauli Gung in District Barabanki on the Ghaghara River, and at Village Bahadurpur in District Gonda on the Saryu River. These two sites were identified as high-risk zones where approximately 22,000 residents, 2,960 houses, and 8,000 hectares of agricultural land were directly threatened by riverbank erosion and flooding. The core objective of this study is to evaluate the effectiveness of sectoral dredging through pilot channels, called cunettes, in reducing hydraulic pressure on vulnerable banks. The methodology used in this study brings together LiDAR surveys, UAV-based mapping, bathymetric data, and 2D hydrodynamic modelling using HEC-RAS to validate the performance of the dredging design and the deployment of Geotubes and Balli piling for bank stabilisation. Projected increases in widespread riverine flooding across India under a warming climate make it even more necessary to develop and test scalable and evidence-based river management solutions (Nanditha & Mishra, 2024). The growing need for ensemble and model-based flood management tools in India further supports this kind of integrated study (Kushwaha et al., 2024). This paper presents the technical outcomes, economic analysis, and socio-hydrological impacts of the interventions, and aims to offer a replicable template for flood risk reduction in similar alluvial river systems.

2. LITERATURE REVIEW

A large amount of research has been done on flood risk, river behaviour, and flood modelling across India and other parts of the world. This section brings together the most relevant studies to place the present research in its broader academic context and to show where gaps remain that this study aims to address.

2.1 Flood Hazard and Risk in Indian River Basins

India has a long history of dealing with floods, and the Gangetic plains and Himalayan forebelt river systems are among the most flood-prone regions in the country. Research carried out on flood frequency and intensity in the Kosi sub-basin showed that embankment construction changed the nature of flooding over time and that marginalized communities were disproportionately affected depending on their location, caste, and class (Sahani et al., 2023). Studies from the Rarh Plains of India also showed that riverine flood risk is shaped by both physical and social factors, and that community-level assessments are important for understanding who is most at risk (Islam & Ghosh, 2022). Flood risk mapping in the Gangetic interfluvial floodplain region highlighted the complexity of identifying vulnerable zones in flat, low-lying terrain where water spreads over large areas (Das, 2022). Research from Himalayan foothill regions confirmed that geospatial data combined with multi-criteria decision tools can effectively identify flood-prone areas and help in planning protective measures (Roy et al., 2021). A more recent study that used multi-criteria decision analysis and GIS tools across India found that large parts of the country remain inadequately mapped for flood exposure (Ahmed et al., 2024). Work on the Brahmaputra Valley identified critical flood-prone districts and suggested that shelter zones need to be planned more carefully in high-risk regions (Ghosh & Dey, 2021). Flood management strategies in tropical river basins in India have also been reviewed, showing that existing strategies lack integration between structural and community-based approaches (Ghosh et al., 2023). Studies focusing on the Ganga and Brahmaputra basins found that flood protection structures sometimes increase socio-vulnerability rather than reducing it, particularly for communities living near embankments (Kaur et al., 2024). Research linking extreme monsoon rainfall with flood generation in northeast India and Bangladesh further confirmed that the scale and speed of flood events is growing (Fahad et al., 2024).

2.2 Monsoon, Climate Variability, and Extreme Flood Events

The Indian Summer Monsoon is the primary driver of river flooding across the subcontinent, and its behaviour is changing in ways that make flood events harder to predict and manage. A review of Indian Summer Monsoon Rainfall trends showed that both the spatial distribution and intensity of rainfall are shifting under the influence of a changing climate, which directly affects how rivers respond during the monsoon season (Sahastrabuddhe et al., 2023). Research on ensemble flood forecasting in India pointed out that the current forecasting systems are not sufficient to handle the level of uncertainty in flood predictions, and that better tools are urgently needed (Nanditha & Mishra, 2022). A study on the Pakistan floods of August 2022 showed how extreme monsoon events can cause catastrophic damage when rivers exceed their banks by large margins, offering lessons that are directly relevant to Indian rivers with similar characteristics (Nanditha et al., 2023). Further research on extreme precipitation events in the Brahmaputra basin found a strong link between atmospheric moisture transport and the occurrence of very heavy rainfall episodes during the monsoon period (Sahastrabuddhe et al., 2024). Work on monsoon-induced disasters in Himachal Pradesh confirmed that geospatial and statistical tools can be used to track the growing frequency and impact of such events over time (Tripathi et al., 2022). Together, these studies make it clear that the flood problem in the Ghaghara-Saryu system is not isolated but is part of a broader pattern of increasing flood risk driven by monsoon variability and climate change (Fahad et al., 2024).

2.3 River Morphodynamics, Sediment, and Channel Behaviour

The behaviour of alluvial rivers is closely connected to how sediment moves through the channel and how the channel shape changes over time. Research on the Lower Ganga River used a hydro-geomorphological approach to understand how the channel has been shifting and how sediment budgets have changed, which is directly relevant to understanding similar processes in the Ghaghara and Saryu rivers (Sinha et al., 2022). A study on morphometric diversity in Himalayan foreland rivers showed that some rivers are limited by how much sediment is supplied, while others are limited by how much sediment they can carry, and that this difference has important effects on channel stability and flood behaviour (Swarnkar et al., 2020). Longer-term research on sediment transport across the Indo-Gangetic Plain found that tectonics, climate, and vegetation all play a role in controlling how much sediment moves through these large river systems over decades to millennia (Tandon et al., 2022). A more recent study used satellite-based radar data to measure sediment aggradation rates in Himalayan rivers, finding that some reaches are filling up with sediment at rates that significantly reduce their flood-carrying capacity (Sinclair et al., 2023). Research on eco-friendly dredging methods showed that changing fluvial landforms through dredging can simprove hydraulic habitat quality and restore channel continuity, which supports the use of dredging as a river management tool (Yang et al., 2024). A study on the River Lærdal in Norway raised important questions about whether traditional flood measures conflict with maintaining healthy river ecosystems, which is a concern that soft-engineering approaches like sectoral dredging are designed to address (Bø et al., 2021).

2.4 Hydrodynamic Modelling for Flood Assessment and River Management

Hydrodynamic modelling has become a standard tool for flood assessment and river management across India and globally. HEC-RAS has been widely used in Indian river basins for flood inundation mapping, and a case study on the Krishna River Basin showed that 2D modelling using HEC-RAS can accurately reproduce flood extents and water surface profiles across complex terrain (Vashist & Singh, 2023). The latest version of HEC-RAS was tested in a coastal urban floodplain in India and found to be highly effective for 2D hydrodynamic modelling when combined with a GIS framework (Shaikh et al., 2023). A 2D hydrodynamic model developed for the lower Narmada basin demonstrated that such models can support flood risk assessment at the basin scale and help identify areas needing urgent intervention (Mangukiya & Sharma, 2024). Real-time flood forecasting using integrated hydrologic and hydraulic models was tested in the Vamsadhara and Nagavali basins in eastern India, showing that coupled models can significantly improve forecast accuracy during extreme events (Jayaraman et al., 2024). HEC-RAS was also applied to the Indus River basin for flood inundation modelling by integrating satellite imagery, which improved the spatial accuracy of flood predictions (Afzal et al., 2022). Research on flood hazard assessment under changing flood regimes used severity-frequency analysis to show how hydrodynamic models can be adapted to future conditions (Jena et al., 2024). The impact of riverine dredging on flooding in low-gradient coastal rivers was assessed using a hybrid 1D/2D model, confirming that dredging can reduce flood levels and improve channel conveyance (Saad & Habib, 2021). Comprehensive flood risk assessment using AHP and HEC-RAS 2D in the lower Teesta River Basin provided a strong example of how these tools can be combined for practical planning (Patri et al., 2022). A recent review of HEC-RAS modelling across Indian rivers confirmed that the tool is widely applicable and continues to be refined for better performance in complex alluvial environments (Singh et al., 2025). A systematic review of flood analysis techniques across river basins in India found that no single method is sufficient on its own and that integrated approaches give the best results (Raghunathan et al., 2023). Machine learning models have also been applied for flood susceptibility mapping in the Middle Ganga Plain, showing that data-driven tools can complement physically-based models (Arora et al., 2021). Research using decision tree-based ensemble learning for flood susceptibility mapping further confirmed that combining different modelling approaches improves overall prediction accuracy (Pham et al., 2021).

2.5 Socio-Economic Vulnerability and Livelihood Impacts of Flooding

Flooding does not only cause physical damage — it also deeply affects the livelihoods and economic stability of rural communities, particularly those who depend on agriculture and land for their survival. Research on recurrent tropical flood hazards in India showed that rural communities face compounding vulnerabilities when floods occur repeatedly, and that livelihood recovery becomes more difficult with each event (Islam & Ghosh, 2024). A study on the Mayurakshi River Basin examined how both in-situ and ex-situ livelihood strategies can help reduce flood risk for communities, finding that access to diverse income sources is one of the most important protective factors (Islam et al., 2022). Research on flood recession farming in the Ganga River Basin showed that floodplain agriculture, while risky, also provides important livelihood benefits and food security to many rural households, which means that simply removing communities from floodplains is not always a practical or desirable solution (Biswas et al., 2022). A broader review of flood management strategies in a tropical river basin in India found that better community resilience requires integrating structural flood control with social support systems and early warning tools (Ghosh et al., 2023). These studies collectively highlight that any engineering intervention for flood control, including the sectoral dredging approach examined in this paper, must be evaluated not just for its hydraulic performance but also for its ability to protect the social and economic wellbeing of the communities it serves.

3. STUDY AREA AND SITE DESCRIPTION

The Ghaghara River is one of the largest tributaries of the Ganga River system and flows through the northern part of Uttar Pradesh before joining the Ganga near Chhapra in Bihar. It originates from the Tibetan Plateau and passes through Nepal before entering the Indo-Gangetic plains, where its character changes significantly. In the plains, the river becomes wide, shallow, and highly unstable, carrying enormous amounts of sediment that it deposits and reworks continuously. The Saryu River, also known as the Ghaghra in its upper reaches, is a distributary channel of the same system that flows through the central and eastern parts of Uttar Pradesh. Both rivers are classified as highly active alluvial rivers that are known for frequent lateral migration, bank erosion, and seasonal flooding driven by monsoon discharge. The two study sites selected for this research are Village Sirauli Gung in District Barabanki, located along the Ghaghara River, and Village Bahadurpur in District Gonda, located along the Saryu River. Both sites lie in the middle Gangetic plains at elevations that make them highly vulnerable to inundation during peak monsoon flows. The terrain surrounding these villages is flat and low-lying, with very little natural topographic protection against rising water levels. The rivers at these locations display a braided to semi-meandering planform, with multiple active channels, shifting sandbars, and unstable concave banks that are subject to intense erosion during high-discharge events. These two sites were selected because field assessments and satellite monitoring identified them as critical erosion zones where active bank undercutting was advancing rapidly toward settled areas. Together, the sites placed approximately 22,000 residents, 2,960 houses, and 8,000 hectares of fertile agricultural land under immediate threat of submergence and permanent land loss. The combination of high sediment load, seasonal discharge variation ranging from very low dry-season flows to extreme monsoon peaks, and the loose alluvial composition of the riverbanks made these locations particularly difficult to protect using conventional hard-armoring structures. This context provided a strong case for testing sectoral dredging as an alternative river training approach under real field conditions.

4. RIVER BEHAVIOUR AND HYDRAULIC REGIME

The behaviour of alluvial rivers is governed by the complex interaction between flow hydraulics, sediment transport, channel geometry, and boundary resistance. Sediment-laden flows play a decisive role in shaping river planform and cross-sectional characteristics, giving rise to processes such as scouring, deposition, meandering, braiding, and channel migration. These processes directly affect flood conveyance capacity, channel stability, and the performance of hydraulic structures (Garg, 2017).

In straight reaches, velocity distribution is non-uniform, with maximum velocities concentrated near the channel centre and reduced velocities towards the banks. This transverse velocity gradient induces secondary circulation, contributing to bed and bank adjustments. However, straight reaches are inherently unstable in alluvial rivers, and even minor disturbances promote the development of bends. Within bends, centrifugal forces generate higher velocities along the concave (outer) bank, resulting in localized scour, while sediment deposition occurs along the convex (inner) bank, forming point bars. The persistence of these processes leads to the progressive formation of meanders. Meandering is now widely attributed to excess sediment load during flood events, which induces aggradation and destabilizes uniform flow conditions. Continuous erosion at the concave bank and deposition at the convex bank cause downstream migration and amplification of meander loops. In highly sinuous reaches, natural cut-offs may develop, shortening the river course and restoring hydraulic efficiency.

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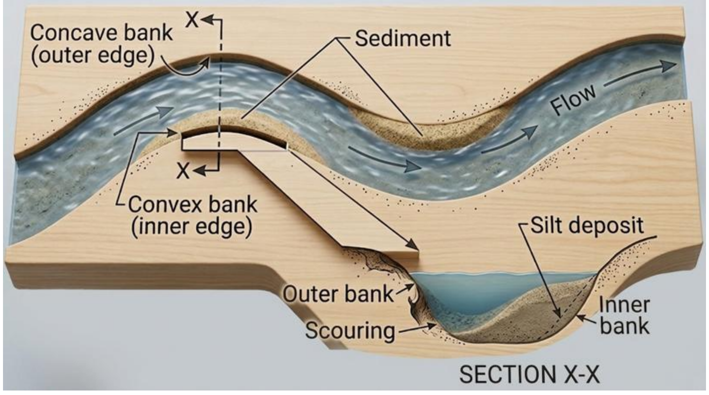
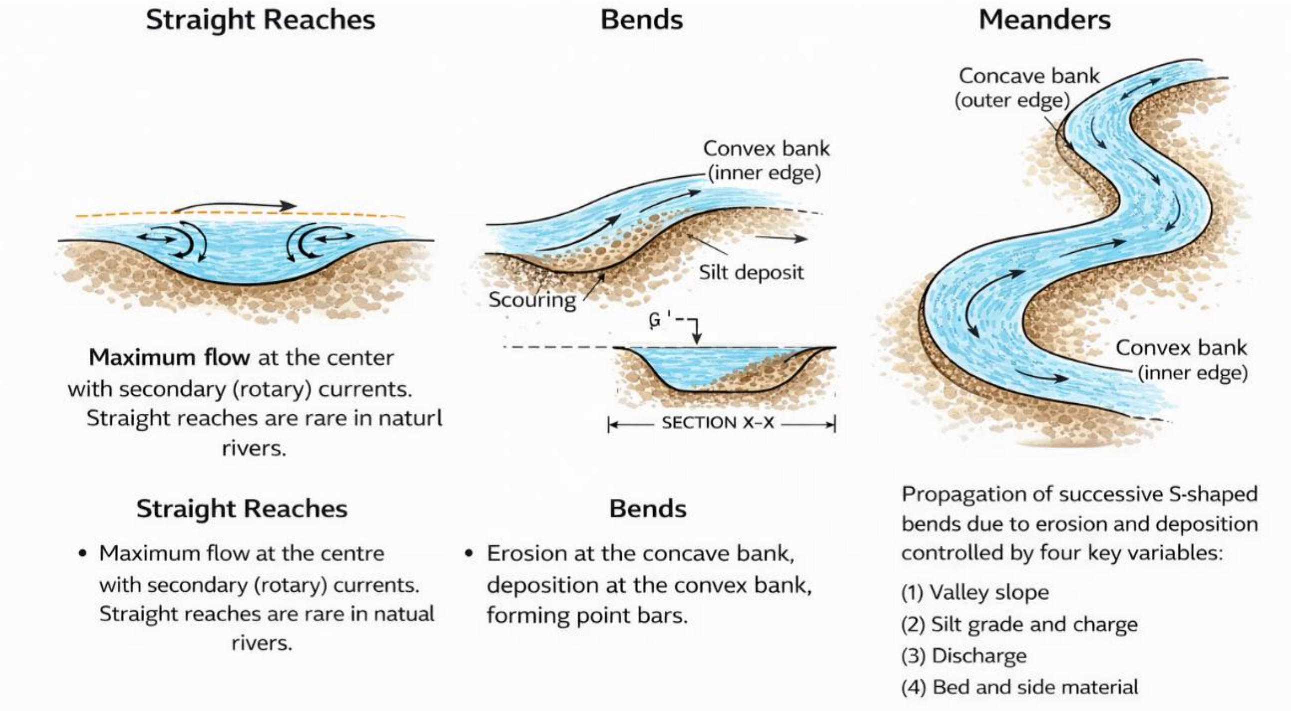


Figure 1. *Illustration of Meandering River Behaviour in an Alluvial Flood Plain*



Maximum flow at the center with secondary (rotary) currents. Straight reaches are rare in naturl rivers.

Straight Reaches

- Maximum flow at the centre with secondary (rotary) currents. Straight reaches are rare in natual rivers.

Bends

- Erosion at the concave bank, deposition at the convex bank, forming point bars.

Propagation of successive S-shaped bends due to erosion and deposition controlled by four key variables:

(1) Valley slope
(2) Silt grade and charge
(3) Discharge
(4) Bed and side material

Figure 2. *Behaviour Of River Summary with Diagrams*

5. ARTIFICIAL CUT-OFF CHANNEL: PRINCIPLES AND DESIGN

Artificial cut-offs are engineered channels constructed across meandering sections of rivers to create a shorter, straighter path for flow, mimicking the process of natural cut-offs but under controlled conditions. The primary objectives of such interventions include flood mitigation, river training, navigation improvement, sediment management, and reclamation of land from abandoned bends. Typically, the site is selected at a pronounced meander neck, where a straight channel is excavated to connect the upstream and downstream ends of the bend. Hydraulically, the new channel is designed to align tangentially with the main flow and accommodate the design discharge, while bank stabilization measures such as stone pitching, gabions, or vegetation are employed to prevent erosion. Once the river is diverted through the artificial channel, the abandoned meander may silt up, often forming an oxbow lake. While artificial cut-offs provide substantial benefits, including reduced river length, improved flood conveyance, and enhanced navigation, they may also induce temporary instability, bank erosion, and socio-economic disruptions along the abandoned bend. Careful planning, hydraulic design, and environmental considerations are therefore essential to ensure the long-term sustainability and efficiency of artificial cut-off projects.

Cut-off Ratio

The cut-off ratio is a quantitative measure used to describe the severity of a river bend before it is abandoned in favor of a shorter channel. It is defined as the ratio of the length of the river bend (ACB) to the chord length connecting the bend ends (AB), providing a clear indicator of bend elongation and the potential for cut-off formation. For natural cut-offs, this ratio typically ranges from 1.7 to 3.0, although in specific local conditions, such as soft bed materials or very high discharge events, it may reach values as high as 8.0 to 10.0. Hydraulic efficiency of cut-offs is maximized when the side channel is tangential to the main flow, and when the ratio of the bend's radius of curvature to the square root of the maximum discharge ($r/\sqrt{Q_{\max}}$) falls between 13 and 24. Understanding and applying the cut-off ratio is essential in river engineering, as it helps predict natural cut-off formation and guides the design of artificial channels for flood control, navigation, and river training (Garg, 2017).

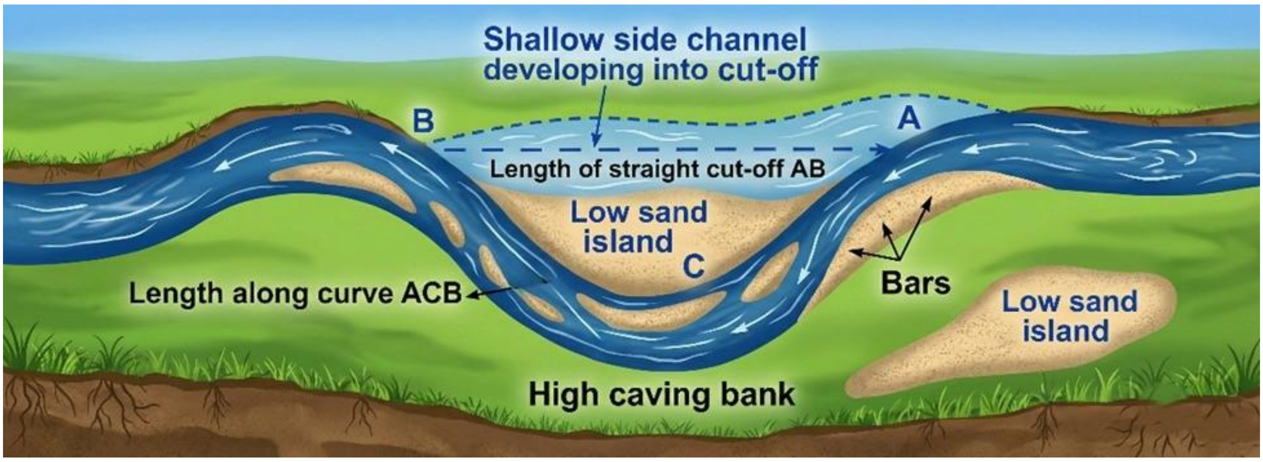


Figure 3. *Artificial cut off Representation*

6. RIVER TRAINING USING GEOTUBE STRUCTURES

Geotubes, when used as river-training structures, perform functions analogous to conventional groynes by modifying near-bank flow patterns, inducing sediment deposition, and controlling erosion. The hydraulic response of the river to a geotube depends primarily on its alignment with respect to the bank line and flow direction, which governs the formation of eddies, scour holes, and low-velocity zones.In the present study, geotubes of 20 m length and 3.0 m diameter, fabricated using high-strength woven geotextile of minimum 350 GSM and 80 KN bi-axial minimum strength, are considered. These dimensions ensure adequate structural stability, resistance to puncture, and long-term hydraulic performance under flood flows.

Figure 4. *Hybrid implementation of Geotubes and wooden Balli piling at the Bahadurpur gonda and Sirauli Goong Barabanki*

6.1 Types of Geotube Alignment

Based on alignment, geotubes may be classified into normal (perpendicular), repelling (upstream-inclined), and attracting (downstream-inclined) geotubes, as illustrated by classical flow behaviour patterns reported for groynes and adapted here for flexible geosynthetic structures.

6.1.1 Normal (Perpendicular) Geotube

A normal geotube is aligned perpendicular to the bank line. In this configuration, the approaching flow impinges directly on the structure, resulting in the formation of vertical eddies near the nose. These eddies gradually lose intensity from the head towards the bank, leading to reduced shear stress along the protected bank. Scour development near the head is relatively moderate compared to inclined configurations, and sediment deposition occurs in the sheltered zone downstream and behind the geotube. Normal geotubes are therefore well suited for convex banks, where flow attack is less severe and bank stabilization is the primary objective.

6.1.2 Repelling (Upstream-Inclined) Geotube

A repelling geotube is aligned inclined upstream, generally at an angle of 10°–30° to the normal of the bank, consistent with hydraulic practice. This alignment causes the flow to be deflected away from the bank, thereby reducing erosive forces acting on the bank face. Hydraulically, the upstream inclination generates a still-water pocket on the upstream side of the geotube, where suspended sediment settles and contributes to progressive bank accretion. At the head of the geotube, however, strong vertical and spiral eddies are formed, producing a localized scour hole away from the bank, rather than adjacent to it. This characteristic makes repelling geotubes particularly effective for protecting concave banks, which are prone to severe erosion in meandering rivers. Due to intense flow disturbance at the nose, additional toe and head protection measures may be required to prevent excessive local scour.

6.1.3 Attracting (Downstream-Inclined) Geotube

An attracting geotube is oriented inclined downstream, typically forming an angle of 60°–80° with the bank line. This alignment draws the main current towards the bank, increasing near-bank velocity and shear stress. As a result, scour holes develop close to the bank and near the head of the geotube, making the protected bank more susceptible to erosion and structural instability. Although attracting geotubes may be employed in specific channel-training situations, they are generally avoided for bank protection works, particularly in alluvial rivers with erodible banks.

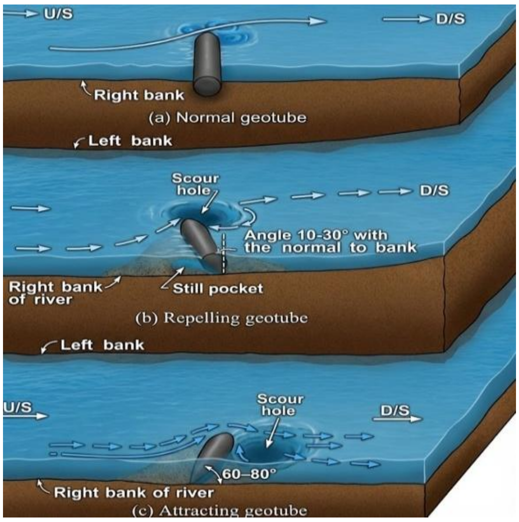


Figure 5. *Representation of Geotube Laying Method*

6.2 Engineering Implications

Based on hydraulic behaviour and field experience, geotubes are preferably aligned either perpendicular to the bank or inclined upstream. Normal alignments are typically adopted on convex banks, while upstream-inclined (repelling) alignments are recommended for concave banks subjected to high flow attack. When installed in series, geotubes promote the formation of extended low-velocity zones, facilitating sustained sediment deposition and long-term bank stabilization. In river training and bank protection works, the spacing of Geotube structures is a critical design consideration. Since each Geotube is designed to protect a specific reach of the shoreline, the primary factor determining the distance between two adjacent units is their physical length. Generally, the spacing is established as a direct proportion of this length. However, the specific geometry of the riverbank also dictates the installation density:

- **Convex Banks:** On these outer curves, where the flow energy is typically more dispersed, a larger spacing is permissible. A common engineering standard for Geotubes in these areas is 2 to 2.5 times the length of the unit.
- **Concave Banks:** These areas are subject to higher erosive forces and direct flow impingement. Consequently, a tighter configuration is required to maintain a continuous protective barrier, with spacing usually equal to the length of the Geotube.
- **River Crossings**: For transitional zones or crossings, intermediate spacing values are adopted to balance hydraulic efficiency.

7. METHODOLOGY

The methodology employed in this study followed an integrated framework of computational hydraulic modelling and field-based morphological engineering. The process moved from high-resolution data acquisition to numerical simulation, followed by technical execution. The methodology adopted for this study follows a multi-phased approach, integrating advanced geospatial data acquisition, hydrodynamic modelling, and specialized execution protocols for river training and bank protection.

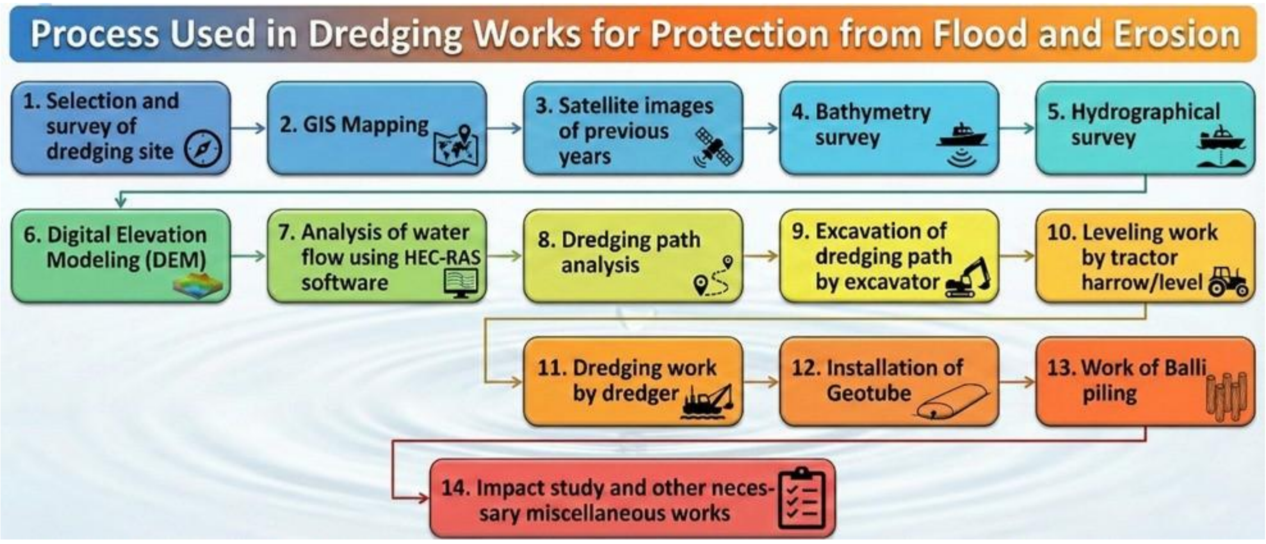


Figure 6. *Process Used in Dredging Work*

7.1 Geospatial Data Acquisition and Digital Modeling

The foundation of the project relies on high-resolution topographic and hydrographic data:

- **Comprehensive Site Survey:** Initial physical reconnaissance and Differential Global Positioning System (DGPS) surveys were conducted to establish precise benchmarks and ground control points.
- **Aerial and Sub-aquatic Mapping: Unmanned Aerial Vehicle (UAV/Drone):** surveys provided high-resolution orthomosaics of the floodplain, while Bathymetric surveys were performed to map the submerged riverbed morphology.
- **LiDAR Survey (Light Detection and Ranging):** LiDAR uses rapid laser pulses to create highly accurate 3D point clouds of the terrain. Its primary advantage is the ability to penetrate dense vegetation, mapping the "bare earth" where cameras cannot see. It functions as an active sensor, meaning it works perfectly in low-light or night conditions. This technology significantly reduces field time compared to traditional ground surveys while increasing data density. It is essential for topographic mapping, flood modeling,
- **Bathymetric Survey:** Acoustic sounding was used to map the riverbed, which was then integrated into the DEM to create a continuous terrain model for hydraulic simulation**.**
- **DEM Generation:** The raw spatial data was processed to generate a high-fidelity Digital Elevation Model (DEM). This model provided the vertical and horizontal accuracy necessary to identify the "excessive erosion" zones and calculate the precise volume of sediment to be excavated for the 3.8 km and 3.9 km cunettes /channel. The integrated survey data was processed to develop a Digital Elevation Model (DEM), providing the necessary terrain input for computational analysis.

7.2 Hydrodynamic Simulation using HEC-RAS

The validation process using HEC-RAS extended beyond channel design to include a comprehensive assessment of flood risk and bank stabilization. By performing sensitivity analyses with variable discharge rates, the model identified the precise geographical limits of water inundation. This allowed for a predictive understanding of which areas remain at risk during extreme flow events, ensuring that the intervention is robust enough to handle fluctuating monsoon volumes. A critical component of this numerical study was the strategic spatial planning of dredged material. HEC-RAS simulations were utilized to pinpoint high-scour zones and depressions where the excavated sediment could be most effectively repurposed. By integrating this "cut-and-fill" approach into the model, we validated that filling specific bank sections would not only prevent erosion but also act as a physical barrier against flooding. The resulting 2D hybrid model confirms that by diverting the thalweg through the 45-meter-wide cunette and simultaneously reinforcing the banks with dredged material, hydraulic pressure is significantly neutralized, securing the long-term stability of the Sirauli Gung and Bahadurpur riverfronts.

- **Discharge Sensitivity & Inundation Mapping:** The software was used to simulate variable discharge scenarios to determine water reach and flood extents across the floodplain.
- **Strategic Sediment Management:** Analysis identified critical zones where dredged material should be deposited to backfill scour holes and strengthen the riverbank.
- **Erosion & Flood Mitigation:** By modeling the interaction between the new channel and the reinforced banks, the design ensures a dual benefit, diverting high-velocity flow and physically buffering vulnerable areas.
- **Simulation Parameters**: Evaluated Shear Stress, Velocity Distribution, and Water Surface Elevation (WSE) to validate that the sediment-filled zones remain stable under peak hydraulic loading.
- **Protection Focus:** Specifically targets the protection of Sirauli Gung and Bahadurpur by optimizing the balance between excavation (dredging) and reclamation (filling).

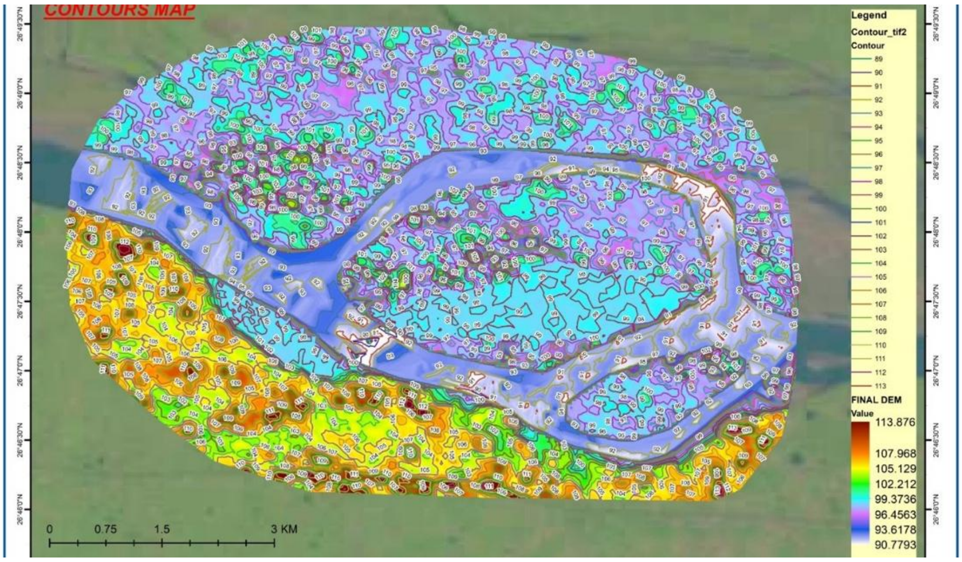


Figure 7. *Bahadurpur Gonda Dredging Site 2D flood simulation*

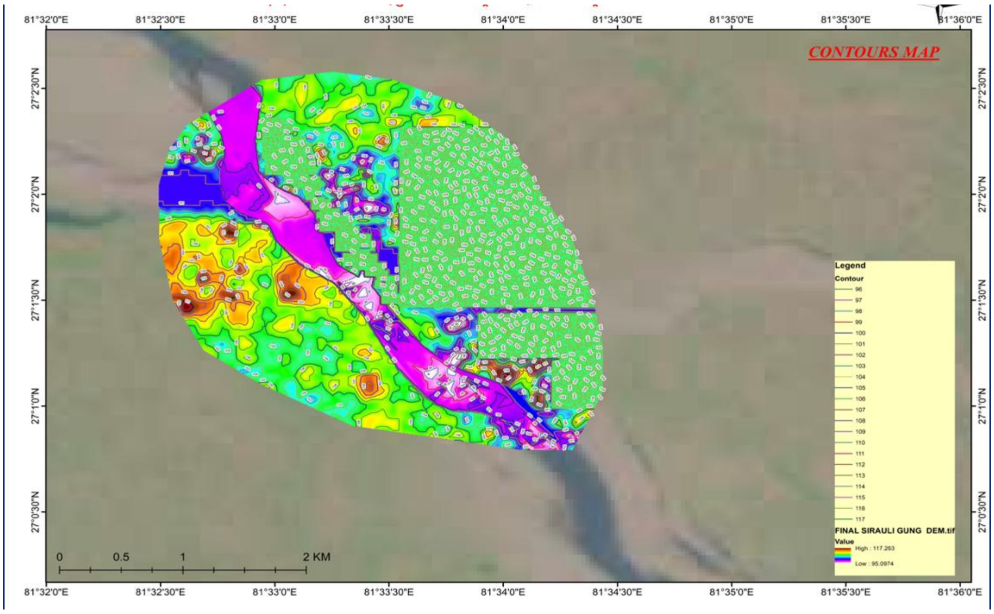


Figure 8. *Sirauli Goong Barabanki Dredging Site 2D flood simulation*

7.3 Engineering of the Artificial Cut-off Channel

The design of the artificial channel followed a strategic hydraulic gradient:

- **Alignment Strategy:** The cunette was designed by interconnecting the lowest bed levels (thalweg) of the upstream and downstream sections, ensuring a self-scouring velocity.
- **Two-Stage Excavation**: Mechanical Excavation: Initial earthwork was executed using hydraulic excavators to define the channel geometry above the water lable. Hydraulic Dredging Subsequent deepening to the desired design level was achieved through specialized dredging, ensuring precision in bed slope and channel capacity.

7.4 Spoil Management and Protection Works

A sustainable approach was adopted for the management of dredged materials (spoil):

- **Fill Management:** The dredged material was strategically utilized to fill low-lying areas on the protection side, creating a secondary barrier against inundation.
- **Geotube Foundations:** The spoil served as a stable base for the installation of Geotubes, enhancing the structural integrity of the river training works.

7.5 Flow Diversion and Bank Stabilization

The final phase focused on directing the river's energy away from vulnerable banks:

- **Flow Training Structures:** A combination of Geotubes and Balli (timber) Piling was deployed to act as flow-deflecting structures.
- **Functional Application:** Geotubes structures function similarly to spurs/groynes, providing bank protection and providing the necessary hydraulic "push" to divert the main current into the newly created channel.

8. DISCHARGE CALCULATION USING LACEY'S REGIME THEORY

To calculate the discharge (Q) passing through the specified trapezoidal channel using Lacey's Regime Theory, we use the relationship between the channel's cross-sectional area (A), the silt factor (f), and the velocity (V).

8.1 Design Parameters

Bottom Width (B): 45 m

Average Depth (d): 5 m

Side Slope (z): 0.5: 1 (Typical for alluvial rivers like the Ghaghara/Saryu)

Silt Factor (f): 1.1 (For medium sand as per the Indo-Gangetic plains)

8.2 Area Calculation (A)

For a trapezoidal section:

$A = (B + z \cdot d) \cdot d$

$A = (45 + 0.5 \times 5) \times 5$

$A = (47.5) \times 5 = 237.5\ m^2$

8.3 Velocity and Discharge Calculation Using Lacey's Regime Theory

- **Velocity Calculation**

Using Lacey's velocity relationship involving slope:

$$V = \frac{\left(R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}\right)}{n}$$

However, to stay consistent with Lacey's regime equations for Q and S, the combined Lacey formula relating Velocity (V), Hydraulic Mean Depth (R), and Slope (S) is used:

$$V = 10.8 \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{3}}$$

- **Given Parameters**

Cross-sectional Area (A) = 237.5 m^2

Wetted Perimeter (P) = $B + 2d\sqrt{1 + z^2} = 45 + 2(5)\sqrt{1 + 0.5^2} \approx 56.18\,m$

Hydraulic Mean Depth (R) = A / P = 237.5 / 56.18 = 4.23 m

Longitudinal Slope (S) = 0.35 / 1000 = 0.00035

- **Calculation**

$$V = 10.8 \cdot (4.23)^{\frac{2}{3}} \cdot (0.00035)^{\frac{1}{3}}$$

$V = 10.8 \cdot 2.615 \cdot 0.0705$

$V \approx 1.99$ m/s

- **Resulting Discharge (Q)**

$Q = A \cdot V$

$Q = 237.5 \cdot 1.99$

$Q \approx 472.63\ m^3/s$

Cusecs Equivalent ≈ 16,690 Cusecs

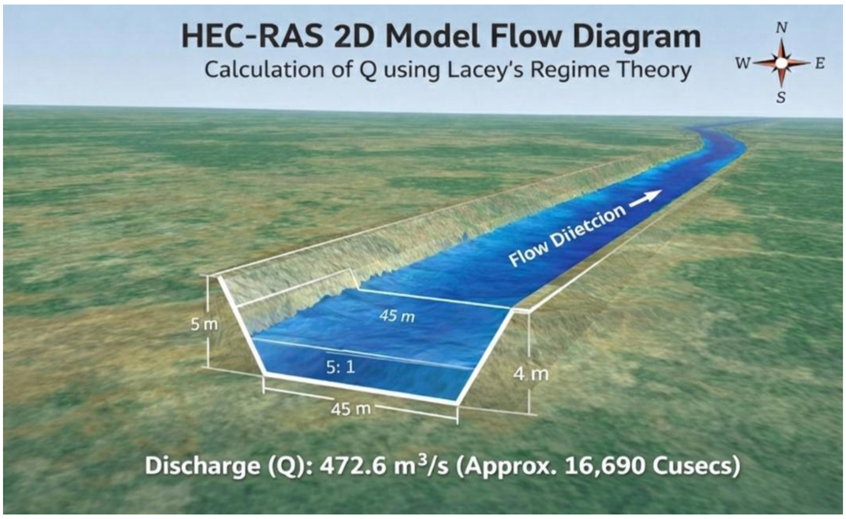


Figure 9. *HEC-RAS 2D Flow Diagram*

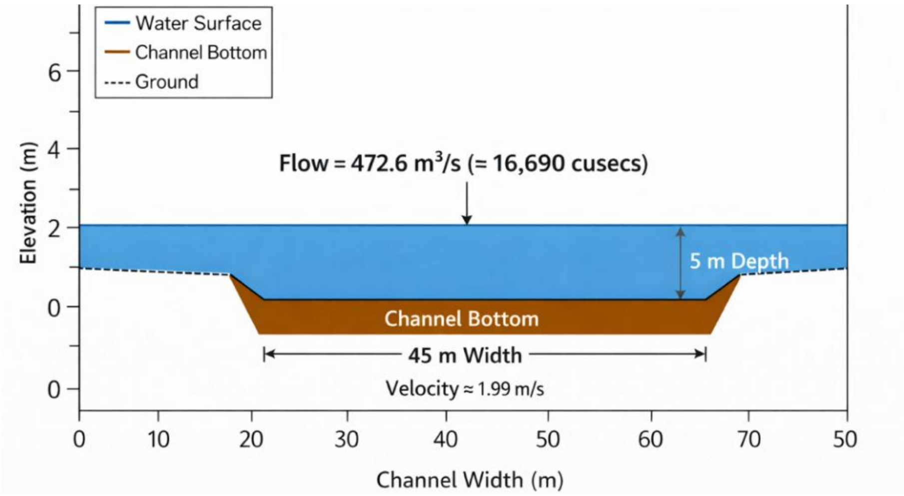


Figure 10. *Cross Section Plot Channel Flow Representation*

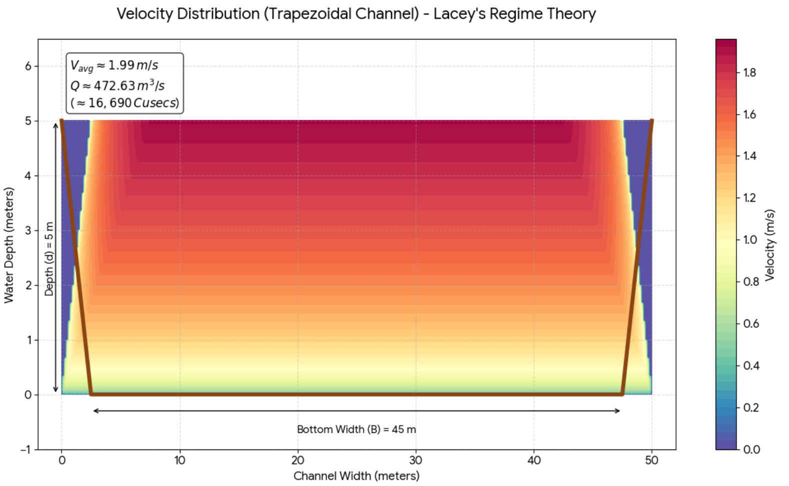


Figure 11. *Hec-Ras 2D Model Velocity Representation*

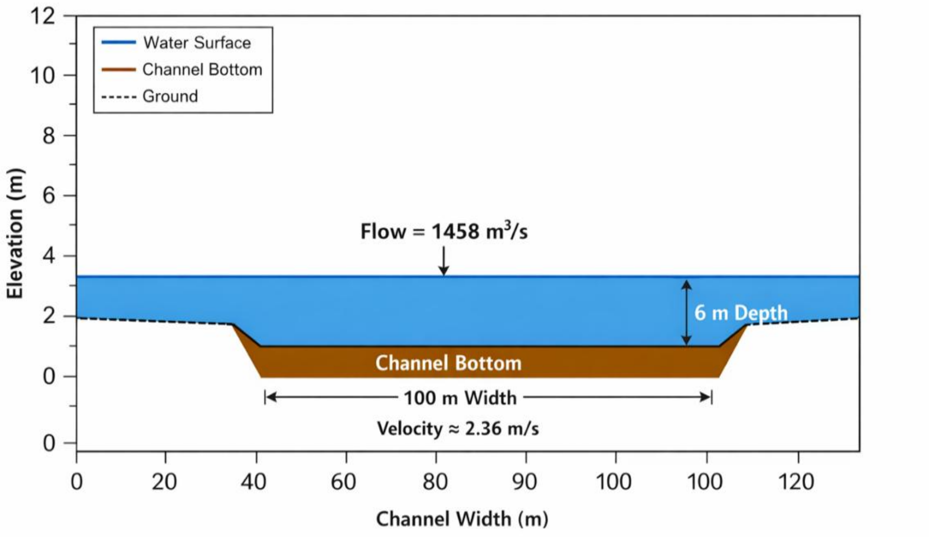


Figure 12. *Water Flow Representation Through Widened Channel*

8.4 Discharge Calculation for Widened Channel (B = 100 m, d = 6 m)

- **Updated Design Parameters**

Bottom Width (B): 100 m

Average Depth (d): 6 m

Side Slope (z): 0.5: 1

Longitudinal Slope (S): 0.00035 (same as earlier)

- **Area Calculation (A)**

For a trapezoidal section:

$A = (B + z\,d) \cdot d$

$A = (100 + 0.5 \times 6) \times 6$

$A = (103) \times 6 = 618\ m^2$

- **Wetted Perimeter (P)**

$$P = B + 2d\sqrt{1 + z^2}$$

$$P = 100 + 2(6)\sqrt{1 + 0.5^2}$$

$P = 100 + 12\ (1.118) \approx 113.42$ m

- **Hydraulic Mean Depth (R)**

$R = A / P$

$R = 618 / 113.42 = 5.45$ m

- **Velocity Calculation (Lacey Regime)**

$$V = 10.8 \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{3}}$$

$$V = 10.8 \times (5.45)^{\frac{2}{3}} \times (0.00035)^{\frac{1}{3}}$$

$$(5.45)^{\frac{2}{3}} \approx 3.10$$

$$(0.00035)^{\frac{1}{3}} \approx 0.0705$$

V = 10.8 × 3.10 × 0.0705

V ≈ 2.36 m/s

- **Resulting Discharge (Q)**

Q = A × V

Q = 618 × 2.36

Q ≈ 1458 m^3/s

- **Cusecs Equivalent**

Q = 1458 × 35.3147

Q ≈ 51,500 Cusecs

9. RESULTS AND DISCUSSION

The hydraulic evaluation of the trapezoidal alluvial channel was carried out using Lacey's Regime Theory, supported by 2D HEC-RAS–style flow visualization and cross-sectional plotting. The channel geometry, consisting of a 45 m bottom width, 5 m flow depth, and 0.5:1 side slopes, is representative of stable regime conditions commonly observed in the Indo-Gangetic plains. A longitudinal slope of 0.00035 and a silt factor of 1.1 were adopted to reflect medium sand bed material. The analysis yielded a cross-sectional area of 237.5 m^2, hydraulic mean depth of 4.23 m, and an average flow velocity of approximately 1.99 m/s. The resulting discharge capacity of 472.6 m^3/s (≈16,690 cusecs) indicates that the channel section is hydraulically efficient and capable of safely conveying the design flow under regime conditions. The implementation of pilot channels (cunettes) in District Barabanki and District Gonda has yielded significant hydraulic and socio-economic outcomes:

(a) (b)

Figure 13. *Water Flow Through Dreged* Channel

(a) Sirauli Goong Barabanki (b) Bahadurpur Gonda.

9.1 Hydraulic Efficiency

The 45-meter wide channel demonstrated a discharge capacity of approximately 472.63 m^3/s (16,690 Cusecs), while the widened 100-meter section / channel proved capable of handling up to 1,458 m^3/s (51,500 Cusecs). This diversion effectively shifted the thalweg away from the vulnerable concave banks.

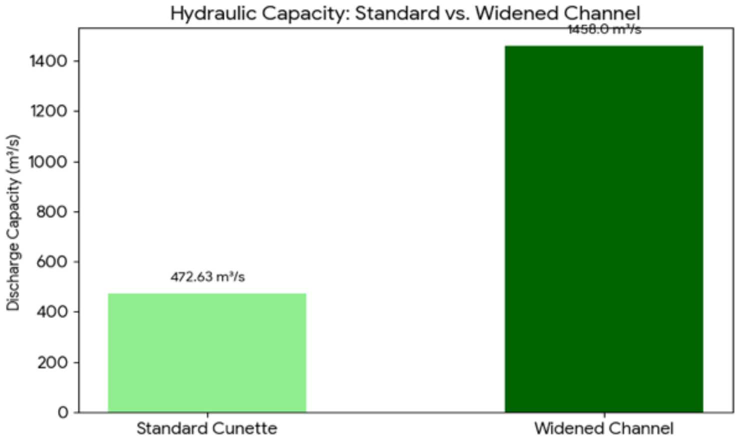


Figure 14. *Comparison of Hydraulic Capacity*

Table 1. *Comparison of Hydraulic Parameter*

Parameter	Standard Cunette	Widened Channel
Bottom Width (B)	45 m	100 m
Average Depth (d)	5 m	6 m
Cross-sectional Area (A)	237.5 m^2	618.0 m^2
Flow Velocity (V)	1.99 m/s	2.36 m/s
Discharge Capacity (Q)	472.63 m^3/s	1,458.00 m^3/s
Equivalent Discharge	≈ 16,690 Cusecs	≈ 51,500 Cusecs

9.2 Erosion Mitigation

Drone surveillance and post-monsoon modeling confirmed a substantial reduction in shear stress along the banks of Village Sirauli Gung and Village Bahadurpur. The hybrid use of Geotubes and Balli piling successfully induced siltation in the abandoned reaches.

Figure 15. *Post Dredging Siltation Near the Bank Protection at Sirauli Goong Barabanki*

Figure 16. *Post Dredging Siltation Near the Bank Protection at Bahadurpur Gonda*

9.3 Economic Viability

Both projects achieved favorable Benefit-Cost Ratios (1.41:1 for Ghaghara and 1.35:1 for Saryu). The in-situ use of 13.46 lakh cubic meters of dredged silt for embankment reinforcement saved significant transportation costs and provided land reclamation benefits for local communities.

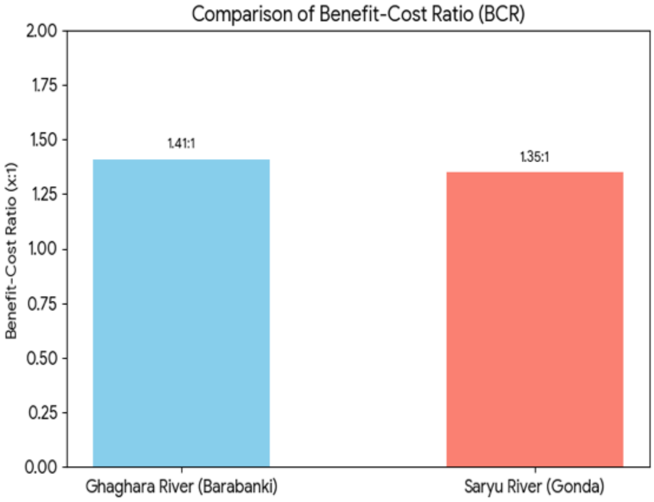


Figure 17. *Benefit Cost Ratio Representation*

9.4 Socio-Hydrological Impact

A total of 22,000 residents and 8,000 hectares of fertile agricultural land were protected from imminent submergence and erosion, preserving the local rural economy. The execution of this project successfully generated 15,288 temporary man-days of employment, providing substantial livelihood support to the local rural community.

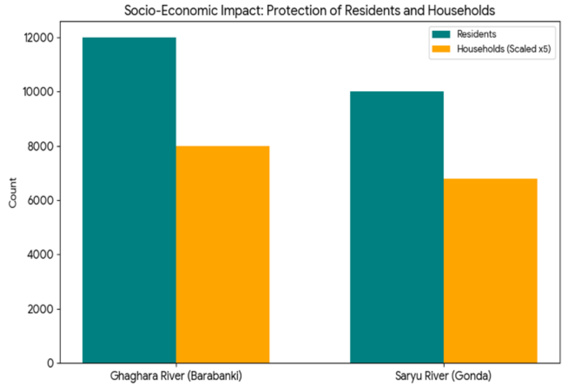
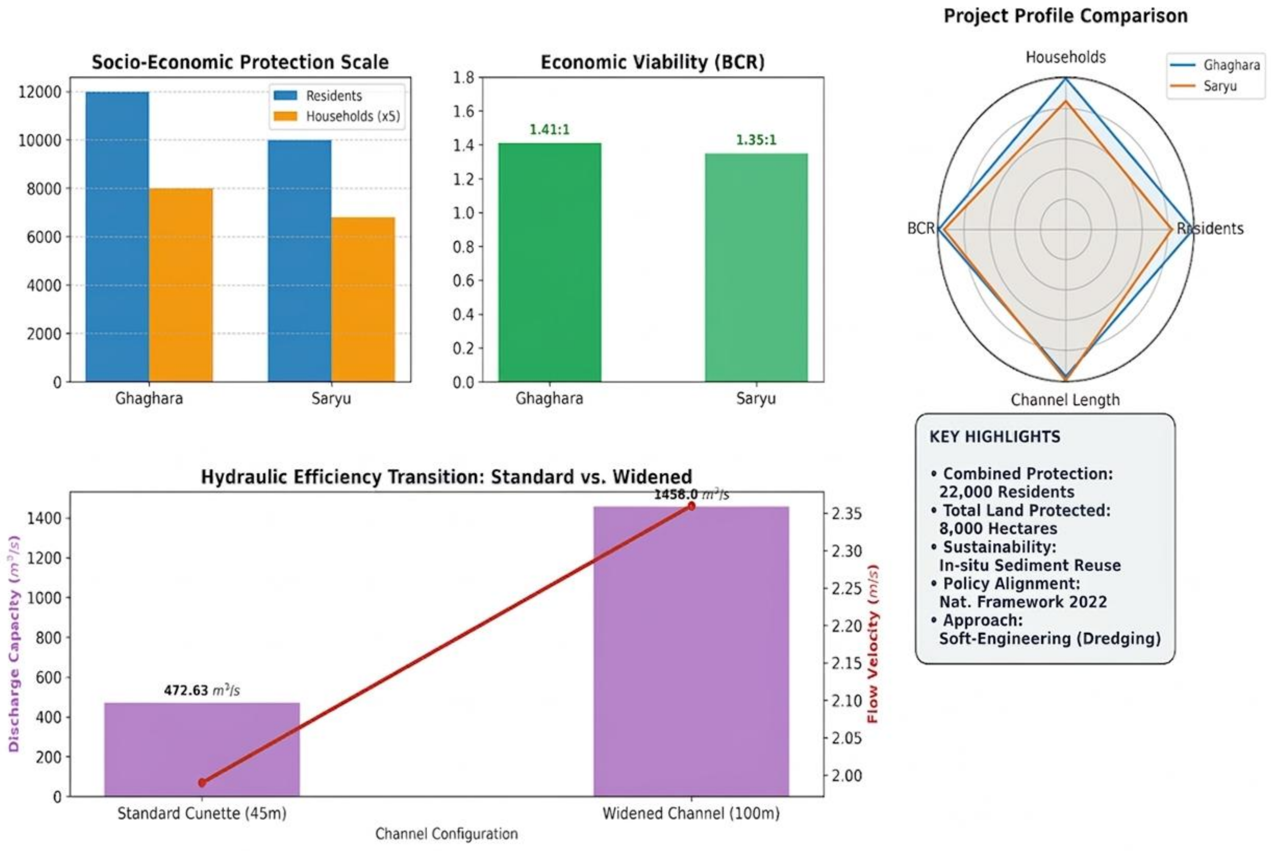


Figure 18. *Representation of Socio Economic Impact*



KEY HIGHLIGHTS

- **Combined Protection:** 22,000 Residents
- **Total Land Protected:** 8,000 Hectares
- **Sustainability:** In-situ Sediment Reuse
- **Policy Alignment:** Nat. Framework 2022
- **Approach:** Soft-Engineering (Dredging)

Figure 19. *Representation of Socio Hydrological Impact*

Table 2. *Comparative Hydraulic Parameters Before and After Cunette Development with DEM*

Hydraulic Parameter	Stage	Vulnerable Bank	New Dredged Channel (Cunette)
Flow Velocity (m/s)	Before	High (2.5 – 3.2)	Low / Negligible
	After	Reduced (0.8 – 1.2)	Increased (2.2 – 2.8)

Shear Stress (N/m²)	Before	Extreme (45 – 60)	Low
	After	Minimal (<15)	Moderate (35 – 50)
Water Surface Elevation	Before	Elevated (Risk of Overtopping)	N/A
	After	Stabilized / Controlled	Optimized for Conveyance
Bed Morphology	Before	Scouring & Deepening	Siltation
	After	Reclaimed / Filled with Dredged Material	Developed Thalweg

The data is being validated for a high-magnitude discharge of 300,000 cusecs (approximately 8,500 m^3/s).

9.5 Velocity Profile and River Morphology Observations

a comparative analysis of velocity distribution patterns in two distinct hydraulic environments: the Ghaghara River at Sirauli Gung (Barabanki) and the Saryu River at Bahadurpur (Gonda). While the Saryu reach is characterized by high-gradient velocity concentrations driven by its meandering geometry, the Ghaghara reach at Sirauli Gung demonstrates a managed velocity profile influenced by strategic dredging and bank protection works. Field observations and velocity mapping indicate that dredging successfully shifts the Vmax core toward the central channel, thereby reducing the shear stress on the protected banks. These findings highlight the effectiveness of pilot channel dredging in stabilizing river morphology and protecting critical infrastructure against scouring.

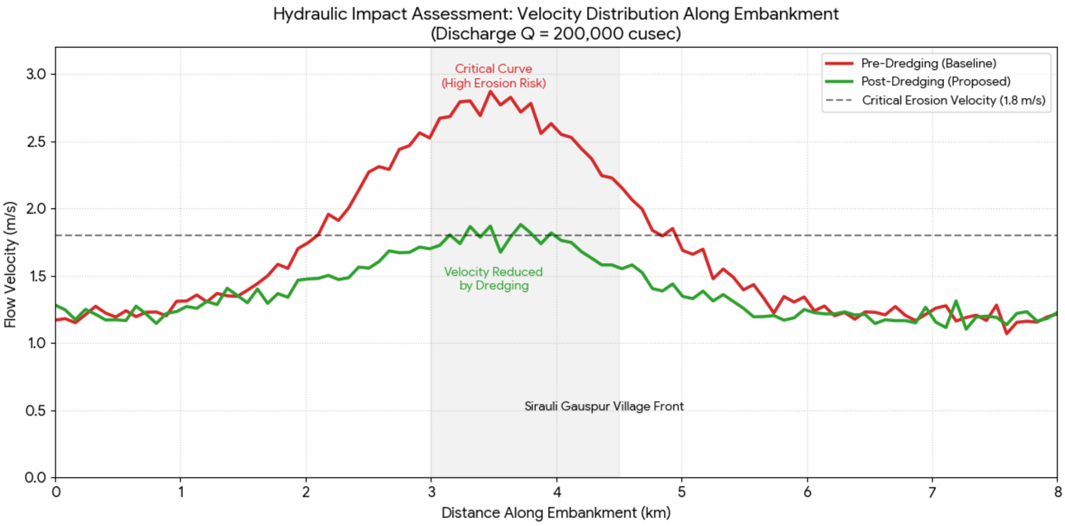


Figure 20. *Velocity Distribution Representation Ghaghara River At Sirauli Goong Barabanki*

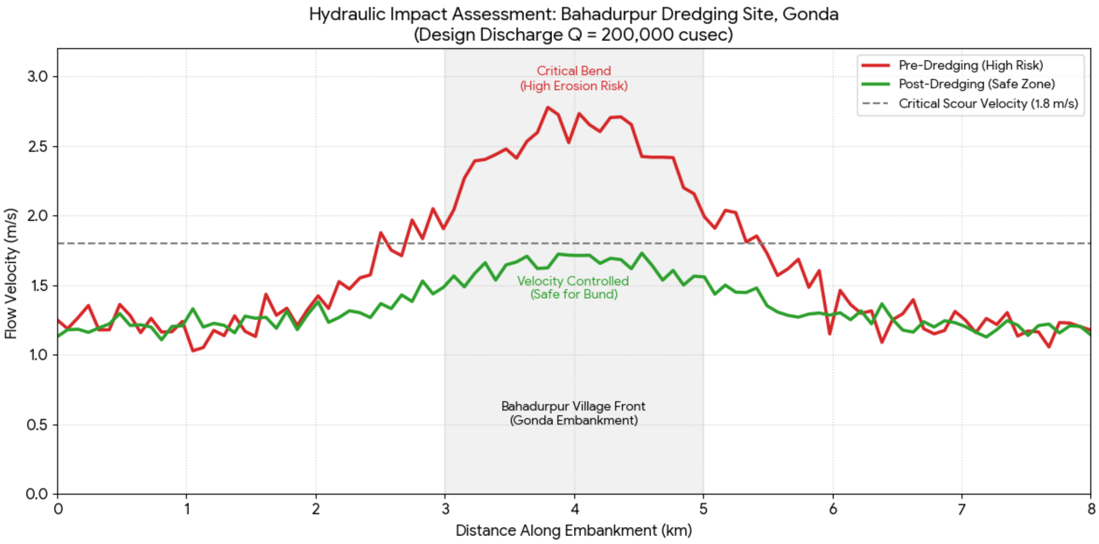


Figure 21. *Velocity Distribution Representation Saryu River At Bahadurpur Gonda*

10. CONCLUSION

The study concludes that Sectoral Dredging, when governed by the *National Framework for Sediment Management-2022*, represents a paradigm shift in river training. This study demonstrates that transitioning from traditional “hard-armoring” to a soft-engineering approach—specifically sectoral dredging combined with nature-based solutions—is highly effective for flood risk reduction in the dynamic alluvial reaches of the Ghaghara and Saryu rivers. By implementing 45-meter-wide pilot channels (cunettes), the river’s main current, or thalweg, was successfully redirected away from the vulnerable concave banks at Sirauli Gung and Bahadurpur. Technical assessments using HEC-RAS simulations and field data validated this strategy, showing a significant reduction in flow velocity to 0.8–1.2 m/s and a drastic decrease in boundary shear stress to below 15 N/m² at the protected sites.Furthermore, the hybrid deployment of Geotubes and Balli piling served as an effective flow-deflection mechanism that encouraged accelerated siltation in abandoned channels. This process not only stabilized the bank “toe” but also reinforced the overall structural longevity of the river training works. From an economic and environmental perspective, the projects achieved favorable Benefit-Cost Ratios (1.41:1 for the Ghaghara and 1.35:1 for the Saryu), proving to be more viable than conventional methods. By strictly adhering to the National Framework for Sediment Management-2022, the project successfully reused 13.46 lakh cubic meters of dredged silt in-situ for land reclamation and embankment strengthening. This created a sustainable circular economy model with a minimal carbon footprint. Ultimately, these interventions provided immediate security to approximately 22,000 residents and protected 8,000 hectares of fertile agricultural land, effectively preventing socio-economic displacement in these rural regions of Uttar Pradesh.

11. FUTURE SCOPE

The success of the Ghaghara-Saryu dredging project provides a foundation for future research and more advanced river management. Future work should focus on the following four key areas:

11.1 Advanced Monitoring Using InSAR and Radar-Based Satellite Systems

- While unmanned aerial vehicle (UAV) surveys provided high-resolution surface mapping in the present study, future monitoring programs should incorporate Interferometric Synthetic Aperture Radar (InSAR) technology integrated with high-resolution satellite radar datasets.

- Unlike conventional photogrammetric drone surveys, InSAR enables detection of millimeter-scale vertical and horizontal surface deformations over extensive spatial domains. Radar-based systems operate effectively under cloud cover and during monsoon conditions, ensuring uninterrupted seasonal monitoring a critical requirement for dynamic alluvial rivers such as the Ghaghara–Saryu system.

11.2 Better Simulations: Moving from 2D to 3D Models

- The current study used 2D HEC-RAS, which is excellent for general flood mapping. However, rivers move in complex, spinning patterns (helical flow).
- 3D CFD Modeling future research should use 3D Computational Fluid Dynamics (CFD) software like FLOW-3D.
- These 3D models help us understand exactly how water hits the banks. This information is critical for placing Geotubes in the perfect position to prevent scouring.

11.3 Predictive Management: AI and Machine Learning

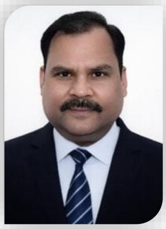
- Instead of waiting for erosion to happen, we can use Artificial Intelligence (AI) to predict it.
- Neural Networks by feeding years of river data into Machine Learning (ML) algorithms, we can train computers to guess where the river will move next.
- This creates a “Smart River Management” system where dredging can be done proactively before the monsoon arrives, saving time and government funds.

11.4 Climate Resilience and the Circular Economy

- As climate change leads to more frequent and larger floods, we must ensure our engineering is “future-proof.”
- Future studies should compare how “soft” solutions (like Geotubes) hold up against “hard” concrete walls during extreme weather.
- Circular Economy we should continue to refine the model of reusing dredged silt for land reclamation. This not only protects villages but also helps restore local ecosystems and creates new land for the community.

Author Contributions:-

Shri Anil Garg (IAS) is presently posted as Principal Secretary, Irrigation and Water Resources Department, Government of Uttar Pradesh, India. He belongs to the 1996 batch of the Indian Administrative Service. He holds a B.Tech. in Electronics and Communication from Thapar University, Patiala. He began his administrative career as Joint Magistrate in Deoria, Haridwar, and Roorkee, and later served as Chief Development Officer, Bareilly. He has extensive experience in district administration, having served as District Magistrate in thirteen districts of Uttar Pradesh, including Bareilly, Ayodhya, Meerut, Jhansi, Ambedkar Nagar, Kaushambi, Pilibhit, Badaun, Shahjahanpur, Basti, Siddharth Nagar, Mainpuri, and Aligarh. He has also served as Divisional Commissioner of the Lucknow, Bareilly, and Aligarh Divisions. In the field of industrial and infrastructure development, Shri Garg has held key leadership positions as Managing Director, Uttar Pradesh State Industrial Development Authority (UPSIDA); Chief Executive Officer, Yamuna Expressway Industrial Development Authority; and Additional Chief Executive Officer, Greater Noida Industrial Development Authority. His service portfolio includes important roles such as Secretary, Higher Education; Special Secretary in the Power and Revenue Departments; Rural Development Commissioner; Excise Commissioner; Director of Land Acquisition; and Judicial Member of the Board of Revenue. He also served as Additional Chief Electoral Officer during the 2017 Uttar Pradesh State Assembly Elections. He is presently heading the Irrigation and Water Resources Department in Uttar Pradesh as Principal Secretary. His present role entails overseeing the country’s longest canal network and managing the state's vital water infrastructure, including dams, reservoirs, and flood control schemes. His role is crucial to the state's agricultural productivity, ensuring the operation of major and minor lift irrigation canals and tubewells to provide essential water resources for the farming sector.



Er. Ashok Kumar Singh is the Engineer-in-Chief (Design & Planning) in the Irrigation and Water Resources Department, Government of Uttar Pradesh. A graduate in Civil Engineering from the Birla Institute of Technology, Mesra, Ranchi, he is a distinguished civil engineer with extensive expertise in water resource management, particularly in canal systems, river rejuvenation, and flood control. Throughout his illustrious career, he has played a pivotal role in the planning and execution of numerous canal and flood management projects across Uttar Pradesh. As Engineer-in-Chief, he leads the department's strategic and technical initiatives in flood control management, integrating sustainable water management practices with advanced hydrological modeling and environmental conservation principles. His areas of specialization include River Rejuvenation and Integrated Basin Management, Floodplain Zoning and Regulation, Flood Risk Assessment and Mitigation Planning, and the Design and Implementation of Mitigation Structures for Wildlife. Among his major contributions, he has spearheaded the "Nadiyon Ka Adhikaar Muhim" (Rivers' Rights Campaign), which emphasizes ecological restoration as a core component of river conservation. He has also led several projects under the River Rejuvenation Programme, focusing on sustainable channelization, sediment control, and natural floodplain recovery. In addition, he has contributed significantly to policy formulation on floodplain zoning and disaster resilience in flood-prone regions of Uttar Pradesh and promoted innovative approaches in the design of wildlife mitigation structures including eco-bridges and underpasses to ensure safe habitat connectivity amid ongoing infrastructural development.

Er. Mahesh Kumar Pandey is a distinguished professional and a retired Chief Engineer from the Irrigation and Water Resources Department, Government of Uttar Pradesh, who holds a Bachelor of Technology degree from the prestigious Madan Mohan Malviya Engineering College (now MMMUT), Gorakhpur. With an illustrious career spanning three decades, Er. Pandey possesses vast expertise in complex water resource infrastructure and management, maintaining a professional portfolio that includes extensive experience in the hydraulic design of both major and minor lift canal systems alongside specialized knowledge in large-scale dredging operations for river channelization and maintenance. Furthermore, his career is marked by significant field experience in tubewell construction and a deep background in the design and renovation of hydromechanical equipment for dams and barrages. This comprehensive understanding of both the civil and mechanical components of irrigation projects establishes him as a seasoned authority in the fields of hydraulic engineering and infrastructure rehabilitation.

Er. Sujeet Kumar Singh is a distinguished mechanical engineer of the 2011 batch of the Irrigation and Water Resources Department, Government of Uttar Pradesh, currently serving as an Executive Engineer. He holds a Master of Technology (M.Tech.) from Motilal Nehru National Institute of Technology Allahabad, a background that has fueled his 14-year career in large-scale water infrastructure transformation. He has successfully spearheaded 20 major hydro-mechanical renovation projects for dams and barrages across Uttar Pradesh and Uttarakhand, alongside 24 critical dredging and channelization projects that have redefined river management and flood mitigation in Northern India. A pivotal figure in national milestones, he led the vital restoration of the Rapti Barrage for the inauguration of the Saryu Canal National Project by the Honourable Prime Minister of India, ensuring the seamless operation of the Rapti Barrage, Rapti Barrage outlet, and Rapti Barrage inlet gates. Beyond surface water, he possesses extensive domain knowledge in the design and construction of Deep-Bore State Tubewells (Rajkiya Nalkoop) using advanced drilling technologies. Honored as the "Best Karmyogi of Uttar Pradesh" in the Department, he played a crucial role in the Mahakumbh 2025 mega-project, where he executed specialized dredging and channelization to manage complex river flows and safeguard the sanctity of the Sangam for millions of pilgrims. His professional journey exemplifies a rare integration of academic excellence with groundbreaking field engineering in high-stakes hydraulic environments.

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