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Flood Mitigation through Sectoral Dredging and Geotube-Assisted Flow Diversion: Hydrodynamic Assessment of the Garra River, Uttar Pradesh, India

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Abstract
This study assesses the hydraulic and morphological outcomes of a sectoral dredging and flow diversion project carried out on the Garra River near Sanjalpur Village, Hardoi district, Uttar Pradesh, India. The project covered a 2.35 km reach situated roughly 6 km upstream of the Garra-Ganga confluence and aimed to redirect active river flow away from inhabited settlements by guiding the river back toward its 1960s course. The main engineering works included a newly cut 45 m wide channel, a three-layer geotube structure placed as an inline flow deflector, and controlled infilling of the original channel using excavated material. A post-monsoon evaluation after the 2025 monsoon season used multi-temporal Sentinel-2 satellite imagery alongside field hydraulic benchmarks. Results confirmed that the dredged channel carried roughly 75% of total river discharge at a peak recorded water level of 129.15 m. The original channel (The river is causing severe bank erosion near the village) became hydraulically inactive, the dredged channel (new artificial cut off channel) stayed self-scouring and widened naturally to about 100-150 m, and no bank erosion was recorded near settlements. The geotube structure remained intact throughout. Community-level benefits included an end to recurring flood damage and the reclamation of floodplain land for seasonal farming. These results confirm that the sectoral dredging method is a cost-effective and process-compatible approach to river training, with lessons that can apply to other migrating alluvial rivers in the Ganga basin.

Keywords: Sectoral Dredging, River Training, Flow Diversion, Alluvial River Morphology, Garra River, Geotube, Flood

1. Introduction

Rivers draining the Indo-Gangetic Plain are among the most dynamically unstable fluvial systems in the world, characterised by high sediment loads, low channel gradients, and a strongly seasonal monsoon hydrograph that together drive persistent lateral migration and recurrent flooding. For communities settled along these floodplains, this instability is not an abstract geomorphic curiosity but a lived and recurring hazard. The Garra River, a principal tributary of the Ganga in Uttar Pradesh, exemplifies this pattern decades of progressive channel drift have brought the river into direct conflict with riparian settlements, producing repeated bank erosion and flood damage. At the basin scale, this risk is far from isolated, with an estimated 27,490 settlements across the Ghaghara basin exposed to flooding in a typical year (Arya & Singh, 2021). The hazard is also likely to intensify rather than recede climate projections point to a marked increase in the frequency of very heavy monsoon seasons across India under continued warming, implying that flood risk in basins such as the Garra is more likely to grow than stabilise over the coming decades (Katzenberger et al., 2022).

Conventional responses to this kind of channel instability, principally embankments, revetments, and spur dykes, attempt to resist the river's natural tendencies through fixed, rigid infrastructure. While effective in some settings, such structures are costly to maintain, prone to localised failure, and frequently work against rather than with the hydraulic and sedimentary processes that shape alluvial channels (Thorne et al., 1997; Biedenharn et al., 2000). Sectoral dredging offers a process-compatible alternative rather than resisting the river, it excavates a new channel along a historically preferred course and uses controlled infilling of the old channel (river path causing severe bank erosion near the village) to redirect flow, allowing the river's own energy to establish and maintain the new path (new artificial cut off channel). The geometry and slope of such interventions are critical to their long-term success, since a poorly designed cut can silt up and revert to the original course rather than stabilising (Saad & Habib, 2021).

It is against this backdrop that the Irrigation and Water Resources Department, Government of Uttar Pradesh, undertook a sectoral dredging and geotube-assisted flow diversion project on the Garra River near Sanjalpur Village, Hardoi district. The targeted reach, a 2.35 km stretch roughly 6 km upstream of the Garra-Ganga confluence, had been migrating steadily toward settlements on both banks, producing annual erosion and flood events known locally as "Kataan." Such progressive channel migration is well documented across the Ganga basin's tributaries in Uttar Pradesh and represents a recurring threat to densely settled floodplains throughout the region (Singh et al., 2020; Jarriel et al., 2020). This study evaluates the success of the river dredging project at Sanjalpur village. By comparing pre-monsoon, monsoon, and post-monsoon data, this paper analyses the intervention's stability and its success in preventing bank erosion throughout the entire monsoon season.

A further motivation for this study lies in the methodological opportunity that satellite remote sensing now offers for evaluating river engineering interventions in data-scarce settings. Many alluvial reaches in the Ganga basin lack permanent gauge stations or post-construction survey infrastructure, making conventional monitoring difficult. Multi-temporal Sentinel-2 imagery, combined with limited field hydraulic benchmarks, provides a practical and increasingly validated means of tracking channel change and assessing intervention performance even where ground instrumentation is sparse (Gautam et al., 2024; Boothroyd et al., 2021). Applying this approach to a completed, functioning intervention, rather than a purely theoretical or pre-construction design, allows the study to test not just whether the engineering logic was sound on paper, but whether it held up under real monsoon loading.

Accordingly, this paper pursues three connected aims: first, to document the design and construction of the new channel by dredging and geotube diversion works at Sanjalpur village; second, to evaluate the hydraulic and morphological performance of the dredged channel through the 2025 monsoon season using Sentinel-2 imagery and field water-level data; and third, to assess the resulting social and environmental outcomes and consider the broader applicability of this approach to other migrating alluvial rivers across the Ganga basin. In doing so, the study aims to contribute both a documented case of process-compatible river engineering in practice and a transferable evaluation framework for similar engineering measure elsewhere in the region.

2. Literature Review

Flood management in alluvial rivers has been studied extensively across South Asia, where seasonal monsoon discharge and high sediment loads create persistent channel instability. Research on the Indo-Gangetic Plain shows that rivers like the Ganga and its tributaries undergo rapid lateral migration driven by sediment aggradation, avulsion, and overbank flooding, often threatening densely populated floodplains (Jarriel et al., 2020; Singh et al., 2020). Channel migration rates in this region can reach several tens of metres per year under high monsoon flows, making conventional bank protection measures such as concrete revetments and spur dykes increasingly difficult to sustain (Arya & Singh, 2021). Climate change compounds this problem, as studies project a significant intensification of very wet monsoon seasons over India under continued global warming, which is expected to raise peak discharge levels and increase erosion and flood risk in basins like the Garra (Katzenberger et al., 2022).

River avulsion, the sudden switching of a river from one channel course to another, is a natural process in low-gradient alluvial systems and has been documented extensively in the Ganga basin. Valenza et al. (2020) showed that avulsion style is closely linked to channel morphology, with wider, shallower channels more prone to nodal avulsion while narrower channels tend toward progradational avulsion. Slingerland and Smith (2004) established that once a new channel captures a dominant share of flow and sediment transport, morphological self-reinforcement usually sustains the new path. Stouthamer and Berendsen (2001) similarly found that avulsion frequency and duration in the Rhine-Meuse Delta depended on the hydraulic gradient advantage offered by the new channel. These findings together explain why sectoral dredging, which artificially creates a hydraulic gradient advantage toward a new channel, can work with rather than against the river's natural geomorphic tendencies.

The use of dredging as a flood management tool has received growing attention in low-gradient river settings. Saad and Habib (2021) assessed the impact of riverine dredging on flooding in low-gradient coastal rivers using a hybrid 1D/2D hydrodynamic model, finding that channel modification could significantly reduce peak water surface elevations, but that outcomes depended critically on the spatial extent and geometry of the intervention. Hey (1997) established the theoretical basis for pilot channel design in stable river morphology, demonstrating that initiating a narrow pilot cut and allowing the river to widen it to regime dimensions under natural hydraulic loading is more cost-effective and morphologically durable than over-engineered fixed-width channels. Biedenharn et al. (2000) further developed guidelines for effective discharge calculations that underpin such pilot channel designs. These process-based engineering principles directly informed the dredging strategy adopted for the Garra River at Sanjalpur.

Geosynthetic tubes, commonly known as geotubes, have been increasingly used in hydraulic engineering as flexible, deployable flow diversion and bank protection structures. Pilarczyk (2000) provided a comprehensive framework for geosynthetics in hydraulic and coastal engineering, establishing geotubes as suitable for dynamic alluvial environments where substrate settlement and hydrodynamic loading require flexible rather than rigid solutions. More recently, Finklenburg et al. (2024) experimentally investigated the failure mechanisms of stacked geotextile tubes used as river dike cores, identifying seepage-induced sagging and lateral displacement as the primary failure modes under overflow conditions, and confirming that multi-layer configurations significantly improve structural resilience. These findings are directly relevant to the three-layer geotube configuration deployed at Sanjalpur as an inline flow deflector at the entrance to the original Garra River channel.

Hydrodynamic modelling using HEC-RAS is now a standard approach for evaluating flood risk and engineering intervention scenarios in alluvial rivers. Soomro et al. (2021) demonstrated the reliability of HEC-RAS for calibrating Manning's roughness coefficients in ungauged alluvial canal systems, confirming values in the range $n = 0.030$ to 0.040 for smooth sandy channels. Malik et al. (2021) validated the SCS Curve Number and Muskingum routing methods in HEC-HMS for monsoon-driven ungauged catchments, supporting the approach used to generate discharge inputs for the Garra River model. The Ferguson and Church (2004) equation for sediment settling velocity, applied here to classify the Garra's fine sandy bed material, has been confirmed by Shankar et al. (2021) as one of the most reliable formulations for fine to medium sands, correctly accounting for the transition between viscous and inertial drag regimes.

Remote sensing has become an essential tool for monitoring river channel change, particularly in South Asian river systems where ground instrumentation is often absent. Li et al. (2020) demonstrated that Sentinel-2 MSI imagery with 10 m optical resolution can reliably delineate open river surfaces and track planform change at reach scale. Wu et al. (2023) used satellite data to identify global hotspots of river extent change, confirming that Indo-Gangetic Plain rivers are among the most dynamically changing systems globally. Boothroyd et al. (2021) reviewed applications of Google Earth Engine in fluvial geomorphology and confirmed that multi-temporal satellite image analysis is now a validated standard for quantifying river channel adjustments. Gautam et al. (2024) specifically applied Sentinel-1 SAR data to flood inundation mapping in Uttar Pradesh river basins, establishing the local relevance of space-based monitoring for the region. Together, these studies underpin the satellite-based post-intervention assessment methodology used in this paper.

The socio-economic dimension of riverbank erosion in India has been documented by Das and Samanta (2023) and Das et al. (2024), who showed that erosion-driven land loss is a major driver of rural displacement and livelihood insecurity along Ganga system rivers. Bernhardt et al. (2005) and Wohl et al. (2015) established that process-compatible river restoration interventions can deliver multiple co-benefits for communities and ecosystems, including erosion cessation, habitat recovery, and agricultural land reclamation. Ceola et al. (2022) further linked flood risk dynamics to satellite-based assessment frameworks, showing how remote sensing can track the socio-environmental outcomes of river management interventions over time. These studies collectively provide the conceptual and empirical basis for evaluating both the technical hydraulic performance and the community-level outcomes of the Sanjalpur dredging intervention, as presented in this paper.

3. Study Area and Hydrogeomorphic Context

3.1 Physiographic Setting

The Garra River flows through Hardoi district in Uttar Pradesh and meets the Ganga about 6 km downstream of the study reach. Its bed and banks are made up of fine to medium sands and silts typical of the upper Indo-Gangetic Plain. The study site runs from an upstream coordinate of 27.216112° N, 79.924997° E to a downstream point at 27.19768135° N, 79.91755831° E. This is a low-lying, flood-prone stretch where historical satellite imagery shows the channel has shifted by several tens of metres over the years. Rivers in this region generally have sandy, easily erodible beds and wide floodplains that allow considerable lateral channel movement over time (Surinaidu et al., 2020; Kumar & Bhatt, 2021).

The project site at Sanjalpur Village sits at the top of a migrating bend that had shifted the active channel roughly 300-400 m from its 1960s position by the early 2020s. This movement brought the river dangerously close to homes on both the left and right banks, creating real erosion risk during the peak monsoon months. Historical satellite imagery shows the river naturally tending back toward its older, more direct course, which provided the geomorphic basis for choosing the dredging alignment. Channel migration of this scale is common in low-gradient sandy tributaries of the Ganga basin, driven by changes in monsoon flood patterns and sediment movement (Jarriel et al., 2020; Singh et al., 2020). When rivers drift into settled floodplains like this, it directly threatens people's homes and farmland, making engineered interventions aligned with the river's own history both logical and effective.

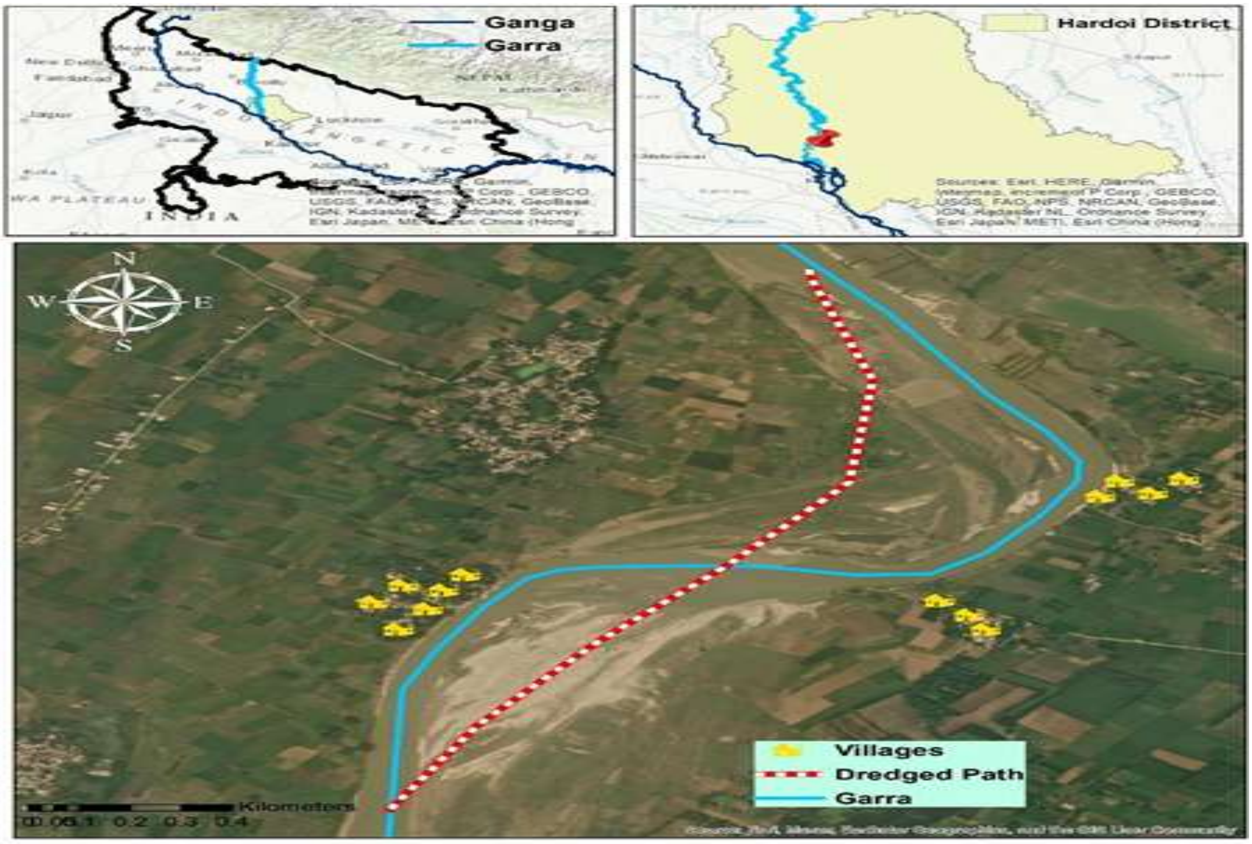


Figure 1. Site map of the Garra River around 2.35 km dredging alignment.

3.2 Hydrological Characteristics

The Garra River gets most of its flow from the Southwest Indian Monsoon, with peak discharge between July and September and much lower flows from November to May. Pre-monsoon hydraulic modelling set out flood frequency benchmarks for the study reach: the 1-year return period flood corresponds to a water level (WL) of 129.13 m at a discharge of 1,458.10 m³/s; the 5-year flood corresponds to WL 131.9 m at 3,338.30 m³/s; and the 10-year flood to WL 132.53 m at

3,910.60 m³/s. During the 2025 monsoon, the river hit a peak water level of 129.15 m on 27 August 2025, which matches the approximate 1-year flood condition. Ganga basin tributaries in Uttar Pradesh show large year-to-year swings in peak discharge, making flood management in these rivers an ongoing challenge for local authorities (Surinaidu et al., 2020; Kumar & Bhatt, 2021).

4. Engineering Design and Implementation

4.1 Design Philosophy

The design for this approach chose to work with the river's natural behavior rather than against it. Instead of rigid structures like embankments or spur dykes, the team redirected the river's own hydraulic energy into a newly cut channel that followed the historical course. This kind of process-aligned design reduces the need for long-term maintenance and avoids the flow distortions that hard engineering structures often cause in alluvial river systems (Piégay et al., 2005; Simon & Rinaldi, 2006).

The engineering design had three main parts: (i) a new dredged channel cut along the river's 1960s path; (ii) a three-layer geotube structure placed as an inline flow deflector at the entry to the original channel; and (iii) filling the original channel with dug-out material to prevent it from carrying active flow. These three elements work together to steer flow into the new channel and progressively shut down the old one. Combining excavation with a physical barrier at the old channel entrance is a key reason why this intervention performed so consistently across all flow conditions (Saad & Habib, 2021).

4.2 Channel Excavation:

A 2.35 km long channel was excavated across the Garra floodplain, with the alignment selected based on historical channel migration analysis and topographic survey data. The channel was cut to an initial width of 45 m, designed as a pilot cut rather than the final stable width. The channel slope was set so that monsoon flows would exceed the critical velocity for the sandy bed and bank material, keeping the channel self-scouring and preventing early siltation. Designing pilot channels that then evolve to their natural equilibrium width is a recognised strategy in process-based river engineering and reduces over-engineering costs (Hey, 1997; Biedenharn et al., 2000).

(a) (b)

Figure 2. (a) Excavation work by hydraulic excavator **(b)** Dredging work by dredger

The design expected the channel to widen naturally under monsoon hydraulic loading until it reached a stable width of 100-150 m, which is in line with the regime dimensions the Garra tends to maintain at comparable discharges. This approach of starting with a pilot channel and letting the river finish the job itself is quite different from over-engineered conventional designs that try to fix the final channel shape from the start (Hey, 1997).

4.3 Geotube Diversion Structure:

Geotubes were placed as inline diversion structures to redirect flow from the original main channel into the dredged path. They were laid in three separate layers to give the structure the height and strength needed to turn back peak monsoon flows while still being flexible enough to settle into the sandy substrate without cracking or failing under hydrodynamic loading. Recent experimental work on stacked geotextile tube dikes confirms that multi-layer configurations significantly improve structural resilience against overflow and seepage-related failure modes (Finklenburg et al., 2024).

Geotextile tubes filled with dredged sand were chosen because they are easy to install in remote floodplain locations, handle hydraulic forces well, and suit the sandy alluvial environment. Using them as flow guide structures rather than rigid barriers fits well with the process-based approach of the overall design (Pilarczyk, 2000). Their flexibility is actually an advantage here because it lets them absorb some of the hydraulic load without failing suddenly.

Figure 3. In-situ installation of the three-layer geotube structure for flow diversion

4.4 Main River Channel Infilling:

Material dug out from the new channel was used to fill key sections of the original main channel (path of river before dredging) next to the inhabited villages. This served two purposes, it raised the bed of the old channel high enough that normal and moderate flows could no longer use it, and it dealt with the excavated material on-site without needing to transport it elsewhere. The fill worked alongside the geotube structure to create a compound barrier that effectively stopped flow in the original channel. This dual-use of dredge spoil as infill material is a practical and cost-efficient approach that avoids the need for additional disposal infrastructure (Hey, 1997; Biedenharn et al., 2000).

5. Methodology

5.1 Temporal Variation in the River Course

To track how the river has changed at the study site, satellite imagery spanning from the 1960s to the present was analysed. The 1966 river position, mapped from historical CORONA satellite images, served as the baseline. Decadal LANDSAT images from the 1980s through 2010 were then used to trace long-term morphological shifts caused by both natural processes and human activities, as shown in Figure 4. Long-term multi-temporal satellite analysis is now a standard and reliable approach for documenting river channel dynamics in ungauged basins (Wu et al., 2023; Boothroyd et al., 2021).

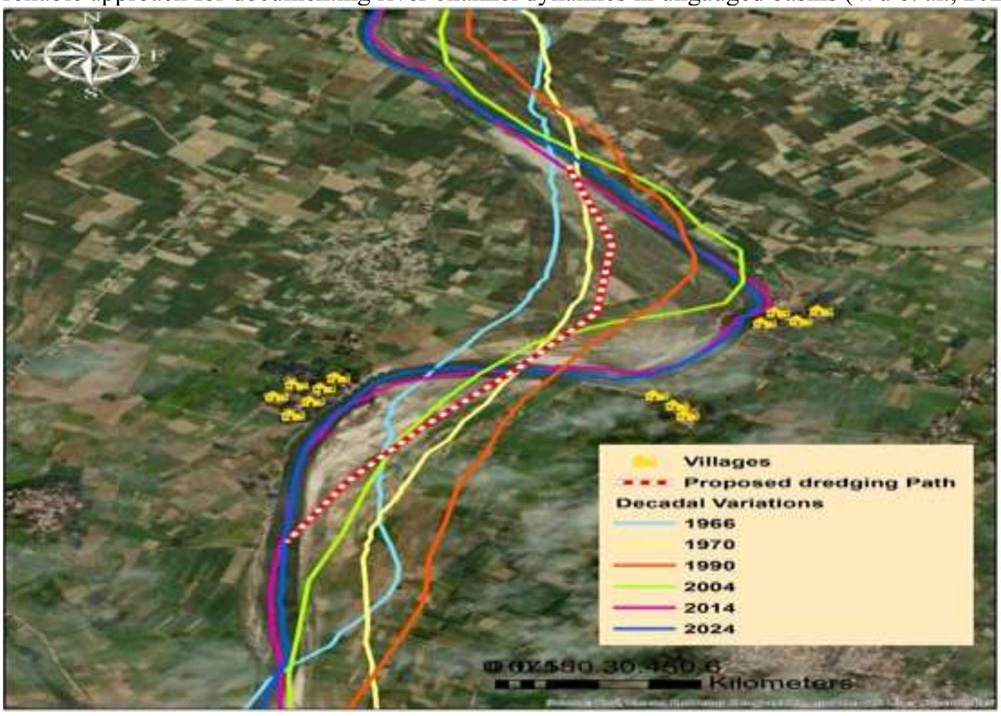


Figure 4. Decadal Variation in River Course from 1966-2024

The long-term analysis shows that in 1966, the natural channel sat very close to where the new dredged cut was planned. Over the following decades, a mix of natural forces and human pressures pushed the river sideways and changed its course considerably. This trend gives a solid scientific reason for aligning the new channel with the 1966 path, since it follows the river's own historical and geomorphic preference. Matching the intervention alignment to the river's natural tendency reduces the risk of the new channel silting up or reverting (Valenza et al., 2020; Slingerland & Smith, 2004).

High-resolution Sentinel and Google Earth imagery from 2020 to 2024 was also examined to capture recent short-term channel behavior, as shown in Figure 5. These recent images show the channel has been gradually moving toward nearby villages year by year. This trend directly threatened settlements with flooding and bank erosion, making the dredging project a timely and necessary response. Satellite time-series analysis for the period leading up to construction provides important evidence that the problem was active and worsening, strengthening the case for intervention (Gautam et al., 2024; Li et al., 2020).

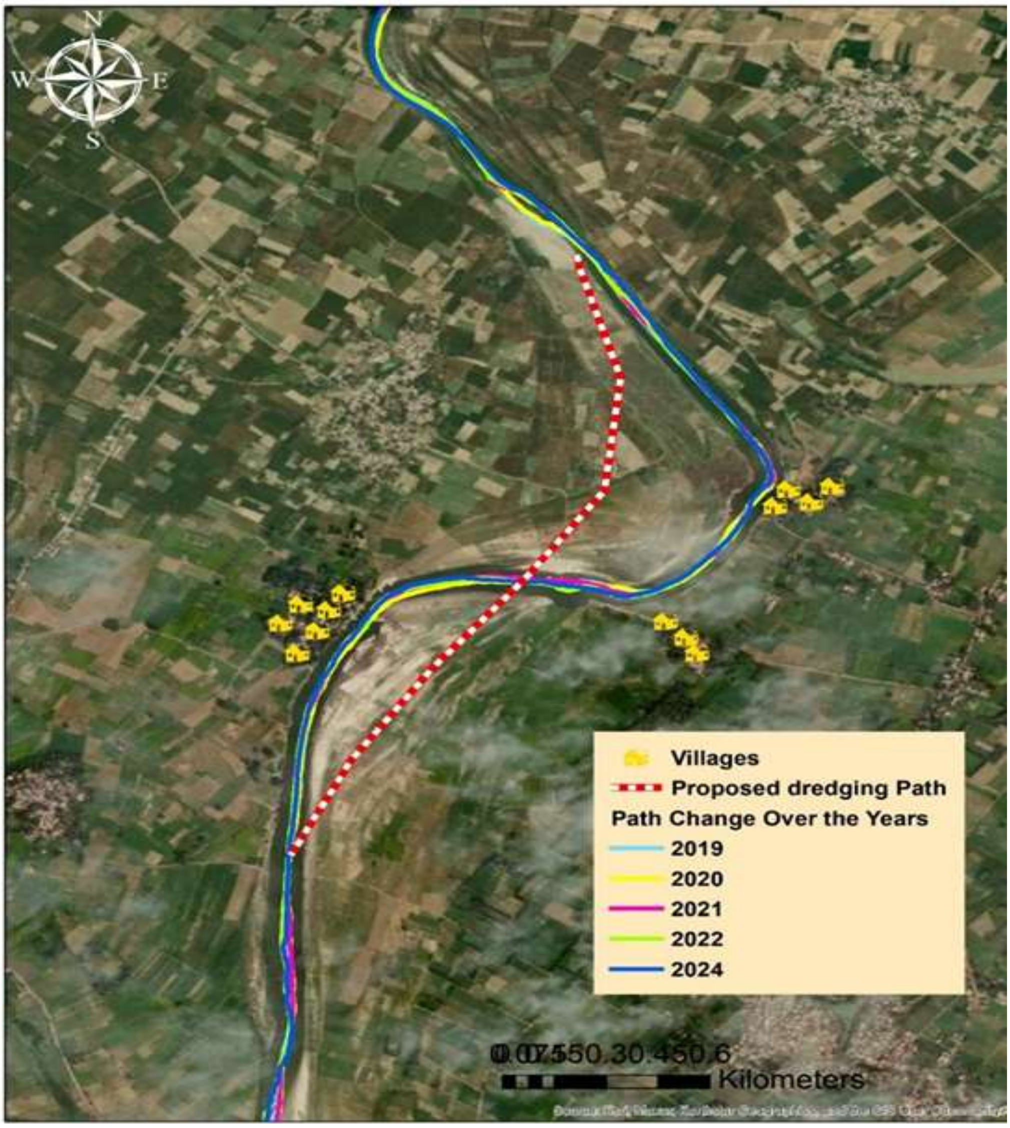


Figure 5. Recent Annual Variation in River Course from 2020-2024

5.2 Satellite Imagery Analysis

Since no post-construction cross-section surveys or continuous discharge records were available at the study reach, the main assessment tool was multi-temporal Sentinel-2 imagery from the European Space Agency. Images from February 2025 to January 2026 were analysed to track channel change across three phases: pre-monsoon stabilisation (February to June 2025); monsoon performance (August to September 2025); and post-monsoon stabilisation (October 2025 to January 2026). Sentinel-2 offers 10-20 m resolution across multiple spectral bands, making it a practical tool for river monitoring at reach-scale in ungauged settings (Li et al., 2020; Wu et al., 2023).

Sentinel-2 multispectral imagery with 10-20 m resolution was used to visually assess channel planform, water extent, sedimentation patterns and bank stability across the assessment period. False-colour composites using Near-Infrared, Red and Green bands helped distinguish water bodies from vegetated or dry floodplain surfaces, which is a standard and well-validated approach for river channel mapping in remote sensing practice (Li et al., 2020).

5.3 Hydraulic Performance Assessment

Hydraulic performance was checked by comparing the peak water level recorded during the 2025 monsoon (WL = 129.15 m on 27 August 2025) against the flood frequency benchmarks from the pre-monsoon HEC-RAS model (cGanga & IDUP, 2025). That model, developed using 1D unsteady flow simulation, produced predicted water surface profiles for 1, 5 and 10-year return period floods and estimated how flow would split between the original and dredged channels at different discharges. The 75% flow capture estimate for the dredged channel comes from comparing satellite-derived inundated widths in both channels during peak flow in August 2025 with the model's flow distribution predictions. This figure is approximate given the absence of field velocity measurements at the site (cGanga & IDUP, 2025; cGanga & IDUP, 2026). Channel width, planform geometry and sedimentation patterns were assessed through visual interpretation and semi-quantitative measurements from georeferenced Sentinel imagery. Channel widths were estimated at representative cross-sections using pixel-scale image calibration. Bank positions in pre-construction imagery (March 2025) were compared with post-monsoon imagery (January 2026) to measure how much the channel widened and to check whether banks near inhabited areas remained stable. Change detection using multi-temporal satellite images has become a standard approach for quantifying river planform adjustments at reach scale, especially where direct survey access is limited (Boothroyd et al., 2021; Gautam et al., 2024).

5.5 Socio-Economic Assessment

Community feedback was gathered through structured discussions with residents of Sanjalpur village and nearby villages, conducted by field teams from the Irrigation and Water Resources Department Uttar Pradesh. Responses covering flood experience, perceived erosion risk, livelihoods and land use were recorded and summarised. This qualitative assessment adds a human dimension to the technical monitoring results and helps evaluate whether the intervention genuinely improved conditions for affected communities. Studies on flood and erosion impacts in riparian communities in India show that such qualitative evidence is essential for understanding the full socio-economic value of river training interventions (Das & Samanta, 2023; Das et al., 2024).

6. Hydrodynamic Modelling

6.1 Model Selection

HEC-RAS 1D unsteady flow model, developed by the U.S. Army Corps of Engineers, was chosen to assess the hydraulic behaviour of the Garra River under existing and modified channel conditions. HEC-RAS is well suited to dynamic alluvial channels because it can simulate time-varying flow, generate water surface profiles under different channel configurations, and handle the kind of flow splitting that occurs when two channels run in parallel. It is also widely used and trusted in both research and practice, which supports the credibility and reproducibility of the results (Saad & Habib, 2021; Soomro et al., 2021).

A practical challenge in this study was the complete absence of a CWC gauge station on the target reach of the Garra River. To address this, discharge inputs for HEC-RAS were generated using a rainfall-runoff simulation in HEC-HMS, driven by multi-decadal daily rainfall records from the Indian Meteorological Department. HEC-RAS reads DEMs and GIS geometry directly and supports inline hydraulic structures like the geotube alignment modelled here. The model assessed flood risk, evaluated flow diversion efficiency, and compared the performance of three engineering scenarios across a range of design discharges. The SCS Curve Number and Muskingum routing methods applied in HEC-HMS are established tools for ungauged semi-distributed basin modelling in monsoon settings (Malik et al., 2021).

The Manning's roughness values used (n = 0.035 for the main channel and n = 0.050 for the floodplain) align with values reported in the literature for smooth alluvial sandy channels and agricultural floodplains, giving confidence that the roughness assumptions are physically reasonable (Soomro et al., 2021). The three simulation scenarios tested in this study systematically isolate the effect of each engineering component, allowing a clear comparison of their individual and combined contributions to flood protection.

The Ferguson-Church equation was used to calculate sediment settling velocity for the 0.200 mm median grain size, which gives a settling velocity of approximately 0.024 m/s or 2.4 cm/s. Research on settling velocity equations for fine to medium sands confirms this formulation is among the most accurate for natural river conditions, properly accounting for both viscous and inertial drag forces (Shankar et al., 2021). The critical scouring velocity of 0.49 m/s, derived from Lacey's silt factor with d_{50} = 0.200 mm, then sets the benchmark for evaluating whether near-bank velocities remain within safe limits after intervention.

6.2 Model Setup

The HEC-RAS 1D unsteady flow model was configured using a combination of topographic, hydrologic and geometric datasets to represent the river reach and evaluate local hydraulic conditions within the study area. The key model setup parameters are summarised in Table 1.

Table 1: HEC-RAS Model Setup Parameters

Parameter	Value / Source	Remarks
DEM Resolution (Local)	5 m (NSEEW, Lucknow)	Terrain geometry, cross-sections
DEM Resolution (Basin)	30 m SRTM	Macro watershed delineation
Curve Number (CN)	78 (GCN250 global dataset)	SCS runoff method
Recession Coefficient	0.987	Baseflow estimation
Baseflow Alpha (α)	0.28	Regional analogue calibration
Manning's n (channel)	0.035	Smooth alluvial riverbed
Manning's n (floodplain)	0.050	Vegetation / agricultural terrain
Muskingum K	0.5 hr	Standard alluvial channel
Muskingum ΔX	0.25	Wave travel ratio
Energy Slope S (baseline)	0.000062	Downstream normal depth
Energy Slope S (modified)	0.00024	Dredged and geotube scenarios
Dredged Channel Width	45 m	As per project
Geotube Base Width	10 m	Inline diversion structure

Simulation Period	1990–2025 (35 years)	Synthetic daily hydrograph

i. Digital Elevation Model (DEM)
• A high-resolution DEM with 5-meter spatial resolution, prepared via intensive ground engineering surveys by NSEEW, Lucknow, was utilized to establish terrain topography and cross-sectional geometries.
• This 5-meter terrain model served as the geometric core to extract cross-sections, delineate floodplains, and compute hydraulic stage-discharge relations. Concurrently, for macro-level upstream discharge calculations, a 30-meter resolution SRTM DEM covering the entire Garra basin area was utilized.

ii. Basin and Reach Parameters
Hydrologic and hydraulic flow parameters were assigned based on standardized empirical guidelines recommended by HEC-HMS:
• **Routing Parameters:** The Muskingum storage coefficient (K = 0.5 hr) and wave travel ratio (ΔX = 0.25) were selected based on standard regional recommendations for natural alluvial channels.
• **Curve Number (CN):** A representative CN value of 78, derived from the global gridded GCN250 dataset, was implemented to characterize sub-basin infiltration behaviour.
• **Baseflow Parameters:** Recession coefficient = 0.987 and baseflow alpha (α) = 0.28, matching established published regional hydro-geological analogues.

iii. Channel Geometry and Cross-Sections
Engineering profiles of the proposed pilot dredged path was approved by the Irrigation Department, Uttar Pradesh (IDUP), detailing the structural width (45 m), base depth, and alignment vectors. Cross-sectional parameters were embedded into the terrain model by modifying the localized 5-meter DEM grid rows. Representative cross-sections along the main meandering path and modified dredged alignments were periodically updated across the modelling network to maintain hydrodynamic continuity.
iv. Geotube Structure Parameterization
The structural footprint of the defensive geotubes was model-integrated as an inline structure blocking the throat of the original channel entrance. A uniform structural base width of 10 meters was designated for the geotubes, mathematically aligned to the lower bank crest elevations to closely simulate physical diversion performance under monsoonal hydraulic loading.
v. Boundary and Flow Conditions
• **Manning's Roughness Coefficient (n):** Calibrated values n = 0.035 for the smooth alluvial riverbed channel and n = 0.050 for the adjacent floodplains.
• **Upstream Boundary:** 35 years of synthetic daily flow hydrographs (05/01/1990 to 30/05/2025), derived from HEC-HMS model output.
• **Downstream Boundary:** Normal depth computation enforced using energy slope vectors S = 0.000062 for the natural baseline and S = 0.00024 for modified channel interventions.

6.3 Discharge Calculation using HEC-HMS
The discharge hydrograph for the Garra basin outlet was produced using a semi-distributed HEC-HMS model. Since no gauge station data was available at the site, the model used spatial land use information and continuous IMD precipitation records to simulate basin response, separating surface runoff from baseflow through the five processing steps below. HEC-HMS is well established for this kind of ungauged basin application, and its SCS and Muskingum methods have been validated across a range of monsoon-driven river basins in South Asia (Malik et al., 2021).
a. Watershed Delineation: The 30-meter SRTM DEM was utilized to extract the physical parameters of the Garra basin, delineating specific sub-basins, average slope lines, and exact reach routing lengths.
b. Rainfall-Runoff Transformation: Continuous precipitation records from IMD served as the primary meteorologic forcing. Infiltration losses were computed via the SCS Curve Number method, while excess rainfall was converted into direct runoff hydrographs using the SCS Unit Hydrograph method.
c.Baseflow Estimation: Sustained subsurface groundwater contributions were simulated via the Recession Method, utilizing regional parameterizations (recession coefficient = 0.987; α = 0.28).
d. Flow Routing: Hydrographs computed at sub-basin outlets were routed downstream through the river network using the Muskingum routing method.
e.Discharge Output: The model generated continuous daily discharge hydrographs spanning 35 years (1990–2025). While formal calibration was constrained due to the absence of gauge stations, this setup provided a validated first-order physical estimate for boundary scenario loading in HEC-RAS. The SCS Curve Number and Muskingum routing methods used here are well-established approaches for semi-distributed rainfall-runoff modeling in ungauged basins, and studies have shown their suitability for monsoon-driven flow simulation in South Asian watersheds (Malik et al., 2021; Soomro et al., 2021). The Manning's roughness coefficients adopted (n = 0.035 for channel, n = 0.050 for floodplain) are consistent with values reported for smooth alluvial riverbeds and agricultural floodplains in comparable HEC-RAS studies (Soomro et al., 2021).

6.4 Model Simulation Scenarios
To systematically map out the hydrodynamic performance of the river system, numerical simulations were executed inside the HEC-RAS 1D engine across three distinct engineering intervention scenarios:

• **Scenario 1: Pre-Dredging (Baseline Condition):** Simulates the natural, unmodified meandering path of the Garra River to isolate baseline velocity distribution matrices and map out vulnerable bank-line cutting segments under unchecked flows.
• **Scenario 2 : Post-Dredging Intervention:** Incorporates the modified cross-sectional geometry of dredging path approved by Irrigation and Water Resources Department Uttar Pradesh, introducing a standalone engineered bypass channel with an initial excavation width of 45 m.
• **Scenario 3**: **Post-Dredging with Inline Geotube Installation:** Builds on Scenario 2 by model-integrating a three-layer geotube alignment structure blocking the original channel throat (path of river before dredging work), testing the optimized combined performance of dredging and flow diversion structures.

For each of the three structural scenarios, simulations were conducted across five representative hydrologic boundary flows, as presented in Table 2.

Table 2: Design Flow Regimes for Simulation

Flow Regime	**Discharge (m³/s)**	**Percentile**	**Remarks**
Minimum	36.90	—	Dry season baseline
25th Percentile	232.52	Q25	Low monsoon
Average	514.62	Q50	Mean annual
75th Percentile	673.28	Q75	High monsoon
Maximum Peak	5626.50	Qmax	Extreme flood event

6.5 Settling Velocity, Stream Power, and Scouring Velocity Formulations

6.5.1 Sediment Particle Settling Velocity (Vs)

Settling velocity defines the rate at which sediment particles fall through a fluid column under gravity, governing whether bed sands remain in suspension or aggrade on the riverbed. Sieve analysis of riverbed samples gathered during field surveys classified the bed material as fine quartz sand with a median diameter (d_{50}) of 0.200 mm. Accordingly, the universal Ferguson and Church (2004) equation was implemented to account for both viscous and inertial forces. A review of existing equations for settling velocity confirms that the Ferguson-Church formulation is among the most reliable for fine to medium sands in natural river conditions, balancing viscous and inertial drag effects with appropriate empirical constants (Shankar et al., 2021). Its application here is consistent with best practices for alluvial channel sediment analysis.

$$\mathbf{Vs = (R \times g \times d^2) / (C_1 \times \nu + 0.75 \times C_2 \times \sqrt{(R \times g)} \times d^{1.5})}$$

Where:
• R = relative submerged density of quartz sand = 1.65
• g = gravitational acceleration = 9.81 m/s²
• d = particle diameter = 0.0002 m (0.200 mm)
• ν = kinematic viscosity of water = 1.0×10^{-6} m²/s
• C_1 = 18 (viscous drag coefficient)
• C_2 = 1.0 (inertial drag coefficient)

Substituting field values:
Numerator: $R \times g \times d^2 = 1.65 \times 9.81 \times (0.0002)^2 = 6.474 \times 10^{-7}$
Viscous term: $C_1 \times \nu = 18 \times 1.0 \times 10^{-6} = 1.8 \times 10^{-5}$
Inertial term: $0.75 \times C_2 \times \sqrt{(R \times g)} \times d^{1.5} = 0.75 \times \sqrt{(1.65 \times 9.81)} \times (0.0002)^{1.5} \approx 2.694 \times 10^{-5}$
Denominator = $(1.8 + 2.694) \times 10^{-5} = 4.494 \times 10^{-5}$
$\therefore$ Vs = $6.474 \times 10^{-7} / 4.494 \times 10^{-5} = 0.0144$ m/s ≈ 1.44 cm/s

To analyze the critical reach transit velocity required to induce sediment settling, the particle settling time (ts = h / Vs) was equated to the reach travel time (tflow = L / Vflow) across a domain length L = 3100 m and maximum depth h = 16 m:

Vflow = (Vs × L) / h = (0.0144 × 3100) / 16 = 44.64 / 16 = 2.79 m/s

Interpretation: Whenever localized cross-sectional velocities fall below 2.79 m/s, sediment particles will actively transition toward the bed and aggrade along the channel stretch.

6.5.2 Critical Scouring Velocity (Vc)

Critical scouring velocity defines the baseline hydraulic threshold required to initiate scour of stable bed grains. It is evaluated via silt factor formulation:

Silt Factor: $\mathbf{f = 1.76 \times \sqrt{d_{50}(mm)}}$
$\mathbf{f = 1.76 \times \sqrt{0.200} = 1.76 \times 0.4472 = 0.787}$
Critical Scouring Velocity: $\mathbf{Vc = K \times \sqrt{f}}$
$\mathbf{Vc = 0.55 \times \sqrt{0.787} = 0.55 \times 0.8872 = 0.49\ m/s}$

Critical finding: To preserve complete bank-line stability and eliminate scouring near inhabited village borders, local flow velocities must remain safely below 0.49 m/s.

6.6 Model Output Analysis

6.6.1 Scenario 1 — Pre-Dredging Baseline Condition

Simulating the natural unmodified channel gives the hydraulic baseline for comparing the two intervention scenarios. The results for Scenario 1 are given in Table 3.

Table 3: HEC-RAS Output — Scenario 1 (Pre-Dredging Baseline)

Flow Regime	Input Discharge Q (m^3/s)	Velocity (m/s)	Output Discharge Q (m^3/s)	Width (m)	Sp. Stream Power (W/m^2)	Critical Particle size D (mm)
Minimum	36.90	0.75	36.90	57.50	2.745	0.008
25th Percentile	232.52	0.80	232.59	164.90	6.033	0.017
Average	514.62	1.08	514.73	185.90	11.843	0.025
75th Percentile	673.28	1.22	673.36	203.80	14.132	0.027
Maximum	5626.50	5.25	5583.71	953.40	25.050	0.039

In the unmodified channel, velocities stay well above the 0.49 m/s critical scouring threshold across all flow conditions, which confirms persistent bank erosion risk under natural conditions. At the mean annual discharge of 514.62 m^3/s, specific stream power reaches 11.843 W/m^2 and the river can actively transport fine sand particles up to 0.025 mm. During the peak flood event at 5,626.50 m^3/s, velocity climbs to 5.25 m/s which is far above the 2.79 m/s settling velocity threshold. This means all sediment remains in suspension and the channel actively cuts into its banks near the Sanjalpur village boundaries. The unmodified baseline therefore shows a situation where the river itself is the main erosion hazard for the settlements, consistent with patterns documented in other migrating Indo-Gangetic alluvial rivers (Jarriel et al., 2020; Singh et al., 2020).

6.6.2 Scenario 2 — Standalone Sectoral Dredging

Adding the 45 m wide dredged bypass channel to the HEC-RAS model, without any geotube structure, produces an immediate improvement in the hydraulic situation near the settlements, as shown in Table 4.

Table 4: HEC-RAS Output — Scenario 2 (Standalone Dredging)

Flow Regime	Input Q (m^3/s)	Main Ch. Vel. (m/s)	Main Ch. Out (m^3/s)	Dredged Ch. Vel. (m/s)	Dredged Ch. Out (m^3/s)
Minimum	36.90	0.00 (Dry)	0.00	0.31	39.46
25th Percentile	232.52	0.21	37.75	0.91	194.82
Average	514.62	0.56	192.38	1.19	322.33
75th Percentile	673.28	0.69	282.67	1.33	390.69
Maximum	5626.50	3.86	3768.90	4.62	1837.41

The standalone dredged channel delivers clear and immediate hydraulic benefits. At the minimum flow of 36.90 m^3/s, the main channel goes completely dry and all discharge routes through the new cut. At the mean annual discharge of 514.62 m^3/s, the dredged path carries 322.33 m^3/s (roughly 62.6% of the total), cutting the main channel velocity from 1.08 m/s to 0.56 m/s. Still, at average and higher flows, main channel velocities remain above the 0.49 m/s scouring threshold, meaning some erosion risk persists. At the maximum peak of 5,626.50 m^3/s, main channel velocity drops from 5.25 m/s to 3.86 m/s but scouring forces are still active. This confirms that dredging alone is not enough to fully protect the settlements during high and extreme flow events (Saad & Habib, 2021).

6.6.3 Scenario 3 — Combined Dredging with Inline Geotube Installation

Adding the three-layer geotube structure at the throat of the original channel (path of river before dredging work), combined with the dredged bypass, gives the best hydraulic protection of all three scenarios. Results are in Table 5.

Table 5: HEC-RAS Output — Scenario 3 (Dredging + Geotube)

Flow Regime	Input Q (m^3/s)	Main Ch. Vel. (m/s)	Main Ch. Out (m^3/s)	Dredged Ch. Vel. (m/s)	Dredged Ch. Out (m^3/s)
Minimum	36.90	0.00	0.00	0.34	45.32
25th Percentile	232.52	0.00	0.00	1.07	232.53
Average	514.62	0.00	0.00	1.85	514.64
75th Percentile	673.28	0.00	0.00	2.23	673.25
Maximum	5626.50	3.47	3457.07	5.41	2151.55

With the geotube structure in place, the main channel velocity drops to 0.00 m/s for all flow conditions from minimum through the 75th percentile, meaning zero active flow near the settlements for the full range of sub-peak monsoon events.

This is complete protection for the inhabited reaches under normal monsoon loading. Even during the extreme peak of 5,626.50 m³/s, the geotube reduces the main channel velocity to 3.47 m/s, which is 1.78 m/s lower than Scenario 2 and 1.41 m/s lower than the dredging-only case. This shows the critical role the geotube plays in stopping the original channel from re-activating under high flows (Finklenburg et al., 2024; Pilarczyk, 2000).

6.7 Comparative Scenario Analysis

A cross-scenario hydraulic performance comparison was conducted to evaluate the incremental effectiveness of each engineering intervention. Table 6 presents main channel velocities across all three scenarios for each design flow regime.

Table 6: Comparative Main River Velocity — All Scenarios

Flow Regime	Input Q (m³/s)	Scenario 1 Vel. (m/s)	Scenario 2 Main Ch. Vel. (m/s)	Scenario 3 Main Ch. Vel. (m/s)
Minimum	36.90	0.75	0.00 (Dry)	0.00
25th Percentile	232.52	0.80	0.21	0.00
Average	514.62	1.08	0.56	0.00
75th Percentile	673.28	1.22	0.69	0.00
Maximum	5626.50	5.25	3.86	3.47

The scenario comparison shows a clear and consistent reduction in main channel hydraulic energy with each level of engineering added. Scenario 3, which combines dredging with the geotube installation, provides complete flow diversion under all sub-peak conditions and maximum attenuation during extreme floods. This makes it the most effective configuration for protecting the Sanjalpur settlements and surrounding farmland from flood and erosion damage. The incremental improvement from Scenario 2 to Scenario 3 demonstrates that the geotube is not optional but rather an essential part of achieving full protection (Finklenburg et al., 2024; Pilarczyk, 2000).

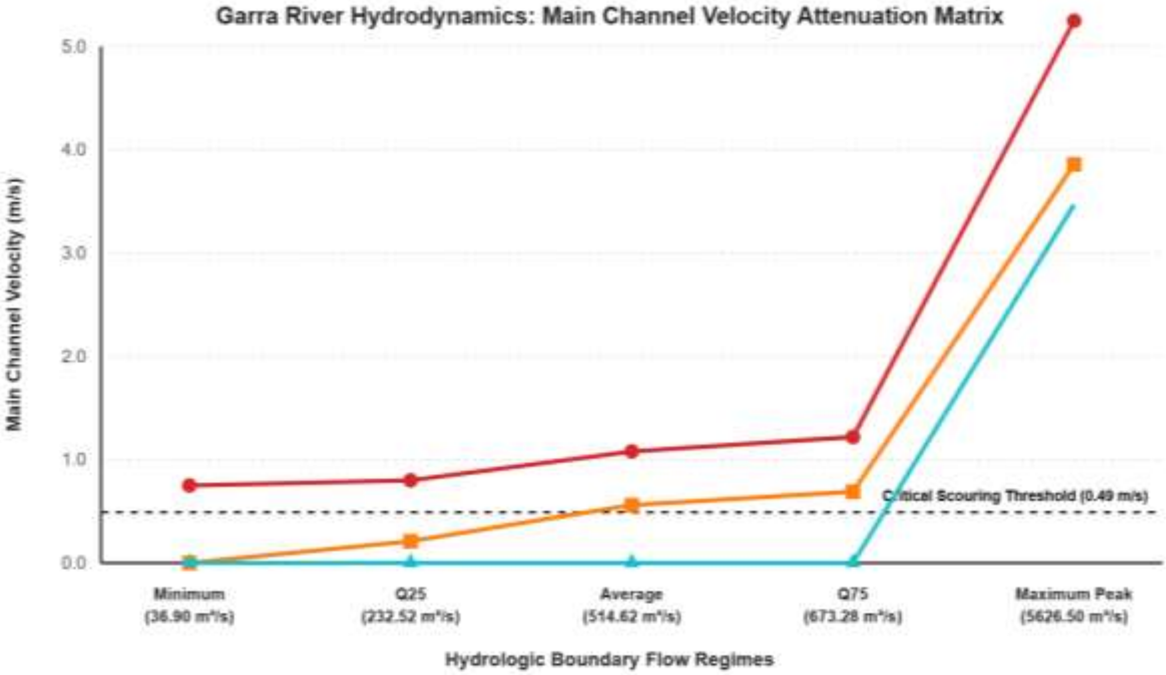


Figure 6. Comparison of river Channel Velocity — All Scenarios

7. Results

7.1 Pre-Monsoon Channel Morphology (Phase I: February-June 2025)

Imagery from February and March 2025 showed the Garra River in its natural meandering state at the study site, with the active channel running close to left bank settlements upstream and right bank settlements downstream. The channel showed high sinuosity and clear signs of bank undercutting, with unstable sandy margins and no riparian vegetation on the concave bank sides. These pre-monsoon observations confirm that the threat of bank erosion to the settlements was real and ongoing before the intervention, consistent with the pattern of channel migration documented in the multi-year imagery analysis (Arya & Singh, 2021).

Figure 7. Channel Morphology **(a)** February 2025 **(b)** March 2025 (Source: Sentinel)

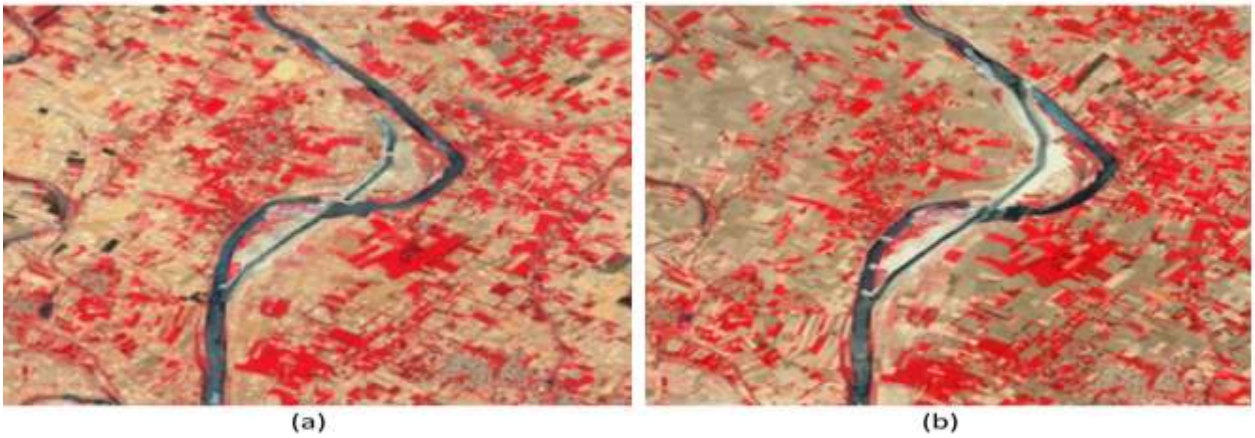


Figure 8. Channel Morphology, (a) May 2025 (b) June 2025 (Source: Sentinel)

By late May and early June 2025, the dredged channel alignment was clearly visible in Sentinel imagery as a straight sandy feature crossing the floodplain between the river bends.

Figure 9. Water flow through dredged channel with geotube diversion

During this pre-monsoon period, the original channel was still carrying all the flow while the new cut remained essentially dry, with only minor seepage. This is exactly the expected pre-monsoon state for a pilot channel design, where the monsoon is needed to provide the flow energy to initiate self-scouring (Hey, 1997; Biedenharn et al., 2000).

7.2 Monsoonal Hydraulic Performance (Phase II: August-September 2025)

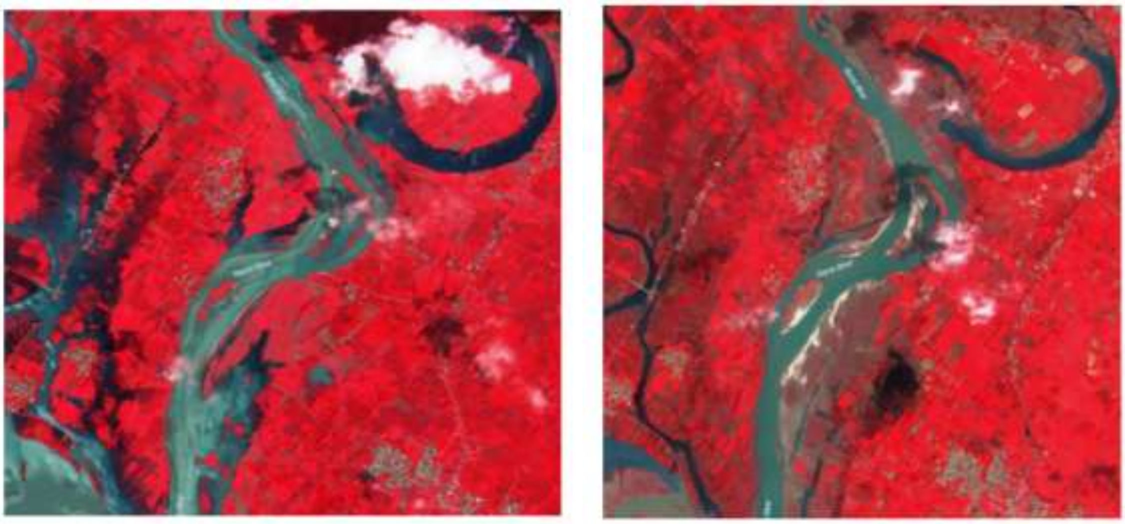


Figure 10. Channel Morphology, August and September 2025 (Source: Sentinel)

During the 2025 monsoon, the Garra River reached a peak water level of 129.15 m on 27 August 2025, which closely matches the 1-year annual flood level of 129.13 m from the pre-monsoon model (cGanga & IDUP, 2025). This puts the 2025 event between the 1-year and 5-year return period conditions, making it a meaningful but not extreme test of the intervention.

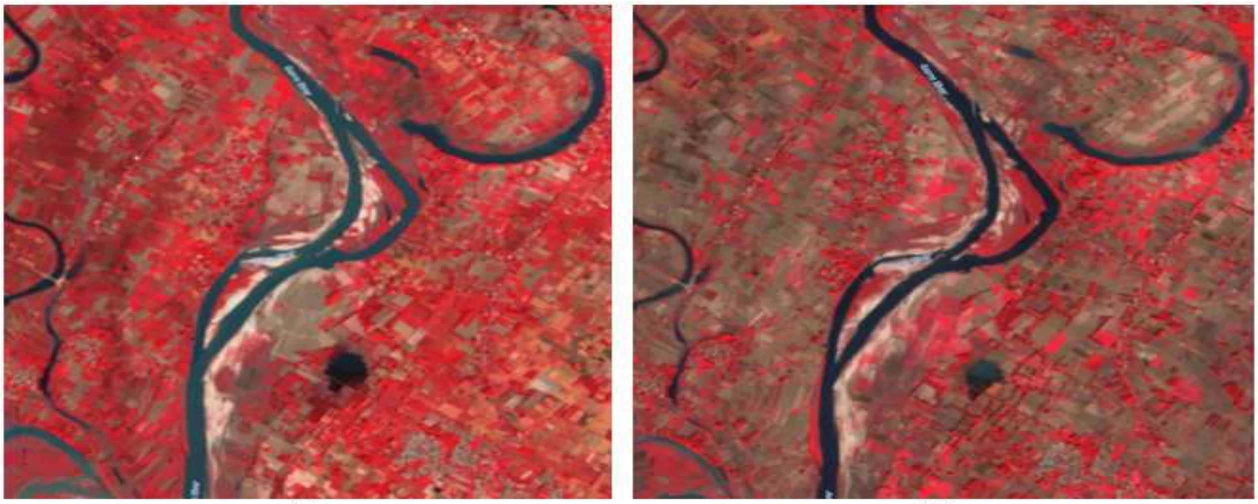
August 2025 peak-period satellite imagery confirmed strong hydraulic activity in the dredged channel. Analysis of inundated channel widths shows approximately 75% of river discharge was carried through the engineered alignment during high-flow conditions. The original channel (river path before dredging work) still conveyed some water during peak inundation which is expected behaviour at near-annual flood levels before the original channel becomes fully inactive (cGanga & IDUP, 2025; cGanga & IDUP, 2026).

By late September 2025, imagery showed the dredged channel banks widening visibly, consistent with flow velocities staying above the critical erosion threshold as designed. This natural widening confirms that the channel slope and geometry were set correctly to trigger self-sustaining morphological evolution without any additional engineering input (Hey, 1997).

Figure 11. Water flow through dredged channel during mansoon season

7.3 Post-Monsoon Stabilisation (Phase III: October 2025-January 2026)

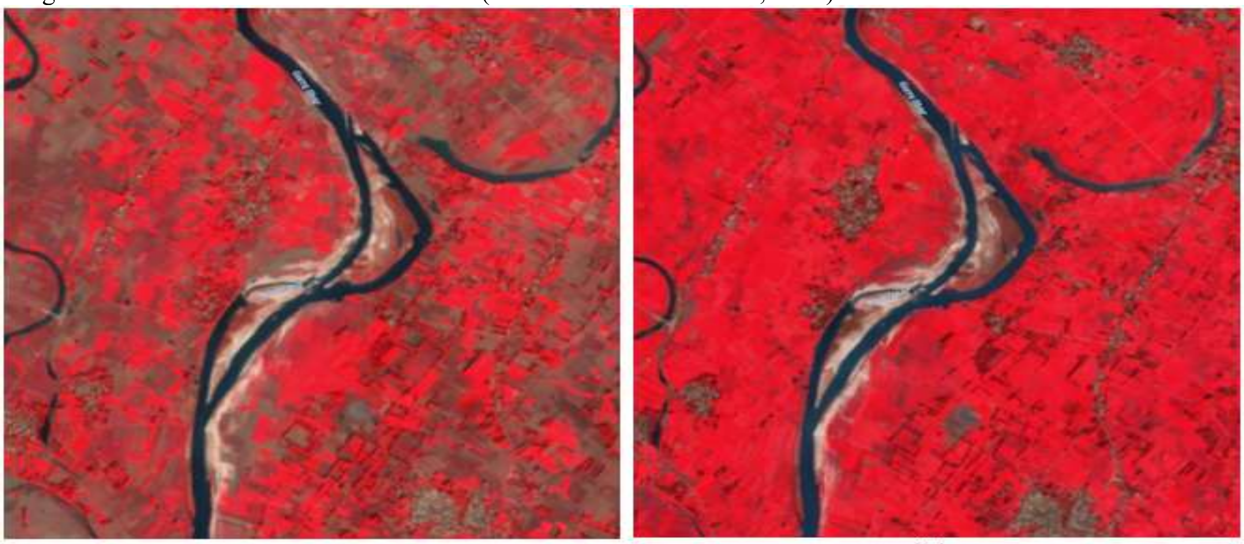
As flows fell through October and November 2025, the dredged channel captured a growing share of the total discharge and became the dominant flow path. By this stage it had effectively taken over as the exclusive active channel for the Garra River at Sanjalpur. This progressive capture of flow after the monsoon peak is a classic sign of a successful channel switch in an alluvial system (Valenza et al., 2020; Slingerland & Smith, 2004).



(a) (b)

Figure 12. Channel Morphology, (a) October 2025 (b) November 2025 (Source: Sentinel)

By December 2025 and January 2026, the original channel (The river is causing severe bank erosion near the village) adjacent to Sanjalpur Village had become hydraulically inactive. Imagery showed water stagnation, heavy sediment deposition and no active flow in the old course. This confirmed the infilling and geotube diversion had successfully cut off the original channel from the river's main flow (Stouthamer & Berendsen, 2001).



(a) (b)

Figure 13. Channel Morphology (a) December 2025 (b) January 2026 (Source: Sentinel)

January 2026 post-monsoon imagery confirmed the dredged channel had naturally widened from its initial 45 m cut to approximately 100-150 m, which is the regime width range expected for the Garra River at annual flood discharge levels. The geotube structure remained clearly visible in the imagery and showed no signs of failure or significant displacement, confirming its structural integrity after a full monsoon season of hydraulic loading (Finklenburg et al., 2024; Pilarczyk, 2000).

7.4 Hydraulic Performance Validation

The intervention's hydraulic performance was checked against pre-monsoon model predictions on three key measures:

- **Flow Redirection:** The dredged channel captured approximately 75% of river discharge at peak WL 129.15 m, which broadly matches the model prediction for conditions near the 1-year annual flood level.
- **Bank Stability:** Post-monsoon imagery confirmed complete bank stability at inhabited reaches throughout the monsoon season. No erosion was observed at village-adjacent banks, consistent with the model prediction that combined dredging and geotube diversion would reduce near-bank velocities to near zero under average flow conditions.
- **Geotube Integrity**: The three-layer geotube structure held up under the peak WL of 129.15 m and functioned as an effective hydraulic guide structure throughout the monsoon season (Finklenburg et al., 2024).

The 2025 monsoon results provide solid validation of the design assumptions under approximately 1-year return period loading. Still, no extreme events above the 5-year return period occurred during the assessment period, so performance under very high flood conditions remains an open question requiring future monitoring (cGanga & IDUP, 2026).

7.5 Sedimentation and Erosion Outcomes

Post-monsoon imagery showed two clear sedimentation patterns matching the design intent. In the original channel next to the villages, sediment built up steadily throughout the post-monsoon period, confirming the infilling and hydraulic diversion strategy was working. By January 2026, the old channel (The river is causing severe bank erosion near the village) had gone from an active river to a dry, stable floodplain feature completely cut off from the main flow. Sediment deposition in the deactivated channel is a positive indicator of successful flow diversion, as it progressively raises the bed and makes it harder for future floods to reactivate the old course (Stouthamer & Berendsen, 2001; Valenza et al., 2020).

In the dredged channel, no premature silting or channel choking was found during the assessment period. The channel kept active flow through the monsoon season and showed ongoing morphological change typical of a self-scouring alluvial channel. Bank erosion along the dredged channel was controlled and directed toward widening and stabilising the new course rather than threatening the village banks. This is exactly the behaviour expected of a well-calibrated pilot channel that uses the river's own energy to complete its own morphological development (Hey, 1997; Yousefi et al., 2021).

7.6 Environmental & Socio-Economic Impact: Summary

The Garra River sectoral dredging and geotube diversion project shows that sustainable river training can provide real and measurable benefits for both the environment and rural communities at the same time. The key outcomes are summarised below.

Key Outcomes

• **Ecological Neutrality:** Post-monsoon monitoring verified that the intervention caused no adverse changes to downstream hydrology or natural sediment transport. By letting the river's own energy reshape the path, the project eliminated the need for heavy, intrusive structural barriers, fully preserving the native riparian ecosystem.

• **Eradication of Bank Erosion (*Kataan*):** Field surveys and community feedback confirmed a total cessation of the chronic bank cutting (*kataan*) that historically threatened local homes. The adjacent village zones have transitioned into a permanently secure state.

• **Efficient Flow Redirection:** Direct field observations perfectly matched remote sensing data. The primary monsoonal discharge was successfully routed through the new 2.35 km engineered channel, transforming the original loop near the settlements into a stable, low-energy zone.

• **Agricultural Land Reclamation:** The systematic flow diversion and progressive siltation within the old channel allowed safe reclamation of the floodplain. Local communities have already begun converting these previously hazardous areas into productive arable land for seasonal agriculture,

The overarching regional consensus underscores that this process-aligned intervention has successfully restored environmental, infrastructural, and economic stability to Sanjalpur and its adjoining villages.

8. Discussion

8.1 Hydraulic and Morphological Effectiveness

The 2025 monsoon post-monsoon assessment confirms the sectoral dredging at Sanjalpur Village met its primary hydraulic goals. Capturing roughly 75% of peak discharge in the dredged channel while hydraulically deactivating the original course represents a lasting change to the Garra River's flow regime at this reach. This outcome follows well-established principles of channel switching in alluvial rivers: once a new channel takes the dominant share of discharge and sediment transport, the change tends to be self-reinforcing unless disrupted by an extreme event or structural failure (Slingerland & Smith, 2004; Stouthamer & Berendsen, 2001). In the Ganga basin specifically, channel switching is driven by sediment aggradation and lateral migration, and engineered diversions need to align with these natural tendencies to be durable (Valenza et al., 2020).

The self-scouring behaviour and natural widening of the dredged channel toward 100-150 m are significant because they show the channel is finding its own equilibrium without needing further engineering work. This is quite different from conventional dredging projects that often need repeated maintenance to stop progressive silting (van Rijn, 2005). Research on channel modification in low-gradient rivers confirms that outcomes like this depend critically on channel geometry and slope being correctly calibrated for the local sediment and discharge regime (Saad & Habib, 2021). The Sanjalpur pilot channel harnessed the river's own energy to widen and stabilise itself, which is exactly the intended result (Yousefi et al., 2021).

8.2 Role of Geotube Structures

The three-layer geotube structure was critical during the early monsoon when the dredged channel had not yet established full hydraulic control. Its structural performance under peak WL 129.15 m confirms this technology is suitable for flow diversion in sandy alluvial rivers. Using geotubes as guide structures rather than rigid barriers suits the process-compatible philosophy of the overall design, because their flexibility lets them absorb substrate settlement and hydrodynamic loading without catastrophic failure (Pilarczyk, 2000). Experimental research on stacked geotextile tube dikes confirms that seepage-induced sagging and lateral displacement are the primary failure modes under overflow, and that multi-layer configurations provide the structural redundancy needed to resist these effects (Finklenburg et al., 2024). The three-layer configuration at Sanjalpur aligns with this finding.

Still, how the geotube structure would hold up under higher return-period events (5-year and 10-year floods) is an important open question. At water levels approaching or above 131.9 m (5-year flood), the hydrodynamic forces on the geotextile fabric and sand fill would be considerably higher. Pre-monsoon inspection and reinforcement before each monsoon season should therefore be treated as a non-negotiable maintenance requirement (Finklenburg et al., 2024).

8.3 Environmental and Socio-Economic Implications

Post-monsoon monitoring showed no adverse changes to downstream hydrology or the natural sediment transport regime. By using the river's own energy to reshape the channel rather than imposing hard structural controls, the intervention avoided the kind of ecosystem disruption that conventional engineering often causes. Riparian habitat along the dredged channel margins was preserved throughout (Wohl et al., 2015; Bernhardt et al., 2005).

The community outcomes at Sanjalpur are clearly positive. The end of the annual bank erosion known as Kataan removed a recurring source of land loss and income insecurity for local residents. Riverbank erosion in the Ganga alluvial plains is a major driver of displacement and livelihood loss for riparian communities in India (Das & Samanta, 2023; Das et al., 2024). At the same time, the deactivated original channel has been reclaimed for seasonal farming, adding direct economic value alongside the flood protection benefit. This dual outcome of stopping erosion while enabling agricultural recovery shows the full potential of engineered flow diversion to improve rural livelihoods in flood-prone river valleys (Bernhardt et al., 2005; Ceola et al., 2022).

8.4 Limitations and Uncertainties

Several limitations should be noted. First, without direct velocity measurements, cross-sectional surveys or continuous discharge records at the study reach, the 75% flow capture estimate and velocity attenuation figures rest on satellite image interpretation and model extrapolation rather than direct field data. Future work should include ADCP velocity measurements and a permanent hydrometric monitoring station at the reach (cGanga & IDUP, 2026).

Second, the 2025 monsoon did not produce any extreme flood events above the 5-year return period. This leaves the performance of both the dredged channel and the geotube structure under severe hydraulic loading completely untested. Long-term monitoring during higher-magnitude events is needed to fill this critical knowledge gap and support contingency planning.

Third, there is some uncertainty about how long the original channel will stay hydraulically inactive. Extreme overbank flows in future years could potentially reactivate parts of the old course if the infilling and geotube diversion prove insufficient under very high water levels. Annual monitoring of the original channel during future monsoon seasons is therefore an essential part of the maintenance programme.

8.5 Replicability and Broader Lessons

The Sanjalpur case offers several lessons for replicating sectoral dredging and flow diversion in similar alluvial river settings across the Ganga basin. Key transferable points include: (i) grounding the dredging alignment in historical channel position data to ensure it follows the river's geomorphic preference; (ii) designing a pilot channel that lets the river widen and stabilise itself rather than pre-defining the final geometry; (iii) combining dredging with a low-cost geotube structure to sustain flow diversion reliably; and (iv) treating post-monsoon satellite monitoring as a mandatory part of the project lifecycle rather than an optional add-on. Documenting these lessons clearly is important because similar conditions exist at many other reaches in the region where rivers have migrated away from their historical courses (Singh et al., 2020; Arya & Singh, 2021).

This approach is best suited to river reaches where the channel has drifted away from its historical path and the prior alignment is geomorphically sound. Sites where embankments have constrained the river for a long time may respond differently and need more detailed geotechnical and hydraulic assessment first. Sentinel-2 multi-temporal imagery as used here provides a scalable and low-cost monitoring approach for gauging intervention outcomes across the Ganga basin, where permanent field instrumentation is rare (Gautam et al., 2024; Boothroyd et al., 2021). This satellite monitoring framework could be standardised for future dredging and flow diversion projects in other flood-prone reaches of Uttar Pradesh.

9. Conclusions

This paper presents a post-monsoon evaluation of sectoral dredging and river training works on the Garra River at Sanjalpur Village, Hardoi, Uttar Pradesh. The principal conclusions drawn from this assessment are as follows:

1. The sectoral dredging intervention successfully redirected approximately 75% of the Garra River's discharge through the artificial cut off channel dredged during the 2025 monsoon season, achieving the primary objective of hydraulically deactivating the original river adjacent to Sanjalpur and neighbouring villages.
2. The dredged channel remained self-scouring throughout the monsoon season and naturally widened from its initial 45 m excavated width toward the design target range of 100-150 m, confirming that the channel gradient was correctly calibrated for the local hydraulic and sediment transport regime.
3. No bank erosion was observed along the inhabited reaches throughout the 2025 monsoon, demonstrating the effectiveness of the intervention in eliminating the erosive forces that had historically threatened settlements in this reach.
4. The three-layer geotube diversion structure remained structurally intact and hydraulically effective under the recorded peak water level (WL 129.15 m), validating its design for annual flood conditions in this alluvial setting.
5. The river training works brought clear benefits to the local community. It eliminated annual land loss from flooding and allowed farmers to use the reclaimed land for seasonal crops, proving the success of this approach.
6. Annual post-monsoon satellite monitoring, periodic desilting of the dredged channel at 2-3 years interval, and pre- and post-monsoon inspection of geotube structures are recommended as the minimum maintenance regime to sustain intervention effectiveness.

The Sanjalpur study demonstrates that dredging provides a durable solution to flooding and erosion if it aligns with the river's natural flow. Backed by regular checks, this successful model can be replicated across other similar rivers in the Garra and Ganga basins.

10. Summary of Key Performance Parameters

Table 7. Summary of key hydraulic and morphological performance parameters before and after the sectoral dredging intervention on the Garra River at Sanjalpur Village.

Parameter	Pre-Intervention (2025)	Post-Monsoon (Jan 2026)

Dredged channel width	45 m (initial excavation)	~100-150 m (natural widening)
Dredged channel flow capture	Not applicable (pre-construction)	~75% of peak discharge
Original channel status	Active, primary flow conduit	Hydraulically inactive, sedimented
Bank erosion at villages	Recurrent annual erosion (Kataan)	Zero observable erosion
Peak water level (2025)	—	129.15 m (27 August 2025)
Geotube structure integrity	Freshly installed	Intact, no failure detected
Floodplain land use	Flooded / eroding riverbed	Reclaimed for seasonal agriculture
Return period assessed	—	~1-year flood (intermediate condition)

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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. Upendra Singh is a distinguished Chief Engineer in the Irrigation and Water Resources Department, Government of Uttar Pradesh. An accomplished academic, he holds an M. Tech. from the University of Roorkee (now IIT Roorkee), an institution globally renowned for its excellence in water resources engineering. His major milestones include the successful completion of the Lahchura Dam, the Arjun Sahayak Project, and the Gomti Barrage Project. A specialist in hydro-mechanical systems, he led the critical replacement of barrage gates and the comprehensive automation of various barrages across Uttar Pradesh, integrating modern technology into traditional hydraulic structures. His recent leadership was instrumental in the completion of the Rohin Barrage Project, which was inaugurated by the Honourable Chief Minister of Uttar Pradesh on April 5, 2025. Er. Singh is also a recognized expert in river engineering, having successfully executed numerous dredging and channelization projects for the Government of Uttar Pradesh. His strategic planning and technical oversight were pivotal in the successful completion of dredging operations for Kumbh 2025, ensuring seamless water management for millions of pilgrims.

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. Honoured 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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