SCIENTIFIC CULTURE
www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 1.1, (2026), pp. 4251-4583
Open Access. Online & Print

DOI: 10.5281/zenodo. 121126316

INTEGRATED ENGINEERING, ENVIRONMENTAL, AND SOCIO-ECONOMIC IMPACTS OF GANGA RIVER CHANNELISATION FOR MAHA KUMBH 2025, PRAYAGRAJ, INDIA: A CASE STUDY

Anil Garg (I.A.S.)[1], Upendra Singh[2], Sujeet Kumar Singh[3]*

[1] Principal Secretary, Irrigation and Water Resources Department, Government of Uttar Pradesh, India-226001.
[2] Chief Engineer, E&M Irrigation and Water Resources Department, Lucknow, Uttar Pradesh, India-226025.
[3] Executive Engineer, Tubewell Construction Division, Kanpur, Irrigation & Water Resources Department, Uttar Pradesh, India-208004.

Received: 01/12/2025
Accepted: 13/02/2026

Corresponding author: Sujeet Kumar Singh
(ee.barragemechvaranasi@gmail.com)

ABSTRACT

The Mahakumbh Mela is a powerful symbol of the confluence of India's diverse cultural and spiritual traditions. In 2025, it was organised at the sacred Triveni Sangam in Prayagraj, where the rivers Ganga, Yamuna, and the mythical Saraswati meet. The festival was held over 45 days, from Magh Purnima on 13 January to Mahashivaratri on 26 February, attracting more than 660 million pilgrims from India and abroad. The gathering included ascetics, saints, sadhus, sadhvis, kalpavasis, and devotees from all sections of society. Mahakumbh 2025 emerged as the largest human congregation in recorded history, surpassing the anticipated 450 million participants. Pilgrims took holy dip in the Ganga River, observing traditional rituals believed to cleanse sins and attain spiritual liberation. The event also had a significant economic impact, contributing an estimated ₹2 lakh crore to the national economy and increasing Uttar Pradesh's GDP by over 1 per cent. Extensive engineering and environmental measures were undertaken to ensure safety and sustainability. About 8 lakh cubic metres of dredged sand were reused on-site, avoiding external procurement costs of ₹68.89 crore and preventing large-scale vehicle movement, saving ₹107 crore in road maintenance to transport required sand. River channelisation unified three fragmented streams into a single flow, optimising pontoon bridge construction and saving an additional ₹62.4 crore. Overall, the dredging operations generated indirect savings of ₹238.29 crore against a project cost of ₹7.62 crore, yielding a net benefit of ₹230.67 crore translating into a return of approximately 3027 per cent or 30.27 times profit. Reclaimed land was effectively used for ghats, watch towers, and public facilities, enabling smooth management of the massive gathering. The unified river flow improved water depth and quality, ensuring safe and sacred bathing conditions. The restoration of fragmented streams also reinforced the river's natural course, promoting long-term environmental sustainability.

KEYWORDS: Mahakumbh-2025, Triveni Sangam, River channelization, Dredging, Water quality management, Ganga River

1. INTRODUCTION

The Mahakumbh Mela stands as one of India's most important spiritual gatherings, rooted in ancient Hindu traditions and mythological narratives. This sacred festival takes place at the Triveni Sangam in Prayagraj, where the Ganga, Yamuna, and mythological Saraswati rivers meet. The spiritual significance of this confluence comes from the legend of Samudra Manthan, the churning of the cosmic ocean that produced divine nectar believed to grant immortality. Tradition holds that drops of this sacred nectar fell at four locations across India: Prayag, Haridwar, Nasik, and Ujjain, making these sites centers of immense religious importance. Ritual bathing at these confluences is believed to cleanse sins and enable spiritual liberation, making Mahakumbh participation deeply meaningful for millions of Hindus worldwide (Sharma, 2025).

The Mahakumbh follows a unique 144-year cycle, distinguishing it from more frequent Ardh Kumbh and regular Kumbh celebrations. The 2025 Mahakumbh Prayagraj witnessed extraordinary attendance, with over 660 million pilgrims gathering over 45 days from January 13 to February 26, 2025.

Figure 1: The ritual nectar bath at Triveni Sangam in Prayagraj during the Maha Kumbh 2025 (open resources)

1.1. River Channelization and Management: Literature Context

Understanding river system dynamics provides essential context for engineering interventions undertaken for Mahakumbh 2025. Alluvial rivers like the Ganga naturally exhibit channel migration patterns driven by sediment transport, flow variations, and morphological processes. Research demonstrates significant channel morphology changes and migration patterns spanning multiple decades, revealing the dynamic nature of this major river system. Human-induced changes create hotspots of morphological transformation, particularly in regions experiencing intensive development. Human interventions substantially influence river behavior and adjacent land cover changes (Verma et al., 2021; Bulsara et al., 2020; Singh & Yadav, 2023). Recent research raises concerns about long-term sustainability of the Ganga River system, with evidence suggesting current drying trends represent unprecedented conditions not observed in the past 1,300 years. Dredging operations introduce ecological considerations, with studies revealing complex recovery patterns following dredging activities. Effective sediment management requires careful prediction and planning to ensure sustainable outcomes while minimizing adverse environmental consequences. Understanding sediment transport effects on flood hazards remains critical, with ongoing challenges in predicting and mitigating risks during extreme events (Chuphal et al., 2025; Bogan et al., 2024; Aldrees et al., 2022; Slater et al., 2023).

River engineering interventions can fundamentally alter downstream flood risk patterns and channel behavior. Anthropogenic modifications serve as significant drivers of flood risk change, requiring careful evaluation of approaches and their long-term consequences. Research demonstrates that flood control schemes can produce both intended benefits and unintended impacts. Comprehensive adaptation measures are needed to safeguard communities against evolving flood risks in changing climatic conditions (Raven et al., 2024; Nazeer et al., 2005; Carling et al., 2020; Yousefi et al., 2025; Rotimi et al., 2025).

1.2. Mass Gathering Management and Infrastructure

Managing mass religious gatherings presents unique challenges combining crowd dynamics, public health considerations, and infrastructure requirements. Previous Kumbh Mela events have provided valuable lessons regarding crowd movement patterns and social group influences on pilgrim behavior. Public health personnel face significant challenges during Mahakumbh events, requiring comprehensive planning to address health needs of millions of participants in concentrated timeframes. Development of religious tourism sites requires careful synthesis of sustainable destination planning approaches that balance economic development with cultural preservation and environmental protection (Subramanian & Verma, 2022; Kulkarni & Nath, 2025; Mishra & Maheshwari, 2024; Gambhir et al., 2021).

1.3. Water Quality Management in River Systems

Maintaining water quality in major river systems requires understanding multiple factors influencing chemical, physical, and biological characteristics of water bodies. Various natural and anthropogenic factors contribute to degradation, including industrial discharge, agricultural runoff, domestic waste, and hydrological alterations. Seasonal changes demonstrate temporal variability that necessitates adaptive management approaches. Spatial-temporal variations under human-induced land use changes reveal complex patterns requiring comprehensive monitoring. Water quality management approaches could potentially reduce future water scarcity cost-effectively through strategic interventions (Akhtar et al., 2021; Xu et al., 2019; Zhang et al., 2025; Liu et al., 2024; Popović et al., 2023).

1.4. Microplastic Pollution in Ganga

Microplastic contamination represents an emerging environmental concern in freshwater systems, including the Ganga River. Comprehensive reviews examine pathways, mechanisms, and mitigation strategies for addressing this pervasive contaminant. Distribution and impacts of microplastics in Indian freshwater systems require multidisciplinary analysis spanning sources, consequences, and removal approaches. Current trends highlight growing recognition of this pollution challenge. Seasonal variation and spatial distribution demonstrate complex dynamics governing contamination patterns. Assessment of sources and environmental risks reveals connectivity between freshwater and marine pollution (Singh et al., 2025; Kumar et al., 2025; Barman et al., 2023; Nair et al., 2024; Prasad et al., 2025; Mandal et al., 2025; Kumar et al., 2024; Singh et al., 2024).

1.5. Research Gap

Despite extensive research on river management, water quality, and mass gathering logistics, significant knowledge gaps remain regarding integrated approaches simultaneously addressing engineering, environmental, and socio-economic objectives. Limited documentation exists for comprehensive river engineering interventions specifically designed to support massive religious gatherings while maintaining ecological integrity and achieving economic efficiency. Absence of thorough cost-benefit analyses for sacred river management projects hampers evidence-based decision-making. The need for replicable models successfully combining engineering solutions with environmental restoration and socio-economic benefits remains largely unmet in existing literature (Chen et al., 2020; Ding & Yang, 2025).

2. STUDY AREA AND PRE-PROJECT CONDITIONS

The study area encompasses the Triveni Sangam in Prayagraj, Uttar Pradesh, where the Ganga and Yamuna rivers converge with the mythological Saraswati. This confluence represents a unique geographical feature characterized by distinct hydrological patterns and sediment dynamics. The region experiences a subtropical climate with pronounced seasonal variations affecting river discharge and water levels. During the lean period from November to March, the Ganga River maintains flows of approximately 2,0000 cusecs to 11000 cusecs and the Yamuna River experiences flows around 40000 cusecs at Prayagraj. Between Shastri Bridge and Sangam Nose, the slope intensifies to about 90-

100 cm per km, significantly exceeding the normal 12-15 cm per km gradient found elsewhere in the Gangetic plains, creating high velocity flows that directly impact the Sangam Nose area.

2.1. River Morphological Changes (2019-2024)

Satellite imagery analysis from 2019 to 2024, conducted using Google Earth Engine, documented significant morphological changes in the Ganga riverbanks at Prayagraj. The Normalized Difference Water Index distinguished water and non-water features, revealing substantial river dynamics including noticeable course shifts and morphological alterations (Bhattacharjya & Kartha, 2024). Analysis demonstrates that the river migrated approximately 500 meters from its 2019 position, indicating active channel migration processes consistent with patterns observed in other alluvial river systems (Verma et al., 2021; Bulsara et al., 2020).

The observed erosion patterns align with documented riverbank erosion prediction models that identify vulnerable sections based on flow dynamics and sediment transport characteristics. Sangam Nose area reclamation and expansion became essential as the most important location of Triveni Sangam for the sacred bath (Rahman et al., 2024).

Table 1: Quantitative Summary of Left Bank Migration of the River Ganga at Prayagraj Relative to Its Position in January 2019

Longitude	Latitude	2019–2020 (m)	Shifted side	2019–2021 (m)	Shifted side	2019–2022 (m)	Shifted side	2019–2023 (m)	Shifted side	2019–2024 (m)	Shifted side
81°53'17"	25°26'25"	58	right	71	right	75	right	77	right	84	right
81°53'20"	25°26'20"	82	right	117	right	113	right	120	right	121	right
81°53'23"	25°26'15"	84	right	130	right	141	right	137	right	143	right
81°53'25"	25°26'10"	116	right	189	right	201	right	204	right	202	right
81°53'26"	25°26'05"	131	right	203	right	214	right	217	right	226	right
81°53'25"	25°26'00"	133	right	169	right	211	right	222	right	232	right
81°53'24"	25°25'55"	112	right	145	right	187	right	207	right	217	right
81°53'21"	25°25'50"	98	right	96	right	145	right	164	right	187	right
81°53'23"	25°25'45"	23	right	27	right	147	right	151	right	168	right
81°53'24"	25°25'40"	10	right	2	right	131	right	135	right	334	right

Table 2: Quantitative Assessment of Changes in the Sangam Nose Area Relative to the Year 2015

Longitude	Latitude	2019–2020 (m)	Shifted side	2019–2021 (m)	Shifted side	2019–2022 (m)	Shifted side	2019–2023 (m)	Shifted side	2019–2024 (m)	Shifted side
81°53'09"	25°26'25"	96	left	190	right	251	right	87	right	69	right
81°53'05"	25°26'20"	133	left	268	right	570	right	214	right	44	right
81°53'02"	25°26'15"	21	left	390	right	469	right	289	right	140	right
81°53'07"	25°26'10"	22	left	462	right	448	right	371	right	231	right
81°53'09"	25°26'05"	2	left	510	right	497	right	415	right	352	right
81°53'10"	25°26'00"	40	left	466	right	502	right	414	right	407	right
81°53'12"	25°25'55"	110	left	383	right	366	right	351	right	381	right
81°53'15"	25°25'50"	202	left	157	right	269	right	202	right	207	right
81°53'17"	25°25'45"	148	right	25	right	234	right	173	right	238	right
81°53'19"	25°25'40"	229	right	173	right	379	right	390	right	473	right

Table 3: Lost Area Comparison with Respect to 2015

Year	Area (Km²)	Lost Area (Km²) compared to 2015	Percentage area lost compared to 2015
2015	1.068	–	–
2016	1.127	0.40	3.72%
2017	1.018	0.06	6.35%
2018	1.011	0.07	6.93%
2019	1.022	0.06	5.98%
2020	0.866	0.22	20.29%
2021	0.862	0.22	20.69%
2022	0.743	0.34	31.64%
2023	0.715	0.37	34.17%
2024	0.712	0.37	34.46%

2.2. *Pre-Project Challenges*

The Ganga River flowing from Shastri Bridge to Sangam Nose had fragmented into three separate shallow streams, creating multiple operational and safety challenges. These disconnected channels exhibited highly variable depths ranging from 0.4 meters to 9.0 meters, with many sections inadequate for safe ritual bathing. The fragmented flow pattern resulted in scattered ghat locations rather than continuous riverfront access, complicating crowd management (Singh & Yadav, 2023).

Infrastructure constraints presented serious limitations for accommodating projected pilgrim numbers. Only 0.6 hectares of usable land existed at the Sangam Nose, severely restricting space for pilgrims and Akhara movement. The Mela Administration initially estimated 450 million devotees would participate from January 13 to February 26, 2025, with 80-100 million bathers expected on Mauni Amavasya alone. Actual attendance reached 660 million pilgrims, far exceeding projections. Over 8 lakh cubic meters of earth material would be required to level undulated riverbanks and expand usable land by 32 hectares.

Environmental concerns added complexity to pre-project conditions. Religious rituals conducted over years resulted in accumulation of plastic waste, cremation debris, old clothes, ropes, jute bags, and wood fragments in the riverbed. A temporary cremation site near Shastri Bridge contributed partially burnt remains that contaminated sediments and degraded water quality. Microplastic pollution represented a particularly insidious environmental challenge, with synthetic particles ranging from 1 micron to 5 millimeters accumulating in river sediments.

The Ganga River experiences multiple pressures from human activities that threaten biodiversity and water quality (Singh et al., 2025; Kumar et al., 2025; Singhal et al., 2024; Gao et al., 2025).

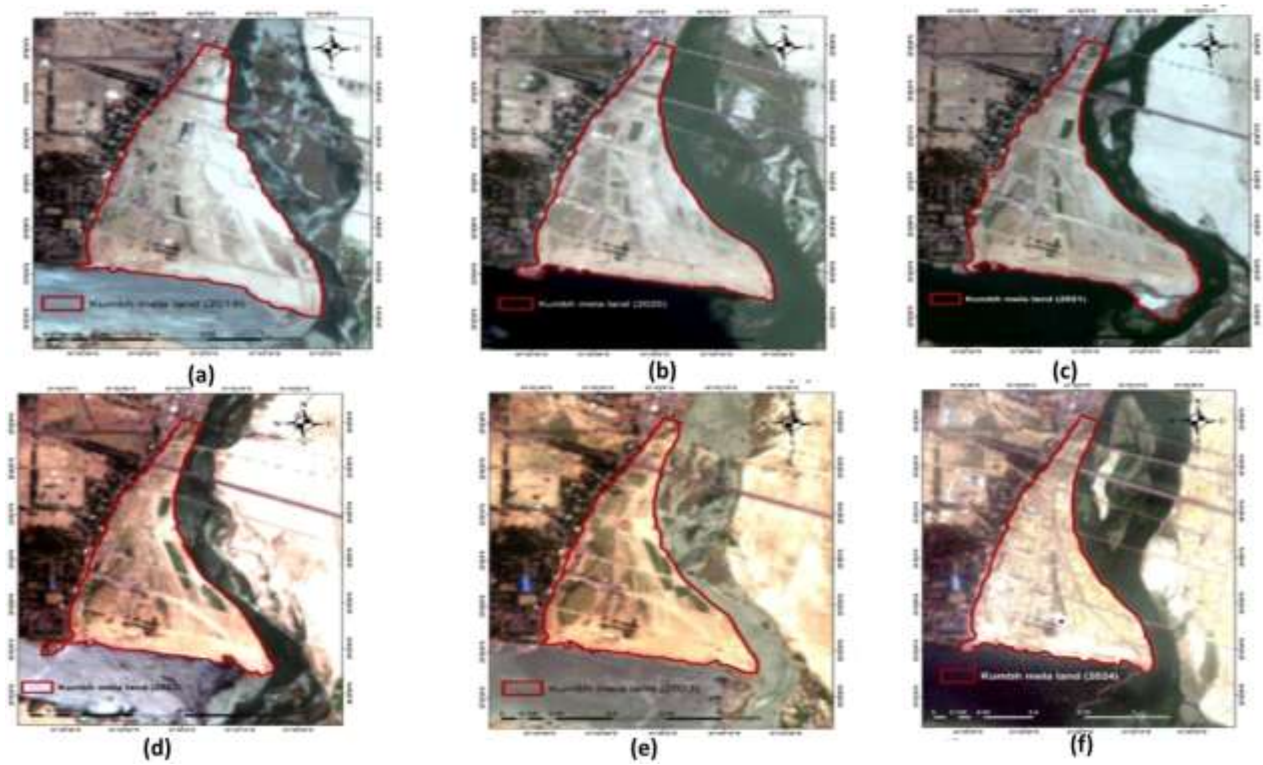

Figure 2: Delineation of the Sangam Nose Area near the Confluence for Selected Years: (a) 2019 (reference year), (b) 2020, (c) 2021, (d) 2022, (e) 2023, and (f) 2024. These images illustrate progressive area loss over the study period

The Ganga River experiences multiple pressures from human activities that threaten biodiversity and water quality (Singh et al., 2025; Kumar et al., 2025; Singhal et al., 2024; Gao et al., 2025).

3. MATERIALS AND METHODS

The river channelization project commenced in September 2024 with planning activities and achieved completion by January 2025, operating under strict time constraints. The project involved collaboration between IIT Guwahati, which provided technical recommendations, and the Uttar

Pradesh Irrigation and Water Resources Department, which executed engineering interventions. Principal Secretary Anil Garg oversaw the entire operation. The operational team consisted of Executive Engineer Sujeet Kumar Singh supported by three Assistant Engineers and nine Junior Engineers from the Barrage Mechanical Maintenance Division in Varanasi.

3.1. River Morphology Analysis

Satellite imagery analysis utilized Google Earth Engine as the primary platform for documenting temporal changes in river morphology from 2019 to 2024. The Normalized Difference Water Index served as the key analytical tool for distinguishing water and non-water features, enabling precise delineation of channel boundaries and quantification of morphological changes.

3.2. Hydraulic Design Parameters

Channel design followed established hydraulic engineering principles using Lacey's regime width formula (W = 4.8Q^1/2) to determine appropriate channel dimensions. Design discharges reflected lean period conditions when the Ganga River maintains approximately 20000 cusec to 11000 cusec (yielding calculated regime width of 215 meters) and the Yamuna River experiences flows around 40000 cusec (corresponding to regime width of 339 meters). The target channel width was established at 250-300 meters, balancing hydraulic efficiency with practical construction considerations (Cheng et al., 2025).

3.3. Dredging Equipment and Specifications

Four cutter suction dredgers were deployed. The equipment fleet included IMS-8012 (1,250 m^3/hr slurry capacity, 550 HP engine, 7m depth, star wheel propulsion), Ellicott 670 Dragon (1,750 m^3/hr slurry capacity, 800 HP engine, 10m depth, spud/tug propulsion), YS-CSD 3010 (1,750 m^3/hr slurry capacity, 480 HP engine, 8m depth, spud/tug propulsion) and CSD-250 (1,250 m^3/hr slurry capacity, 500 HP engine, 6m depth)

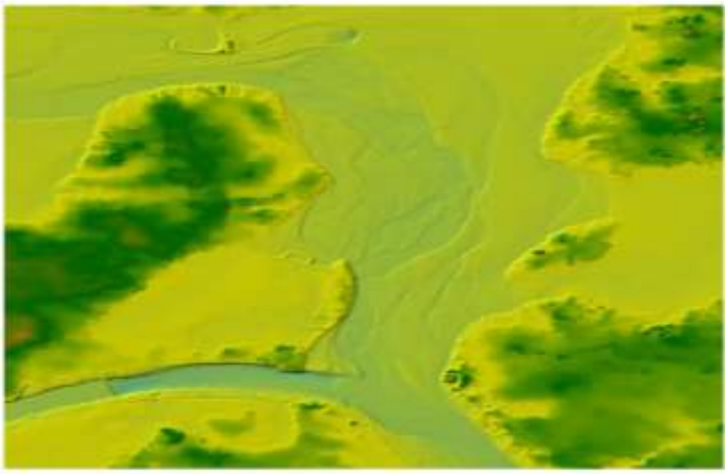

Figure 3: Digital Elevation Model of Sangam Region illustrating topographic features and elevation gradients

Figure 4: Backfill Area Represented by Yellow Boundary indicating zones designated for material placement

Table 4: Comparison of Three Dredger Features detailing

S. No	Description	IMS-8012	Ellicot 670 Dragon	YS-CSD 3010
1	Length	15.7 m	23.62 m	26.1 m
2	Width	3.66 m	6.0 m	4.30 m
3	Weight (without fuel)	22 tons	62 tons	60 tons
4	Draft	0.90 m	0.90 m	1.0 m
5	Engine capacity	550 HP	800 HP	480 HP
6	Discharge pipe diameter	254 mm	350 mm	350 mm
7	Propulsion	Star wheel drive, self-propelled	Spud type, tug boat driven	Spud type, tug boat driven
8	Dredging depth	7 m	10 m	8 m
9	Spud (two)	-	400 mm dia, 13.3 m length	325 mm dia, 10 m length
10	Slurry discharge capacity	1250 m³/hr	1750 m³/hr	1750 m³/hr

This table feature specifications including length, width, weight, draft, engine capacity, discharge pipe diameter, propulsion type, dredging depth, and slurry discharge capacity.

Figure 5: Dredger photographs used for land reclamation and area expansion showing equipment deployed at various project locations

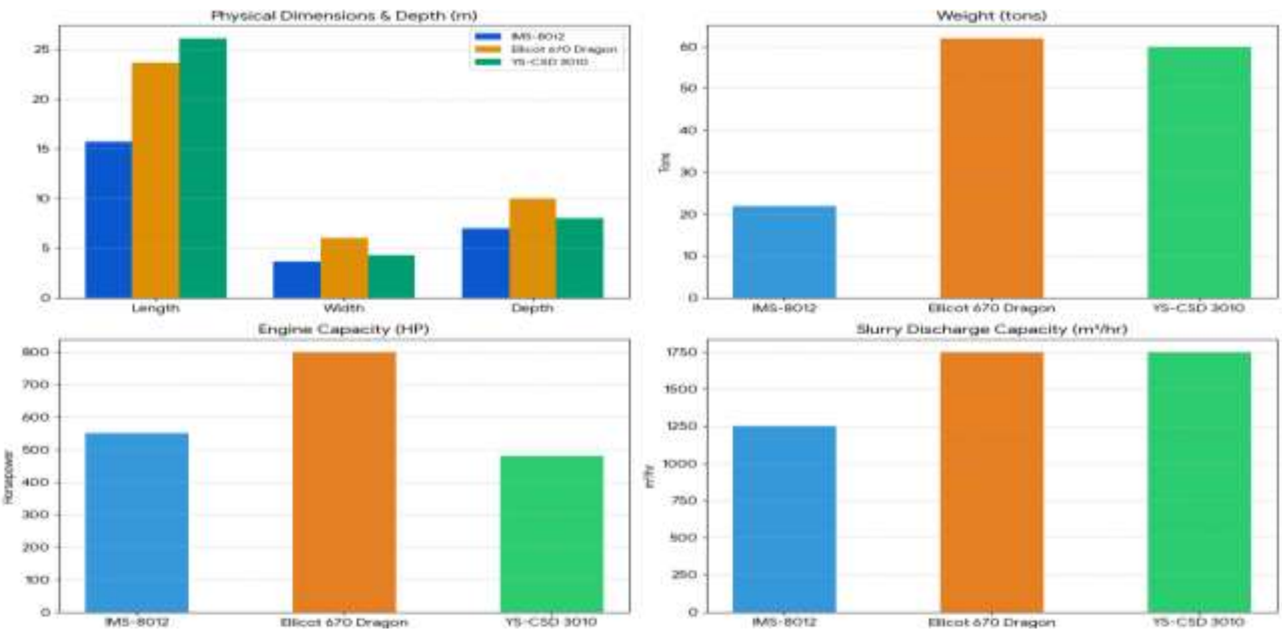

Figure 6: Bar Chart Comparison of Three Dredgers illustrating relative specifications across equipment types

Transportation logistics required extensive coordination. IMS-8012 was transported from Bahraich district (320 km) using six trailers. Ellicott 670 Dragon traveled from Basti district (300 km) requiring nine trailers. YS-CSD 3010 moved from Shravasti district (300 km) also requiring nine trailers. CSD-250 D4 dredger was transported from Delhi (700 km) using six trailers.

3.4. Operational Framework

The project operated continuously through three shifts providing 24-hour coverage. Each dredger required 47-49 personnel distributed across management (Project Manager, Dredger Masters), operational (operators, boat operators, mechanics), and support functions (pipeline supervisors, skilled and unskilled helpers).

Table 5: Representation of Manpower Used in Three Different Dredgers showing personnel allocation by category and equipment type

S.No	Skilled & Unskilled Manpower on Dredgers	IMS-8012	Ellicat 670 Dragon	YS-CSD 3010
1	Project Manager	1	1	1
2	Dredger Master	2	2	2
3	Dredger Operator	3	3	3
4	FRP Boat Operator	2	2	2
5	Engine-driven Boat Operator	2	2	2
6	Mechanic	1	1	1
7	Pipeline Supervisor	2	2	2
8	Skilled Helper (for pipeline)	18	20	20
9	Skilled Helper (for dredger)	3	3	3
10	Skilled Helper (for boats)	3	3	3
11	Unskilled Helper	10	10	10

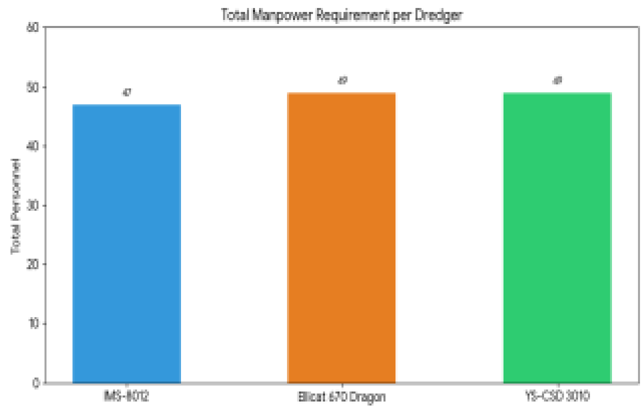

Figure 7: Manpower Requirement Per Dredger Per Day Representation in Bar Chart illustrating staffing levels across personnel categories

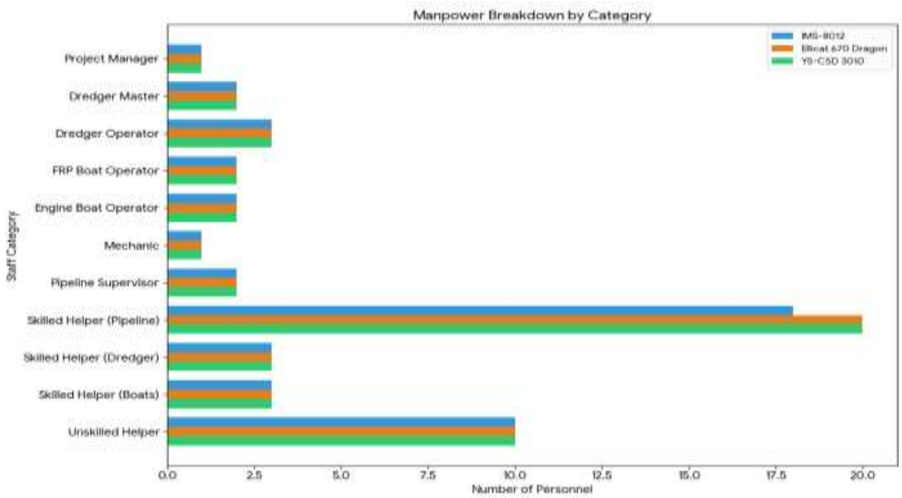

Figure 8: Manpower Breakdown Category Wise Staff showing distribution of project workforce by role and skill level

Figure 9: Tentative Dredging Path from Red Lines showing planned channel alignment and excavation zones

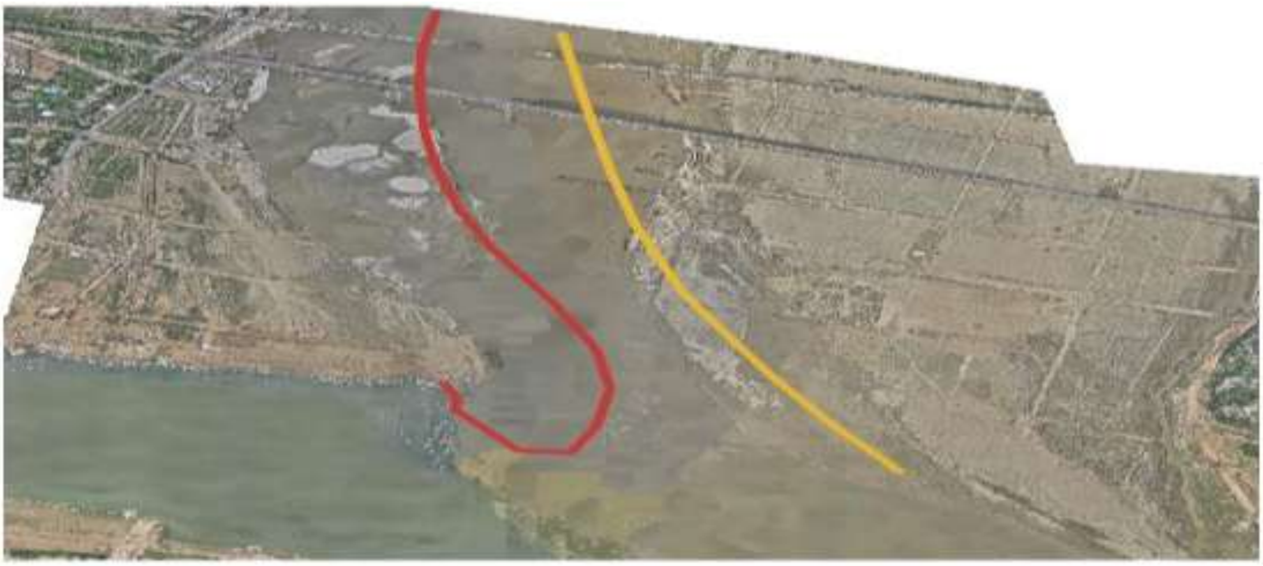

Figure 10: Left bank and right bank alignment for Sangam area illustrating designed channel configuration and bank positions

3.5. Dredging Methodology

Channel alignment followed a defined path from Shastri Bridge to Sangam Nose spanning approximately 1.6 kilometers. The target dredging depth of 2 to 2.5 meters was established to ensure adequate water depth for ritual bathing while removing accumulated pollutants. Channel width targets of 250-300 meters corresponded to Lacey's regime calculations. Dredged material was transported through floating HDPE pipes (254-350mm diameter) with discharge distances extending up to 500 meters. All dredged material was reused on-site for leveling operations and land reclamation.

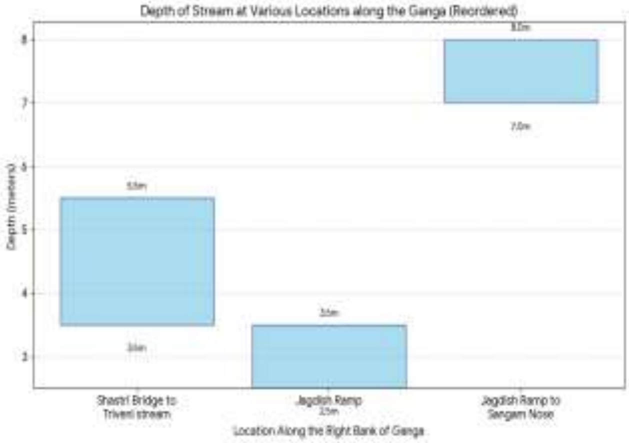

Figure 11: Depth at Various Locations along the Ganga River from Shastri Bridge to Sangam Nose documenting pre-dredging bathymetry variations

3.6. Environmental Monitoring

Water quality monitoring employed systematic sampling at two critical locations throughout the Mahakumbh period. Daily sampling at 8:00 AM measured pH (standard: 6.5-8.5), Dissolved Oxygen (standard: ≥5.0 mg/L), Biochemical Oxygen Demand (standard: ≤3.0 mg/L), Chemical Oxygen Demand, and color. These parameters represent standard indicators for assessing surface water quality and bathing suitability. The monitoring period extended from January 1 through February 26, 2025 (57 days). The UP-Pollution Control Board Regional Office in Prayagraj conducted all sampling and analysis (Akhtar et al., 2021; Xu et al., 2019).

3.7. Hydrological Data Collection

River gauge monitoring tracked water levels at multiple stations (Phaphamau, Shastri Bridge, Sangam Nose, Chhatnag on Ganga; Naini on Yamuna). Daily measurements documented gauge levels relative to the danger level reference of 84.734 meters.

Table 6: Gauge Representation at Different Locations showing water levels across monitoring stations during project period

Date & Time	River	Station	Current Gauge (m)
24-10-2024 08:00 AM	Ganga	Phaphamau	78.21
24-10-2024 08:00 AM	Ganga	Shastri Bridge	75.63
24-10-2024 08:00 AM	Ganga	Sangam Nose	74.23
24-10-2024 08:00 AM	Ganga	Chhatnag	73.81
24-10-2024 08:00 AM	Yamuna	Naini	74.28

Discharge monitoring at Kanpur Barrage quantified water volumes. Discharge measurements in cusecs were recorded daily from December 31, 2024 to February 26, 2025.

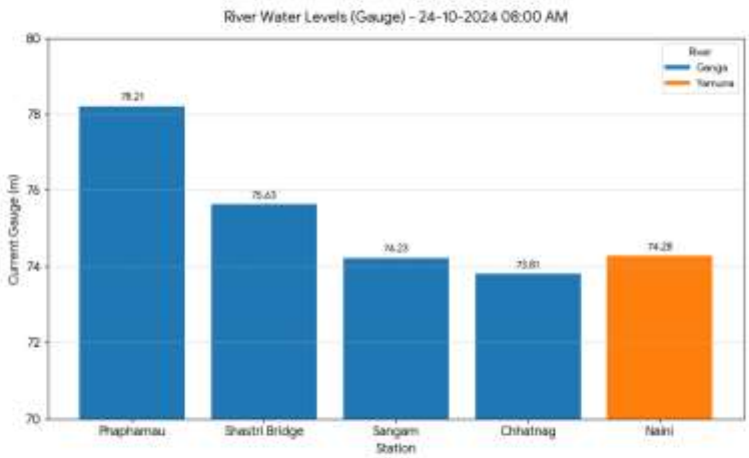

Figure 12: Ganga River gauge level on Dated 24-10-2024 illustrating hydraulic conditions at project commencement

3.8. Economic Analysis Framework

Economic analysis employed comprehensive cost-benefit methodology. Direct project expenditure encompassed dredging operations, equipment deployment, transportation costs, and manpower costs. Benefit quantification applied market-based valuation to dredged material and infrastructure savings. Sand material valuation used local market rates (₹861.2/m^3). Infrastructure savings calculations addressed road damage prevention (reflecting 53,333 tipper trips avoided) and pontoon bridge optimization (400m reduction per bridge × 13 bridges = 5.2 km saved). Return on investment was calculated as (gross benefit - cost)/cost × 100.

3.9. Data Analysis

Data analysis integrated multiple analytical approaches. Morphological changes were assessed through GIS-based NDWI analysis. Water quality data underwent trend analysis using daily time series. Hydrological data analysis examined correlations between gauge levels and discharge measurements. Economic analysis employed cost-benefit methodology integrating material value, infrastructure savings, and operational efficiencies (Smith et al., 2024).

4. OPERATIONAL CHALLENGES AND ADAPTIVE SOLUTIONS

The 2024 monsoon season extended 1 to 1.5 months beyond normal duration, maintaining elevated water levels and strong currents well into October when project operations needed to commence. Initial discharge measurements recorded 19,383 cusecs at the project site, creating challenging conditions for dredger deployment and operation. Water level measurements showed the Ganga at Phaphamau reaching 78.88 meters and Chhatnag downstream from Sangam Nose at 74.48 meters, while the Yamuna River approximately 2 kilometers upstream from Sangam Nose measured 74.93 meters. Flow velocities in the project area ranged from 4.5 to 5.1 kilometers per hour, substantially exceeding the 3 kilometers per hour operational threshold for safe dredger control. These high velocity conditions posed extreme difficulties for maintaining dredger stability and controlling equipment movement during dredging operations. Extended flood seasons and altered hydrological patterns can significantly impact sediment contamination and remobilization, creating additional challenges for river engineering projects (Smith et al., 2024).

Figure 13: High Flow Discharge in Ganga River

Figure 14: Dredger IMS 8012 Unstable due to High Velocity Discharge in Channel

The Ganga River typically exhibits slopes of 12 to 15 centimeters per kilometer in plains regions, but between Phaphamau and Sangam Nose spanning approximately 10 kilometers, the slope increases to 20-26 centimeters per kilometer. The gradient becomes exceptionally steep between Shastri Bridge and Sangam Nose over the 1.5 kilometer project reach, intensifying to 90-100 centimeters per kilometer. This steep gradient causes the Ganga to flow with high velocity before merging with the Yamuna, with a major portion of the flow turning westward and directly impacting the Sangam Nose area. These hydraulic conditions created additional complications for dredger operations, requiring constant adjustments to maintain equipment position and prevent downstream drift.

4.1. Equipment and Technical Challenges

Launching dredging equipment into the river proved extremely challenging due to marshy conditions along the riverbanks resulting from the extended monsoon period. The saturated soil conditions prevented conventional equipment deployment methods and posed risks of equipment damage or personnel injury. Several temporary shops and settlements occupied the right bank area originally identified for dredger launch, along with a temporary cremation site used for religious rituals near Shastri Bridge. Through coordination with the Mela Administration and senior officials, these obstacles were addressed through dialogue with local residents, enabling relocation of temporary establishments. The final launch site was established near Kali Ghat on the right bank, where chequered plates were laid on the marshy ground to create stable working surfaces. Dredgers were then carefully rolled into the river using roller systems that distributed weight and prevented sinking into soft sediments.

Figure 15: Launching of Dredger Machine in Ganga River

Dredger operations encountered significant stability challenges due to insufficient water depth in certain areas and strong currents that threatened equipment control. The IMS-8012 dredger requires a minimum draft of 0.8 meters and moves using a star-wheel rotating system, while the other two dredgers operate using spuds and require 1.0 to 1.2 meters draft. Initial conditions in spill channels on both banks showed depths ranging from 3 to 9 meters, but approaching river merging points, depths reduced sharply to 0.5-0.8 meters.

Figure 16: Depth Measured by Ecosounder at Different Locations in Ganga River Triveni Sangam showing detailed depth profiles obtained through acoustic surveying

Strong river currents caused water to flow over dredger pontoons, creating risks of water entering sensitive equipment components and requiring careful operation to protect machinery while maintaining productivity.

Figure 17: Dredger Ellicot Facing Strong Current in river Ganga during dredging

Cutter mechanisms experienced frequent obstructions from accumulated debris in the river including sacks, old clothes, jute ropes, wooden pieces, and stones that became lodged in cutting heads and suction ends. These obstructions required stopping operations repeatedly, both day and night, to remove materials manually, causing operational disruptions and damage to cutter mechanisms. The accumulation of various debris types reflected years of religious ritual practices and cremation activities that deposited materials into the riverbed.

Figure 18: Materials Stuck in the Cutter and Suction

Discharge pipe failures presented another serious operational challenge, as floating High-Density Polyethylene pipes transporting dredged material to the right bank frequently bent under high pressure from strong currents. Sudden internal pressure changes caused pipes to break completely, interrupting material transport and requiring repairs. To address this persistent problem, a pontoon bridge was constructed to support discharge pipes over distances up to 500 meters, stabilizing the system and reducing failure frequency.

Figure 19: Bending and Breaking of Discharge Pipes

Spud components providing dredger stability suffered bending failures under extreme conditions. Near Jagdish Ramp, strong flow and sand pressure caused the spuds of the Ellicott 670 Dragon to bend, preventing further movement of the equipment. The machine required careful extraction to the riverbank where spuds were removed, straightened through mechanical processes, and then reinstalled before operations could resume.

Figure 20: Bending of Dredger Spud

The Ganga River carries heavy silt loads that created persistent operational challenges throughout the project. Dredged areas rapidly filled back with sediment, requiring repeated dredging/excavation to maintain target depths and channel configurations. Anchors and ropes used to stabilize dredgers and pipelines became repeatedly buried under accumulating sand, making equipment movement and operation difficult. Extracting buried anchors required significant manual effort, adding to the physical demands on the workforce and extending the time required for routine operations.

Several locations within the project area exhibited very shallow water depths that prevented motorboats and fiberglass reinforced plastic boats from reaching worksites. This access limitation forced personnel to conduct pipeline shifting, site inspections, and diesel fuel transportation on foot through the river, substantially increasing manpower requirements and time needed for routine tasks. These constraints added to the overall complexity of operations and contributed to worker fatigue throughout the project duration.

4.2. Design Modifications

The Indian Institute of Technology Guwahati provided initial recommendations defining the dredging path for river channelization based on hydraulic modeling and morphological analysis.

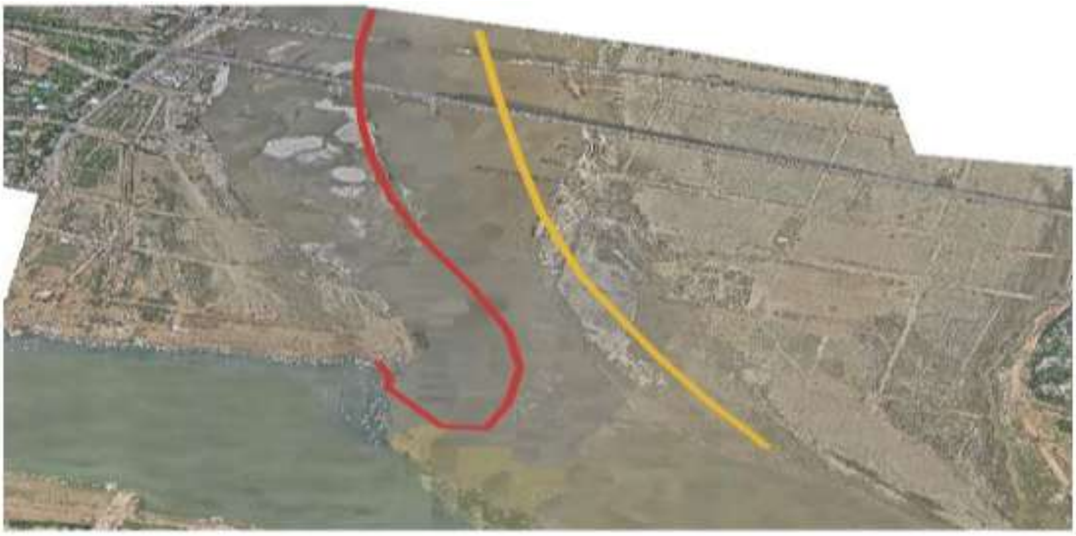

Figure 21: Left bank and right bank alignment for Sangam area

After several days of operations, the Mela Authority revised the alignment based on updated recommendations from IIT Guwahati, shifting the channel centerline 250 to 300 meters to the right of the original design. This mid-project modification required dredgers to excavate new areas and create adequate draft before reaching the revised alignment points, effectively adding unanticipated work to the project scope while maintaining the same aggressive timeline.

4.3. Socio-Cultural Sensitivities

A temporary cremation site located near Shastri Bridge where dredgers needed to be launched presented significant social and religious sensitivities. Relocating or discontinuing cremation activities required careful coordination not only with the Mela Administration but also with local residents who utilized the facility for final rites. Project incharge approached this challenge with cultural sensitivity and respect for religious practices, working through dialogue and consultation to identify alternative arrangements that met community needs while enabling project implementation.

Several temporary shops and settlements had been established on the right bank of the river to provide convenience for people conducting religious rituals at the Sangam site. These structures, combined with marshy land conditions, created major obstacles for launching dredging equipment. With assistance from the Mela Administration and senior government officials, project incharge with mela administration engaged in dialogue with local residents to explain project necessity and timeline constraints. Through these consultations, temporary establishments were relocated to alternative locations, enabling finalization of the dredger launch site near Kali Ghat on the right bank.

4.4. Resource Augmentation

During project review meetings, the Honourable Chief Minister of Uttar Pradesh Sri Yogi Adityanath Ji directed that an additional dredger be deployed to ensure work completion within the established timeline. Arranging specialized dredging equipment proved challenging since such machines are rarely available within the state and mobilization requires substantial time. Through proper coordination with equipment suppliers, a fourth dredger (CSD-250 D4) was successfully launched upstream of Shastri Bridge from the Jhunsi side. This additional equipment helped concentrate the main river flow toward the center channel while providing dredged material for leveling operations on the left bank, effectively expanding project capacity at a critical phase.

Figure 22: Additional Dredger Machine as per Requirement

4.5. Human Factors

Workers faced harsh environmental conditions throughout the project period, particularly during November and December when night temperatures dropped as low as 5 degrees Celsius. Entering the river at night to replace discharge pipes under these cold conditions proved extremely difficult even for skilled helpers experienced in water work. Strong currents created additional obstacles when joining discharge pipes, requiring workers to maintain position in flowing water while manipulating heavy equipment. These environmental challenges tested worker endurance and commitment throughout the accelerated construction schedule.

Repeated equipment failures and operational difficulties adversely affected the mental condition of staff and workers operating the dredgers. Dredger machines repeatedly drifting in strong currents, discharge pipes frequently bending or breaking, and suction pipes regularly becoming choked created a pattern of recurring problems that caused stress and mental exhaustion among the entire dredging staff. Project timelines imposed considerable psychological pressure on all officers and employees at the worksite, as delays could jeopardize the entire Mahakumbh preparation schedule. During the work period, the major festival of Deepawali was celebrated throughout India, but project demands prevented any workers from returning home to celebrate this important occasion with their families, adding to mental distress. At the project beginning, some skilled dredging personnel contracted dengue fever, requiring proper medical treatment and extended recovery time in their home districts. While these individuals received necessary care, their illness created fear among other workers about disease risks associated with the work environment.

Continuous operations across three shifts meant that work never ceased throughout the project duration, creating sustained physical demands on all personnel. Workers repeatedly entered the flowing river to clean suction ends and pipes when plastic bags, jute ropes, wood pieces, and old clothes became lodged in equipment, causing continuous physical stress. Manual extraction of anchors buried under accumulated sand required significant effort and added to overall fatigue levels. The combination of environmental stress, psychological pressure, and physical demands tested worker resilience throughout the challenging project period.

5. RESULTS

The channelization operation successfully merged three fragmented river streams into a single unified channel ranging from 250 to 300 meters in width, fundamentally transforming the river morphology between Shastri Bridge and Sangam Nose.

5.1. Engineering Achievements

This engineering intervention consolidated the previously divided flow pattern into a coherent watercourse extending approximately 1.6 kilometers through the project area. Dredging operations achieved target depths of 2.5 meters below the original riverbed, creating adequate water depth for safe ritual bathing while removing accumulated pollutants and debris.

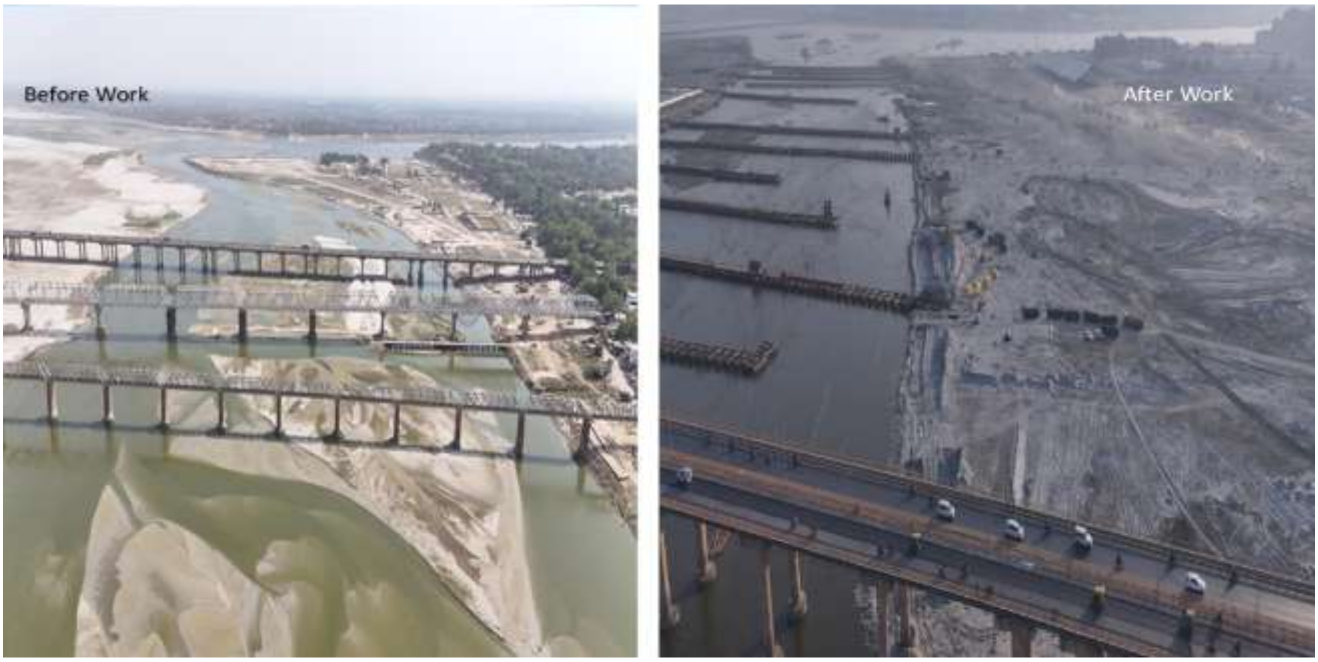

Figure 23: Three distinct streams merged into single stream, before and after work representation

Figure 24: Area Expansion and Reclamation Representation from Shastri Bridge to Sangam Nose and Airavat Ghat

The unified channel configuration eliminated the scattered flow pattern that had characterized the reach for years, replacing it with a stable, predictable watercourse that facilitated infrastructure development and crowd management during the Mahakumbh gathering.

The project reclaimed a total area of 32 hectares through strategic placement of dredged material on both riverbanks, dramatically expanding usable space for pilgrims and infrastructure. All 8.0 lakh cubic meters of dredged material were reused on-site, achieving 100 percent material utilization without requiring external disposal or additional fill procurement. The reclaimed land provided essential space for constructing ghats, circulation zones, watchtowers, and public facilities that supported the massive congregation of devotees during the Mahakumbh. This comprehensive land reclamation approach demonstrated how dredging operations can serve dual purposes of channel improvement and land development, maximize project benefits while minimize environmental impacts associated with material transport and disposal.

The Sangam Nose area, representing the most spiritually significant bathing location at the Triveni confluence, underwent substantial expansion from 0.6 hectares to 2.0 hectares, achieving a 3.3-fold area increase.

Figure 25: Historical Sangam Nose Reclaimed and Expanded by Dredging Process

Figure 26: Nectar Bath at Sangam Nose during Mahakumbh-2025 (open resources)

This expansion proved critical for accommodating the traditional Akhara Amrit Snan ceremonies that constitute the spiritual centerpiece of the Mahakumbh celebration. Bathing capacity at this sacred location increased from approximately 50,000 pilgrims per hour during the 2019 Kumbh to between 200,000 and 300,000 pilgrims per hour during the 2025 Mahakumbh, representing a four to six-fold capacity improvement. The expanded area enabled all participating Akharas to conduct their ritual bathing ceremonies in the traditional manner while safely accommodating the unprecedented numbers of devotees seeking sacred immersion at the confluence point.

The unified channel configuration enabled linear ghat arrangement along the riverbank, replacing the scattered ghat locations that existed before channelization. This organized layout facilitated more efficient crowd movement and improved access to bathing areas throughout the Mahakumbh period. Pontoon bridge requirements were optimized through channel consolidation, reducing the length of floating bridges needed to span the river.

Enhanced crowd circulation zones created by land reclamation provided additional space for pilgrim movement, reducing congestion and improving safety during peak bathing days when millions of devotees converged on the Sangam area simultaneously.

5.2. Hydrological Performance

5.2.1. River Gauge Stabilization

River gauge monitoring from December 31, 2024 through February 26, 2025 documented stable water levels throughout the channelized reach during the critical Mahakumbh bathing period. On January 29, 2025, corresponding to Mauni Amavasya when maximum bathing occurred, gauge measurements at key stations showed Phaphamau at 76.46 meters providing upstream reference conditions, Shastri Bridge at 73.86 meters marking the channel entrance, Sangam Nose at 72.46 meters representing the confluence point where ritual bathing concentrated, and Naini on the Yamuna at 72.53 meters indicating conditions in the tributary river. These measurements remained well below the danger level of 84.734 meters throughout the event period, confirming that channelization successfully managed water levels while accommodating massive pilgrim numbers.

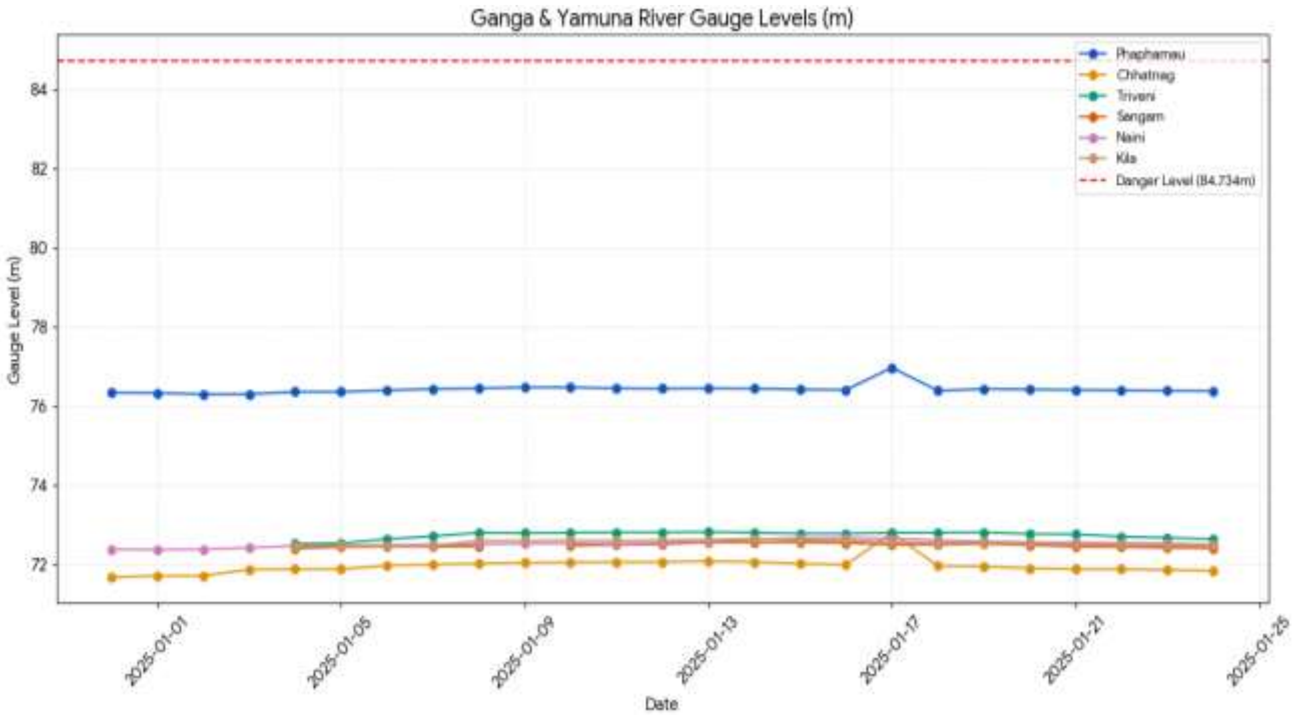

Figure 27: Ganga and Yamuna River Gauge Level (m)

5.2.2. Discharge Management

Discharge monitoring at Kanpur Barrage upstream of the project area showed flows ranging from 8,042 to 10,722 cusecs during the monitoring period, with discharge remaining stable during peak bathing days from January 10 to February 26. No flood alerts were issued despite high pilgrim density at bathing sites, demonstrating that the channelized river configuration maintained safe hydraulic conditions throughout the mass gathering period. The stable discharge regime supported consistent water depths and flow velocities that enabled safe bathing activities while preventing erosion or flooding risks.

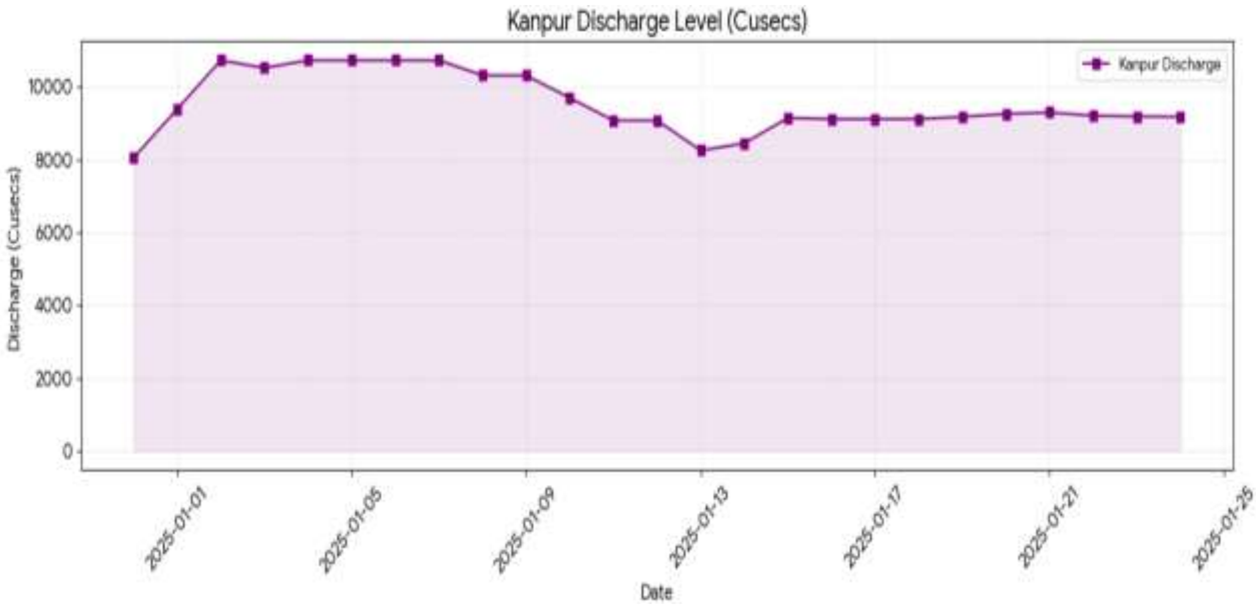

Figure 28: Kanpur Barrage Discharge Level in Cusec

5.3. Environmental Outcomes

Dredging to depths of 2 to 2.5 meters removed accumulated pollutants that had collected in the riverbed over many years of religious activities and cremation practices. Materials extracted included plastic waste representing years of accumulation from ceremonial offerings and ritual practices, cremation debris consisting of bones and partially burnt remains from upstream cremation ghats, microplastic-laden sediments that posed long-term ecological risks, and ceremonial materials such as jute bags, old clothes, and ritual objects disposed in the river. This comprehensive removal of contaminants addressed both visible pollution and microscopic threats to river health. Microplastic pollution represents a growing concern in the Ganga River system, affecting aquatic ecosystems and water quality through various pathways (Singh et al., 2025; Kumar et al., 2025; Barman et al., 2023).

Water quality monitoring at the Sangam Triveni confluence throughout the 57-day Mahakumbh period from January 1 through February 26, 2025 documented consistent compliance with bathing water standards despite unprecedented pilgrim numbers. Daily measurements revealed pH values ranging from 7.93 to 8.18, remaining well within the bathing water standard of 6.5 to 8.5 throughout the entire monitoring period. Biochemical Oxygen Demand showed improvement from an initial value of 3.4 milligrams per liter on January 1 to 3.0 milligrams per liter by January 7, achieving and maintaining compliance with the bathing water standard of 3.0 milligrams per liter or less for the remainder of the event. Dissolved Oxygen levels improved from approximately 8.1 milligrams per liter in early January to 9.0-9.2 milligrams per liter later in the monitoring period, consistently exceeding the minimum standard of 5.0 milligrams per liter and indicating excellent reaeration capacity despite mass bathing activities. Chemical Oxygen Demand remained stable in the range of 10.0 to 11.8 milligrams per liter with no pollution spikes during peak bathing days when hundreds of millions of pilgrims entered the river.

Table 7: Water Quality Data at Sangam Triveni Prayagraj

Sl. No.	Date	Colour (Hazen)	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)
1	01.01.2025	20	7.99	8.1	3.4	12
2	02.01.2025	20	8.02	8.2	3.3	11
3	03.01.2025	20	8.07	8.1	3.3	11
4	04.01.2025	20	8.10	8.1	3.3	11
5	05.01.2025	20	8.13	8.3	3.2	10
6	06.01.2025	20	8.15	8.3	3.1	10
7	07.01.2025	20	8.17	8.3	3.0	10
8	08.01.2025	20	8.18	8.4	3.0	10
9	09.01.2025	20	8.01	8.5	3.0	10
10	10.01.2025	20	8.01	8.5	3.0	10
11	11.01.2025	15	8.06	8.6	3.0	11
12	12.01.2025	20	8.04	8.6	2.9	10
13	13.01.2025	20	8.02	8.5	3.0	10.8
14	14.01.2025	20	7.96	8.4	3.0	11.4
15	15.01.2025	20	7.97	8.6	3.0	11.0
16	16.01.2025	20	7.93	8.7	3.0	10.8
17	17.01.2025	20	7.98	8.8	3.0	11.2
18	18.01.2025	20	8.00	9.2	3.0	11.0
19	19.01.2025	20	8.02	9.2	3.0	11.3
20	20.01.2025	20	8.08	8.8	3.0	11.2
21	21.01.2025	20	8.07	8.9	3.0	11.4
22	22.01.2025	20	8.05	8.9	3.0	11.3
23	23.01.2025	20	8.04	8.8	3.0	11.5
24	24.01.2025	20	8.03	8.9	3.0	11.4
25	25.01.2025	20	8.04	9.0	3.0	11.6
26	26.01.2025	20	8.05	8.9	3.0	11.3
27	27.01.2025	20	8.06	9.0	3.0	11.5
28	28.01.2025	20	8.02	9.0	3.0	11.6
29	29.01.2025	20	8.04	8.9	3.0	11.8
30	30.01.2025	20	8.07	9.0	3.0	11.6
31	31.01.2025	20	8.08	9.0	3.0	11.5
32	01.02.2025	20	8.07	8.9	3.0	11.7
33	02.02.2025	20	8.09	9.0	3.0	11.6
34	03.02.2025	20	8.07	8.9	3.0	11.8
35	04.02.2025	20	8.05	8.8	3.0	11.7
36	05.02.2025	20	8.06	8.9	3.0	11.5
37	06.02.2025	20	8.08	8.8	3.0	11.6
38	07.02.2025	20	8.09	8.9	3.0	11.5
39	08.02.2025	20	8.07	9.0	3.0	11.7
40	09.02.2025	20	8.08	8.9	3.0	11.6
41	10.02.2025	20	8.07	9.0	3.0	11.5
42	11.02.2025	20	8.09	8.9	3.0	11.6

43	12.02.2025	20	8.07	8.8	3.0	11.5
44	13.02.2025	20	8.05	8.9	3.0	11.7
45	14.02.2025	20	8.06	9.0	3.0	11.5
46	15.02.2025	20	8.04	8.9	3.0	11.7
47	16.02.2025	20	8.05	8.8	3.0	11.8
48	17.02.2025	20	8.09	9.0	3.0	11.6
49	18.02.2025	20	8.03	8.9	3.0	11.8
50	19.02.2025	20	8.06	8.8	3.0	11.7
51	20.02.2025	20	8.04	8.7	3.0	11.8
52	21.02.2025	20	8.03	8.8	3.0	11.6
53	22.02.2025	20	8.05	9.0	3.0	11.5
54	23.02.2025	20	8.04	8.9	3.0	11.7
55	24.02.2025	20	8.07	9.0	3.0	11.6
56	25.02.2025	20	8.05	8.9	3.0	11.4
57	26.02.2025	20	8.06	8.8	3.0	11.5

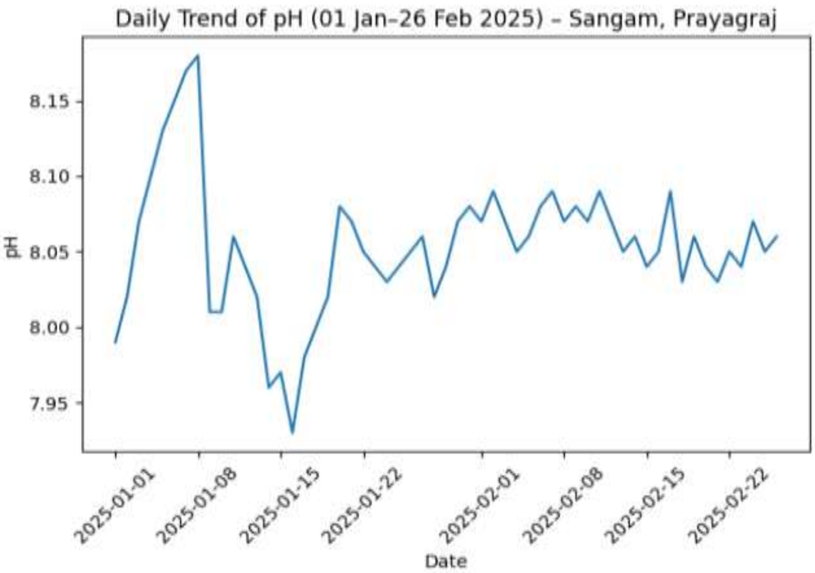

Figure 29: Trend of pH vs Date Sangam Prayagraj

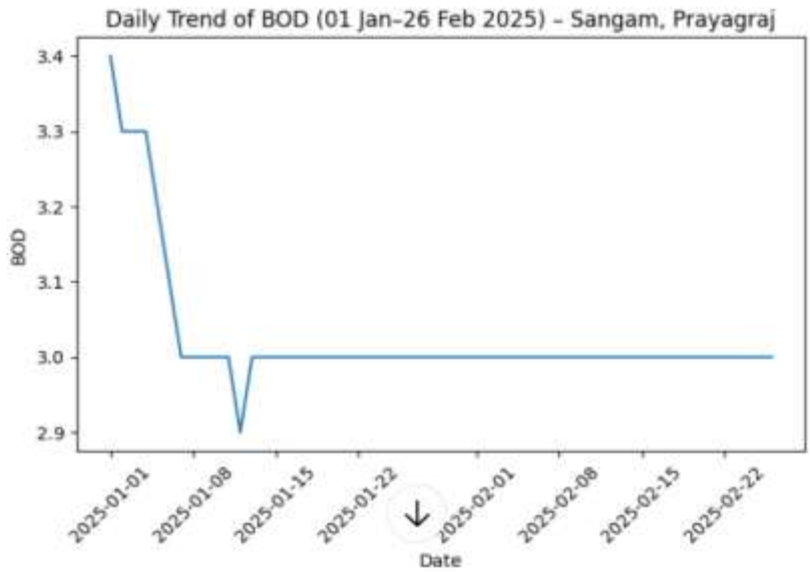

Figure 30: Trend of BOD vs Date Sangam Prayagraj

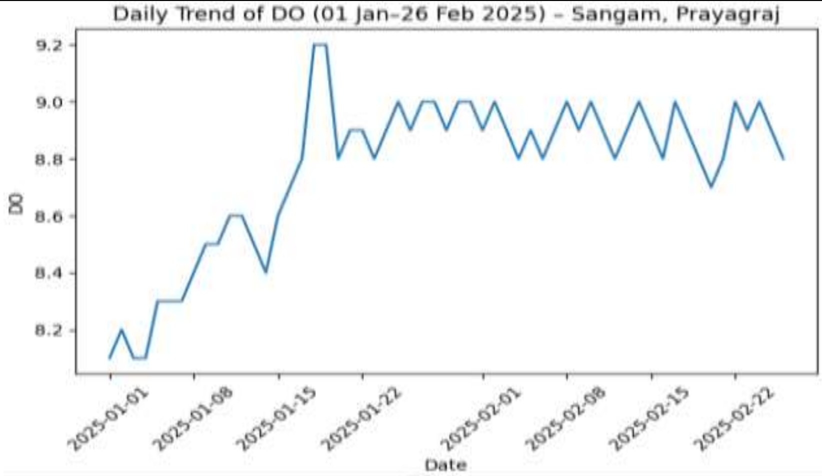

Figure 31: Trend of DO vs Date Sangam Prayagraj

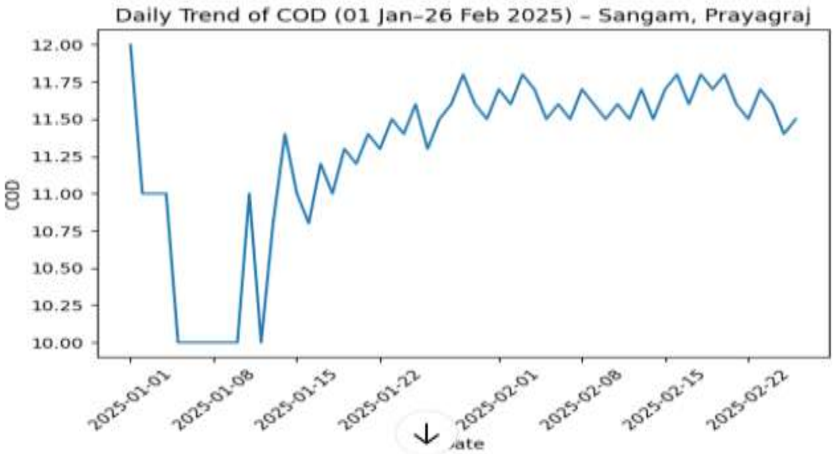

Figure 32: Trend of COD vs Date Sangam Prayagraj

Downstream monitoring near Shastri Bridge showed similar water quality patterns over the same 57-day period. pH values remained stable between 7.94 and 8.14, fully within bathing water standards with no abnormal fluctuations during peak mass bathing days. Biochemical Oxygen Demand started at 3.8 milligrams per liter in early January but quickly stabilized at 3.1 milligrams per liter for the remainder of the period, marginally above the bathing criterion initially but effectively compliant throughout most of the monitoring duration. Dissolved Oxygen demonstrated a clear improving trend from approximately 8.0 milligrams per liter to 9.1 milligrams per liter, consistently well above the 5.0 milligrams per liter standard and indicating strong self-purification and good reaeration despite heavy human activity. Chemical Oxygen Demand ranged between 12.0 and 12.7 milligrams per liter with minor variations but no sudden spikes during large bathing events.

Table 8: Water Quality Data Downstream near Shastri Bridge Prayagraj

Date	Colour (Hazen)	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)
01.01.2025	20	7.94	8.0	3.8	13.0
02.01.2025	20	7.98	8.1	3.7	12.0
03.01.2025	20	8.01	8.0	3.7	12.0
04.01.2025	20	8.04	8.0	3.7	12.0
05.01.2025	20	8.08	8.2	3.6	12.0
06.01.2025	20	8.12	8.2	3.4	11.0
07.01.2025	20	8.14	8.2	3.3	10.0
08.01.2025	20	8.13	8.2	3.1	10.0
09.01.2025	20	8.04	8.4	3.2	10.0
10.01.2025	20	8.02	8.4	3.2	10.0
11.01.2025	15	8.04	8.5	3.2	12.0
12.01.2025	20	8.03	8.5	3.1	12.0

13.01.2025	20	8.06	8.4	3.1	12.3
14.01.2025	20	7.98	8.5	3.1	12.5
15.01.2025	20	7.97	8.7	3.1	12.4
16.01.2025	20	7.94	8.8	3.1	12.3
17.01.2025	20	7.98	8.7	3.1	12.6
18.01.2025	20	8.01	9.0	3.1	12.4
19.01.2025	20	8.03	9.1	3.1	12.6
20.01.2025	20	8.09	8.7	3.1	12.4
21.01.2025	20	8.14	8.8	3.1	12.5
22.01.2025	20	8.08	9.0	3.1	12.4
23.01.2025	20	8.06	8.9	3.1	12.6
24.01.2025	20	8.02	9.0	3.1	12.5
25.01.2025	20	8.05	9.1	3.1	12.7
26.01.2025	20	8.06	9.0	3.1	12.4
27.01.2025	20	8.04	9.1	3.1	12.6
28.01.2025	20	8.01	8.9	3.1	12.7
29.01.2025	20	8.03	9.0	3.1	12.5
30.01.2025	20	8.06	9.0	3.1	12.6
31.01.2025	20	8.07	9.1	3.1	12.4
01.02.2025	20	8.05	9.0	3.1	12.5
02.02.2025	20	8.08	9.1	3.1	12.3
03.02.2025	20	8.06	9.0	3.1	12.6
04.02.2025	20	8.04	8.9	3.1	12.5
05.02.2025	20	8.05	9.0	3.1	12.4
06.02.2025	20	8.07	8.9	3.1	12.6
07.02.2025	20	8.08	9.0	3.1	12.4
08.02.2025	20	8.05	9.1	3.1	12.5
09.02.2025	20	8.07	9.0	3.1	12.6
10.02.2025	20	8.06	9.1	3.1	12.4
11.02.2025	20	8.08	9.0	3.1	12.5
12.02.2025	20	8.05	8.9	3.1	12.6
13.02.2025	20	8.03	9.0	3.1	12.5
14.02.2025	20	8.04	9.1	3.1	12.4
15.02.2025	20	8.02	9.0	3.1	12.6
16.02.2025	20	8.03	9.0	3.1	12.7
17.02.2025	20	8.05	9.1	3.1	12.5
18.02.2025	20	8.02	8.8	3.1	12.6
19.02.2025	20	8.04	8.9	3.1	12.4
20.02.2025	20	8.03	8.8	3.1	12.5
21.02.2025	20	8.01	8.9	3.1	12.3
22.02.2025	20	8.04	9.1	3.1	12.1
23.02.2025	20	8.02	9.0	3.1	12.2
24.02.2025	20	8.05	9.1	3.1	12.3
25.02.2025	20	8.03	9.0	3.1	12.2
26.02.2025	20	8.04	8.9	3.1	12.3

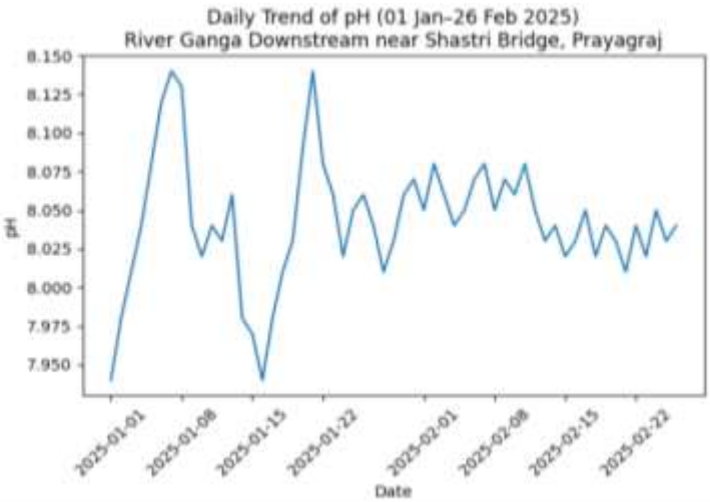

Figure 33: Trend of pH vs Date Near Shastri Bridge Prayagraj

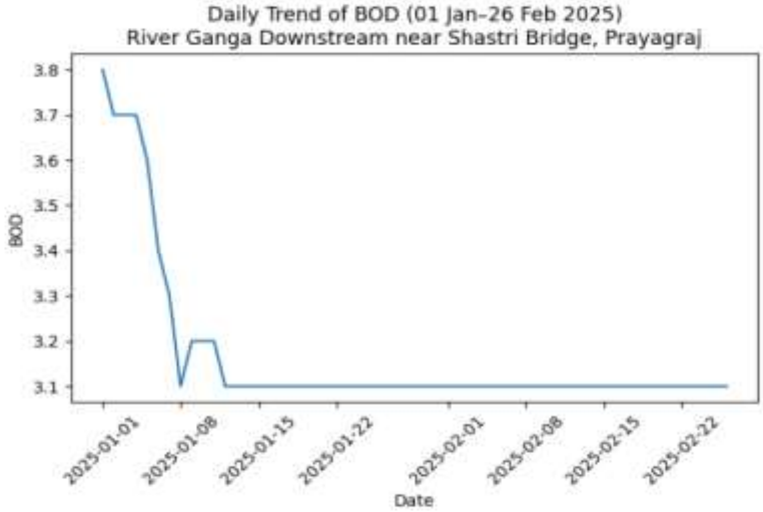

Figure 34: Trend of BOD vs Date Near Shastri Bridge Prayagraj

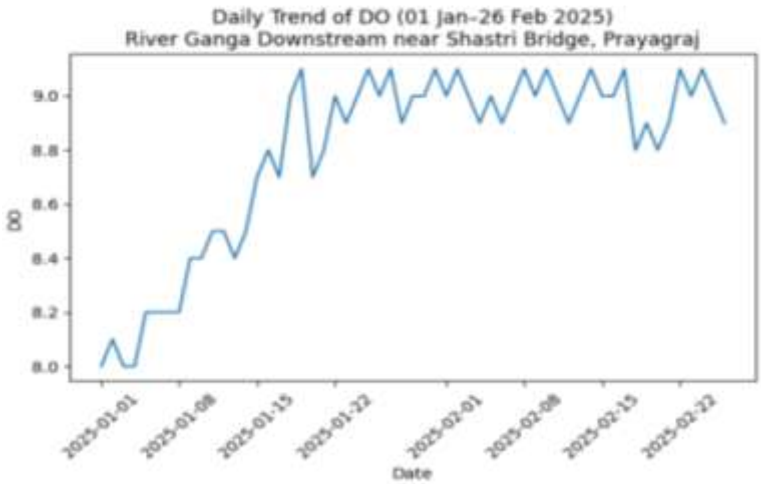

Figure 35: Trend of DO vs Date Near Shastri Bridge Prayagraj

Five key findings emerge from the water quality monitoring program. First, pH stability remained within bathing standards throughout the mass gathering despite variations in pilgrim numbers and bathing intensity. Second, dissolved oxygen improvement from 8 to over 9 milligrams per liter indicated excellent reaeration capacity, suggesting the river maintained healthy oxygen levels that support aquatic life. Third, biochemical oxygen demand compliance achieved the 3.0 milligrams per liter standard by January 7 and maintained this level throughout the remainder of the event. Fourth, chemical oxygen demand stability showed no pollution spikes during peak bathing periods when 660 million pilgrims participated over 45 days. Fifth, the river demonstrated self-purification capacity, maintaining water quality despite unprecedented pollution loads from mass bathing activities. These results align with research demonstrating that effective water quality management can maintain river health even under high human use pressure (Liu et al., 2024; Popović et al., 2023). The findings also support observations that appropriate interventions can help protect biodiversity and water quality in the Ganga River system (Singhal et al., 2024; Gao et al., 2025).

5.4. Economic Performance

Total project expenditure reached 7.62 crore rupees, comprising an initial estimate of 6.35 crore rupees for circulation area expansion on the right bank of the Ganga River from Shastri Bridge to Sangam Nose covering chainage 0 to 1450 meters, plus additional expenditure of 1.27 crore rupees sanctioned for deploying a fourth dredger and extending work downstream of Sangam Nose from chainage 1450 to 1600 meters to supply dredged material for land leveling required for ghat construction. The market value of dredged sand totaled 68.89 crore rupees based on the 8.0 lakh cubic meters of material extracted during operations. This valuation used a rate of 861.2 rupees per cubic meter, calculated by combining transportation costs of 803.2 rupees per cubic meter for hauling sand from external sources 25 kilometers distant including loading and unloading, plus royalty charges of 58 rupees per cubic meter including all taxes. By reusing dredged material on-site, the project avoided procuring this quantity of sand from external sources, generating direct economic benefits equivalent to the market value of the material.

Road damage prevention generated savings of 107 crore rupees by eliminating the need to transport 8.0 lakh cubic meters of sand from external sources. This volume would have required approximately 53,333 dumper or tipper truck trips, each carrying 15 cubic meters of material. These vehicles would have traveled routes comprising 10 kilometers of rural roads and 25 kilometers of urban roads, causing substantial damage to the road network. Road construction costs to build equivalent infrastructure total approximately 105 crore rupees, while routine maintenance requirements of 2 percent of construction costs amount to an additional 2 crore rupees, bringing total road infrastructure preservation benefits to 107 crore rupees.

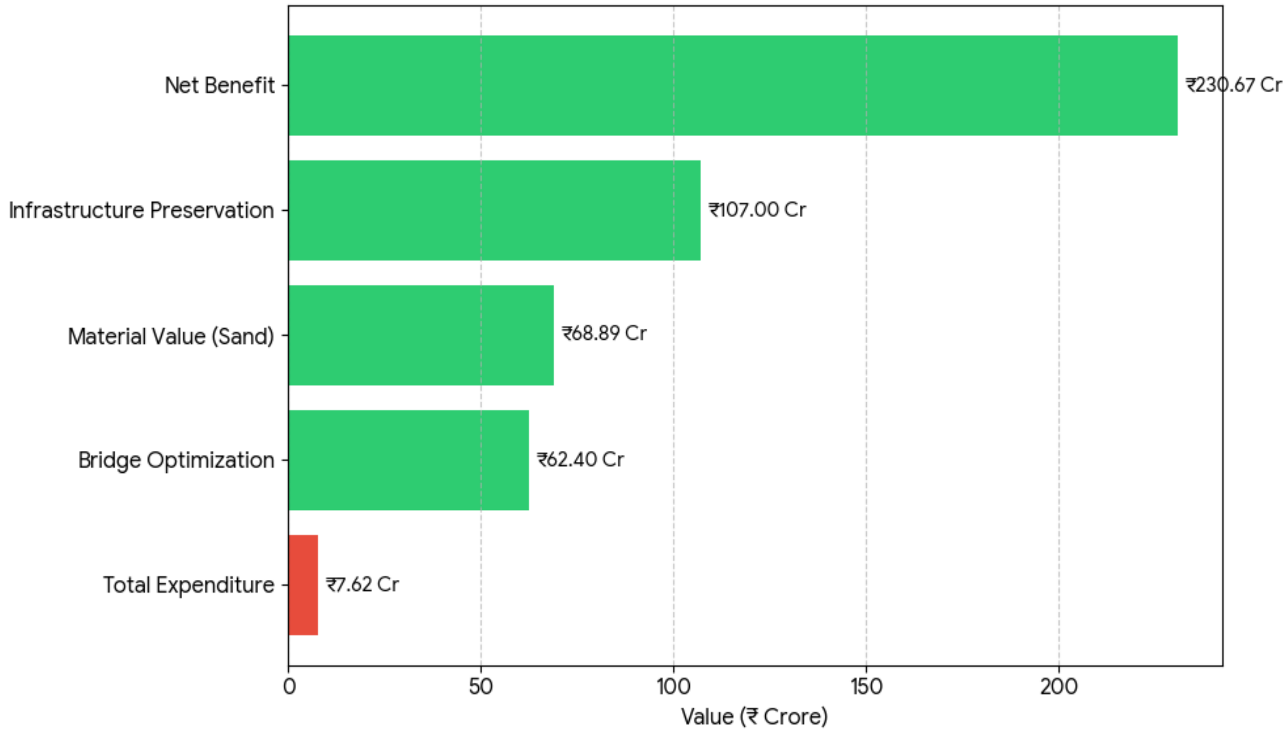

Figure 36: Dredging Project Financial Impact

Table 9: Cost Benefit Analysis Table

Category	Component/Description	Basis of Calculation	Amount (₹ Cr)
Project Cost	Total Dredging Expenditure	Actual project expense	7.62
Direct Material Value	Dredged Sand Quantity	8.0 lakh m^3	
	Market Value of Sand	₹861.2 per m^3 × 8.0 lakh m^3	68.89
Infrastructure Preservation	Avoided Road Reconstruction	Prevention of damage from 53,333 dumper trips	105.00
	Avoided Road Maintenance	2% of reconstruction cost	2.00
	Total Road Infrastructure Savings		107.00
Pontoon Bridge Optimization	Length Reduction per Bridge	400 m × 13 bridges	5.2 km
	Cost per km of Pontoon Bridge	Standard construction cost	₹12 Cr/km
	Total Pontoon Bridge Savings	5.2 km × ₹12 Cr	62.40
Total Gross Benefit	Material + Infrastructure + Bridge Savings	68.89 + 107.00 + 62.40	238.29
Net Financial Outcome	Net Benefit (Profit)	Gross Benefit − Project Cost	230.67
	Return on Investment (ROI)	(230.67 ÷ 7.62) × 100	3,027%
	Profit Multiple	Gross Benefit ÷ Cost	30.27×

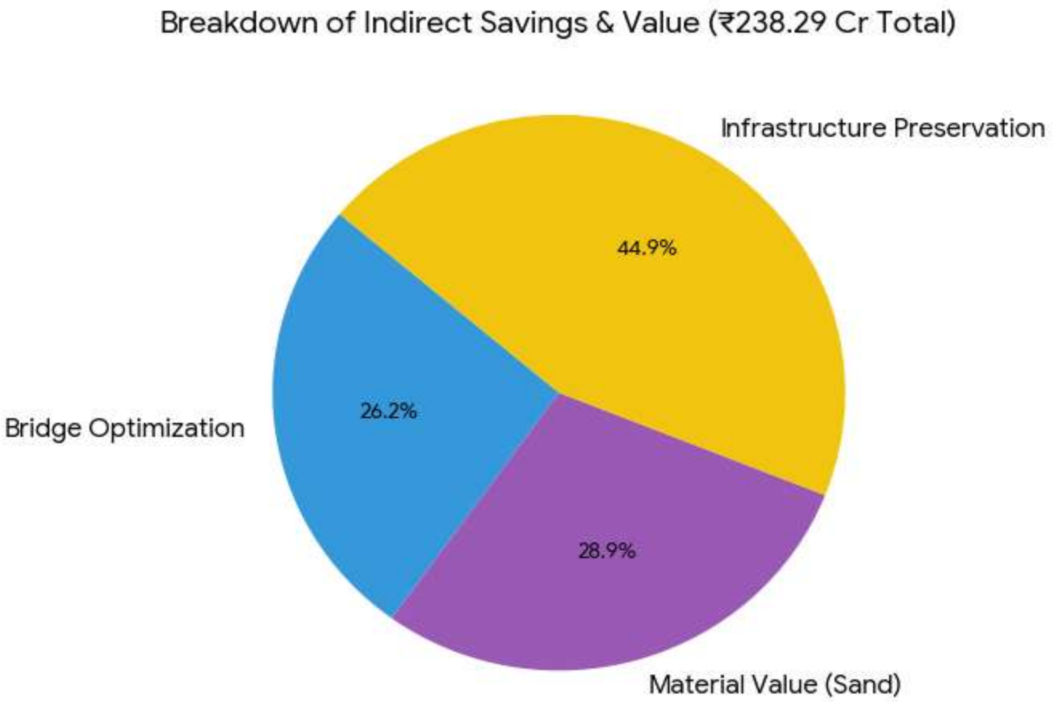

Figure 37: Saving due to Channelisation by Dredging in Ganga River

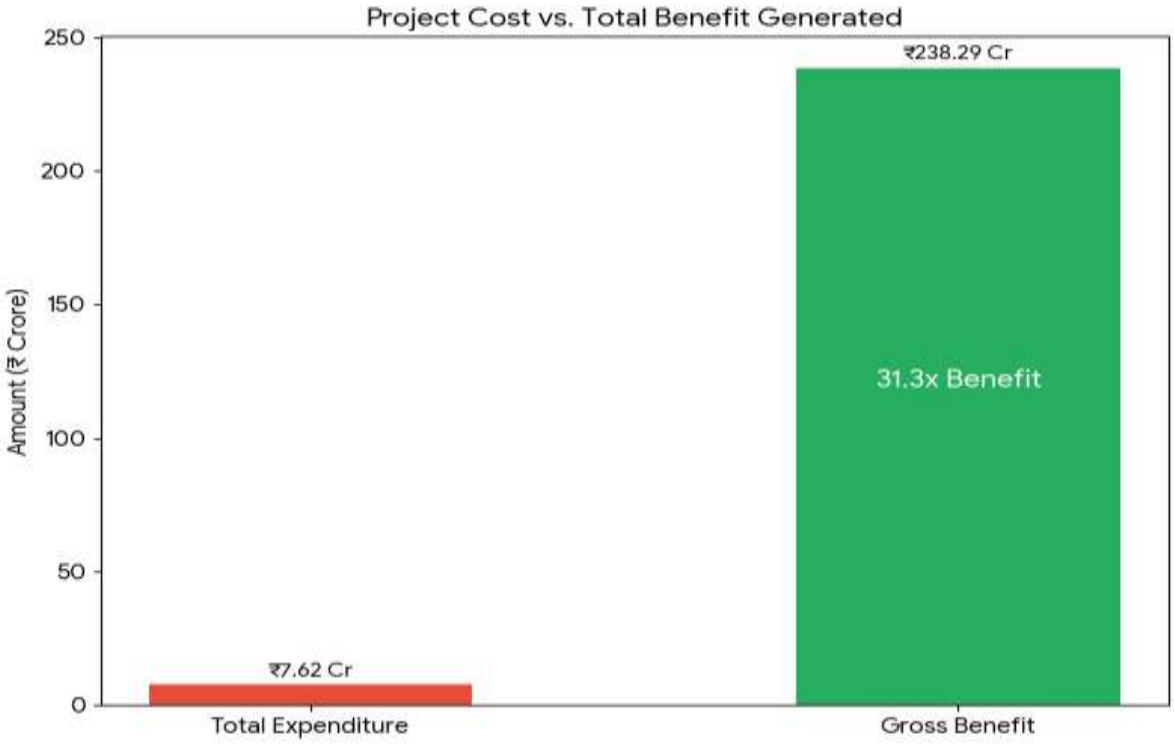

Figure 38: Project Cost and Benefit Representation

Pontoon bridge construction savings reached 62.4 crore rupees through reduced bridge length requirements enabled by channel consolidation. In previous Kumbh Mela events, pontoon bridges spanning the Ganga typically measured approximately 800 meters in length. After channelization merged three fragmented streams into a single central channel, only 350 to 400 meters of pontoon bridges were required between Shastri Bridge and Sangam Nose, generating savings of 400 meters per bridge. With 13 pontoon bridges constructed in the project area, total length saved reached 5.2 kilometers. At a construction cost of 12 crore rupees per kilometer including materials, manpower, installation, two months of operation and maintenance, and all other costs, the total savings from reduced pontoon bridge requirements amounted to 62.4 crore rupees.

Total gross benefit from the channelization project reached 238.29 crore rupees, consisting of material value of 68.89 crore rupees representing 28.9 percent of total benefits, infrastructure preservation of 107.00 crore rupees representing 44.9 percent of total benefits, and bridge optimization of 62.40 crore rupees representing 26.2 percent of total benefits. With project costs of 7.62 crore rupees, net benefit calculated as gross benefit minus project cost totaled 230.67 crore rupees. Return on investment calculated as net benefit divided by project cost and multiplied by 100 reached 3,027 percent, equivalent to 30.27 times return on the initial investment. This extraordinary economic performance demonstrates the viability of integrated river engineering approaches that generate multiple benefit streams. The economic impact aligns with broader observations about the substantial contributions that mass religious gatherings make to regional and national economies (Pandey, 2025).

5.5. Social and Cultural Achievements

The Mahakumbh 2025 accommodated 660 million pilgrims over the 45-day event period, exceeding initial projections of 450 million by 47 percent and establishing the gathering as the largest human congregation in recorded history. Peak bathing occurred on Mauni Amavasya when 80 to 100 million devotees took ritual baths in a single day, testing the capacity of all infrastructure and crowd management systems. Despite these unprecedented numbers, zero major safety incidents occurred throughout the event, demonstrating the effectiveness of the integrated engineering and crowd management approach. The successful accommodation of such massive numbers validated the decision to invest in comprehensive river channelization and land reclamation as essential enabling infrastructure for the spiritual gathering.

All 13 Akharas participating in the Mahakumbh completed their traditional Amrit Snan ceremonies at the expanded Sangam Nose area, maintaining the sacred sequences and rituals that define these spiritual practices. The expanded area enabled Akharas to conduct ceremonies according to traditional protocols without spatial constraints that might have compromised religious observances. Sequential bathing schedules were maintained throughout the event period, ensuring that each Akhara received appropriate time and space for their ritual immersions while managing the flow of millions of individual devotees seeking their own sacred baths.

The Mahakumbh 2025 embodied the principle of "Ek Bharat - Shreshth Bharat" or "One India - Best India" through demonstration of unity in diversity across the massive gathering. International participation brought devotees from numerous countries to join Indian pilgrims in the sacred rituals, reflecting the global reach of Hindu spiritual traditions. Socio-cultural harmony prevailed across all demographic groups including different regions, languages, castes, and socioeconomic backgrounds, with all participants united in their spiritual purpose and respect for the sacred confluence.

The Mahakumbh 2025 contributed an estimated 2 lakh crore rupees to the national economy through direct spending on accommodations, food, transportation, and religious offerings, plus indirect multiplier effects throughout the regional economy. The event increased Uttar Pradesh's Gross Domestic Product by over 1 percent, representing substantial economic stimulus for the state. Employment generation occurred through both direct hiring for event management, infrastructure construction, and service provision, plus indirect employment in supply chains and supporting industries. Tourism infrastructure development undertaken for the Mahakumbh created lasting assets that will support future religious tourism and economic activity in the Prayagraj region. These economic impacts align with research on spiritual tourism development and its contributions to regional economies (Mishra & Maheshwari, 2024; Gambhir et al., 2021; Sharma, 2025; Pandey, 2025).

Figure 39: Amrit Snan at the Sangam Nose on Different Religious Occasions a representation of Ek Bharat - Shreshth Bharat (open resources)

5.6. Crowd Management Capacity Achievements

Comparison between the 2019 Kumbh and 2025 Mahakumbh demonstrates substantial improvements in crowd management capacity enabled by the channelization project. Sangam Nose area expanded from 0.6 hectares to 2.0 hectares, representing a 233 percent increase. Bathing capacity at this sacred location increased from 50,000 pilgrims per hour to between 200,000 and 300,000 pilgrims per hour, representing 400 to 500 percent improvement. Circulation area expanded by 32 hectares of reclaimed land, providing essential space for crowd movement that was severely limited in previous events. Ghat arrangement transformed from scattered locations to linear, organized configurations that improved access and safety. Total pilgrim numbers increased from approximately 120 million in 2019 to 660 million in 2025, a 450 percent increase that was successfully accommodated through the combined engineering interventions.

Table 10: Comparison of 2019 Kumbh and 2025 Mahakumbh

Metric	2019 Kumbh	2025 Mahakumbh	Improvement
Sangam Nose area	0.6 ha	2.0 ha	233%
Bathing capacity	50,000/hr	200,000-300,000/hr	400-500%
Circulation area	Limited	32 ha reclaimed	+32 ha
Ghat arrangement	Scattered	Linear/organized	Optimized
Total pilgrims	~120M	660M	450%

6. DISCUSSION

The documented lateral migration of 500 meters from 2019 and 34 percent loss of Sangam Region area between 2015 and 2024 demonstrate active fluvial processes requiring intervention. This channelization represents the first large-scale effort specifically designed to support mass pilgrimage activities through integrated river engineering, addressing spiritual tourism infrastructure, environmental restoration, and socio-economic development simultaneously.

The dredging operations achieved complete on-site material reuse, contrasting with typical projects requiring off-site disposal. Coordinating four dredgers simultaneously in high-velocity flow conditions represented unprecedented scale for river channelization in India. Infrastructure optimization through channel consolidation reduced pontoon bridge requirements by 62 percent and enabled linear ghat arrangements improving crowd flow patterns. Removal of microplastic-laden sediments through 2.5-meter-deep dredging addressed years of accumulated pollution. Despite 660 million pilgrims participating over 45 days, water quality parameters remained within bathing standards. Dissolved oxygen improvement from 8.0 to 9.0 mg/L indicates robust reaeration processes maintaining healthy oxygen levels.

The return on investment of 3,027 percent represents exceptional economic performance. Integration of material value, road preservation, and bridge optimization demonstrates how thoughtful planning generates multiplicative benefits. The zero-waste model prevented environmental damage from 53,333 dumper trips and external sand mining. Accommodation of 660 million pilgrims while maintaining safety validates the integrated crowd management approach. The dialogue-based approach to cremation site relocation demonstrated respect for local communities. Environmental extremes and psychological pressures tested worker endurance, while real-time problem solving through alignment modifications and innovative launching systems proved essential for maintaining progress.

7. CONCLUSION

The Ganga River channelization for Mahakumbh 2025 achieved remarkable success across engineering, environmental, economic, and social dimensions. Three fragmented streams were unified into a single 250-300-meter-wide channel, while 32 hectares of land were reclaimed and Sangam Nose expanded from 0.6 to 2.0 hectares. This intervention safely accommodated 660 million pilgrims with zero major safety incidents. Environmental restoration removed accumulated plastics, cremation debris, and microplastic-laden sediments. Water quality-maintained bathing standards with pH 7.93-8.18, dissolved oxygen improving from 8.1 to 9.2 mg/L, and biochemical oxygen demand achieving 3.0 mg/L compliance. Economic performance was exceptional with 3,027 percent return on investment. Against costs of 7.62 crore rupees, gross benefits reached 238.29 crore rupees. The intervention achieved complete circular economy principles by reusing all 8.0 lakh cubic meters of dredged material on-site. This project establishes a replicable blueprint for sacred river management merging modern engineering with environmental science and cultural sensitivity, demonstrating that large-scale human activities and environmental sustainability can be synergistically achieved.

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. 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.

REFERENCES

Akhtar, N., Ishak, M., Bhawani, S. A., & Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water, 13*(19), 2660. https://doi.org/10.3390/w13192660

Aldrees, A., Taha, A. T. B., et al. (2022). Prediction of sustainable management of sediment in rivers and reservoirs. *Chemosphere.* https://doi.org/10.1016/j.chemosphere.2022.136369

Barman, J., et al. (2023). Microplastics in freshwater ecosystems of India: Current trends and future perspectives. *ACS Omega, 8*(40), 37158-37174. https://doi.org/10.1021/acsomega.3c01214

Bhattacharjya, R. K., & Kartha, S. A. (2024). Mathematical hydraulic modeling for upstream and downstream stretches of River Ganga at Sangam, Prayagraj. *Unpublished technical report.* IIT Guwahati, Guwahati, Assam, India.

Bogan, M. T., et al. (2024). Macroinvertebrate community development and resilience to channel dredging following flow restoration using effluent in an urban desert river. *Restoration Ecology.* https://doi.org/10.1111/rec.14250

Bulsara, A., et al. (2020). System wide channel network analysis reveals hotspots of morphological change in anthropogenically modified regions of the Ganges Delta. *Scientific Reports.* https://doi.org/10.1038/s41598-020-69688-3

Carling, P., Cao, Z., Holland, M., et al. (2020). Impacts of river engineering on river channel behaviour: Implications for managing downstream flood risk. *Water, 12*(5), 1355. https://doi.org/10.3390/w12051355

Chen, Y. P., Fu, B. J., Zhao, Y., et al. (2020). Sustainable development in the Yellow River Basin: Issues and strategies. *Journal of Clean Production, 263.* https://doi.org/10.1016/j.jclepro.2020.121223

Cheng, Y., Xia, J., Fang, H., et al. (2025). Modelling of flood risks to people's life and property in the Lower Yellow River under different floodplain management modes. *Engineering, 51*(8), 240-253. https://doi.org/10.1016/j.eng.2025.02.011

Chuphal, D. S., et al. (2025). Recent drying of the Ganga River is unprecedented in the last 1,300 years. *Proceedings of the National Academy of Sciences, 122.* https://doi.org/10.1073/pnas.2424613122

Ding, J., & Yang, S. S. (2025). A quantitative assessment framework for water-related policies in large river basins. *Environmental Science and Ecotechnology.* https://doi.org/10.1016/j.ese.2025.100537

Gambhir, D., Khalid, A. M., & Sharma, S. (2021). Religious tourism and sustainable development: Perspectives from hill states in India. In *World sustainability series* (pp. 273–287). https://doi.org/10.1007/978-3-030-59820-4_18

Gao, X., Han, G. L., Zhang, S. T., & Zeng, J. (2025). Sources, water quality, and potential risk assessment of heavy metal contamination in typical megacity river: Insights from Monte Carlo simulation. *Water.* https://doi.org/10.3390/w17020224

Kulkarni, A., & Nath, R. (2025). Mahakumbh 2025 – 'Holy' grail for public health personnel. *Indian Journal of Community Health, 37*(2), 180–182. https://doi.org/10.47203/ijch.2025.v37i02.001

Kumar, R., et al. (2024). Microplastics pollution in Indian marine environment: sources, effects and solutions. *Frontiers in Marine Science, 11.* https://doi.org/10.3389/fmars.2024.1512802

Kumar, S., et al. (2025). Microplastics in Indian freshwater systems: Multidisciplinary analysis of sources, consequences, and mitigation strategies. *Ecotoxicology and Environmental Safety.* https://doi.org/10.1016/j.pce.2025.103942

Liu, Y., et al. (2024). Water quality management could halve future water scarcity cost-effectively in the Pearl River Basin. *Nature Communications, 15.* https://doi.org/10.1038/s41467-024-49929-z

Mandal, M., et al. (2025). Comprehensive study of the microplastic footprint in the urban pond and river of Eastern India. *Scientific Reports, 15.* https://doi.org/10.1038/s41598-025-87452-3

Mishra, D., & Maheshwari, N. (2024). Spiritual tourism development: a comprehensive synthesis for sustainable destination planning and growth. *Journal of Islamic Marketing, 16*(2), 606–626. https://doi.org/10.1108/jima-12-2023-0400

Nair, A. R., Joseph, A., et al. (2024). Seasonal variation, spatial distribution and risk assessment of microplastics in surface waters of Periyar River, Kerala, India. *Environmental Monitoring and Assessment, 196.* https://doi.org/10.1007/s10661-024-12820-x

Nazeer, R., et al. (2005). Impacts of hydraulics and sediment transport in river training works and flood control schemes: Case study Shahroud river. *International Journal of River Basin Management.* https://doi.org/10.1080/15715124.2005.9635260

Pandey, B. S. (2025). Economic impact of Maha Kumbh vs. Hajj: A comparative analysis of tourism, infrastructure, and employment (2000-2024). *Advances in Consumer Research, 2*(2).

Popović, N., et al. (2023). Application of machine learning in river water quality management: a review. *Water Science & Technology, 88*(9), 2297-2315. https://doi.org/10.2166/wst.2023.331

Prasad, G., Mohanty, S., Chakraborty, P., & Bharat, G. K. (2025). Microplastics in the rivers of Gujarat (India) to the Arabian Sea: assessment of the sources, distribution, and associated environmental risk. *Integrated Environmental Assessment and Management, 21*(4), 843-857. https://doi.org/10.1093/inteam/vjaf011

Rahman, M. M., et al. (2024). Prediction of dynamics of riverbank erosion: A tale of the riverine town Chandpur Sadar. *PMC.*

Raven, E. K., Lane, S. N., & Ferguson, R. I. (2024). Anthropogenic river modification as a driver of flood risk change. *Nature Communications Earth & Environment.*

Rotimi, A., et al. (2025). Assessing surface water flood mitigation strategies: A global comparative review. *Journal of Flood Risk Management.* https://doi.org/10.1111/jfr3.70049

Sharma, S. (2025). Tourism finance and temple economics: Shaping India's religious tourism landscape. *International Journal of Unique and New Updates (IJUNU),* ISSN: 3079-4722.

Singh, J., & Yadav, B. K. (2023). Assessment of river channel dynamics and its impact on land use/land cover in the middle Ganga plain, India. *Geomorphology.* https://doi.org/10.1007/s12517-023-11307-2

Singh, J., Yadav, B. K., Schneidewind, U., & Krause, S. (2024). Microplastics pollution in inland aquatic ecosystems of India. *Journal of Hydrology: Regional Studies, 53,* 101798. https://doi.org/10.1016/j.ejrh.2024.101798

Singh, M., et al. (2025). Microplastic pollution in rivers and lakes of India: Sources, ecotoxicological impacts, and removal strategies. *Current Opinion in Environmental Science & Health.* https://doi.org/10.1016/j.impact.2025.100604

Singh, P. K., Singh, A., Srivastava, A. K., et al. (2025). Microplastic pollution in the Ganga River: A state-of-the-art review of pathways, mechanisms, and mitigation. *Water Supply, 25*(2), 249-267. https://doi.org/10.2166/ws.2025.009

Singhal, S., et al. (2024). Ganga, GAP, and lockdown: potential threats to the biodiversity of the river. *Journal of Water and Climate Change, 15*(11), 5482-5502. https://doi.org/10.2166/wcc.2024.322

Slater, L., et al. (2023). Effects of sediment transport on flood hazards: Lessons learned and remaining challenges. *Geomorphology, 441.* https://doi.org/10.1016/j.geomorph.2023.108976

Smith, K., et al. (2024). A global review of river sediment contamination and remobilization through climate change-induced flooding. *Environmental Reviews.* https://doi.org/10.1080/27658511.2024.2440957

Subramanian, G. H., & Verma, A. (2022). Effect of social groups on crowd movement in mass religious gatherings: A case study of Kumbh Mela. *Transportation in Developing Economies, 8,* 8. https://doi.org/10.1007/s40890-021-00145-0

Verma, R. K., Ashwini, K., & Singh, A. (2021). Channel morphology and prediction of mid-line channel migration in the reach of Ganga River using GIS and ARIMA modeling during 1975–2020. *H2Open Journal, 4*(1), 321-335. https://doi.org/10.2166/h2oj.2021.124

Xu, G. C., et al. (2019). Seasonal changes in water quality and its main influencing factors in the Dan River basin. *CATENA, 173,* 131-140. https://doi.org/10.1016/j.catena.2018.10.014

Yousefi, S., et al. (2025). Comprehensive portfolio of adaptation measures to safeguard against evolving flood risks in a changing climate. *Communications Earth & Environment, 6.* https://doi.org/10.1038/s43247-025-02779-z

Zhang, X., Yu, B., Xin, Z., et al. (2025). Spatial–temporal variations of river water quality under human-induced land use changes in large river basins. *Scientific Reports, 15,* 36955. https://doi.org/10.1038/s43247-025-02779-z