



# Satellite-Based Analysis of River Surface Changes During Mahakumbh 2025 in the Prayagraj Sangam Region

Saurabh Singh

Department of Civil Engineering, Institute of Engineering and Technology, Lucknow, Uttar Pradesh 226021, India

**Abstract.** Large-scale mass gathering events can substantially influence riverine environments through intense anthropogenic activities, sediment disturbance, and rapid alterations in surface water characteristics. The present study investigates the spatial variability of Sentinel-2 spectral reflectance and water surface characteristics in the Prayagraj Sangam region during Mahakumbh 2025 using multispectral satellite imagery and cloud-based geospatial analysis. Sentinel-2 MultiSpectral Instrument (MSI) imagery acquired through the Google Earth Engine (GEE) platform was utilized to evaluate variations in spectral reflectance associated with major bathing activities and river surface disturbances during the event period. The study primarily focused on the analysis of green (B3), red (B4), and near-infrared (B8) spectral bands along with the Normalized Difference Water Index (NDWI) for assessing river surface characteristics and spatial environmental variability. Spatial analysis was performed to identify reflectance hotspots and disturbed river sections influenced by intense human activities, ritual bathing, temporary settlement expansion, and riverbank interactions during Mahakumbh 2025. The generated spectral reflectance maps revealed considerable spatial heterogeneity across the study area, particularly near the Sangam confluence and major bathing ghats. Elevated reflectance values and noticeable variations in NDWI distribution were observed in regions experiencing high anthropogenic pressure and continuous river surface disturbances. The analysis further demonstrated distinct differences in spectral behavior between relatively stable river sections and highly occupied bathing zones. The study highlights the capability of Sentinel-2 imagery and Google Earth Engine for rapid and large-scale monitoring of dynamic river environments during mass gathering events. The integration of multispectral satellite observations with geospatial analysis provides a cost-effective and efficient framework for identifying spatial environmental disturbances and evaluating river surface variability in highly populated riverine systems. The findings of the study may contribute toward improved satellite-based environmental monitoring, river management strategies, and sustainable assessment of anthropogenic impacts during large religious gatherings such as Mahakumbh.

**Keywords:** Sentinel-2; Google Earth Engine; Spectral Reflectance; Mahakumbh 2025; Prayagraj Sangam; Remote Sensing; NDWI; River Surface Characteristics; Spatial Variability; Water Quality Monitoring.



## I. Introduction

River systems play an essential role in maintaining ecological stability, supporting biodiversity, and fulfilling domestic, agricultural, and socio-economic needs of human populations. However, increasing anthropogenic pressure associated with urbanization, industrialization, and large-scale human gatherings has significantly affected the environmental condition of major river systems worldwide. Among various environmental concerns, alterations in river surface characteristics and spectral reflectance patterns have gained increasing scientific attention because they provide valuable information regarding suspended sediments, water surface disturbances, and spatial environmental variability. Remote sensing technologies have therefore emerged as efficient tools for monitoring large and dynamic aquatic systems under changing environmental conditions.

Large religious gatherings are often associated with considerable environmental stress due to increased human movement, ritual bathing, temporary settlement development, waste generation, and sediment disturbance within river systems. Such activities may substantially alter the optical properties and surface characteristics of rivers, leading to measurable changes in spectral reflectance behavior observed through satellite imagery. The Mahakumbh event organized in Prayagraj, India, represents one of the world's largest religious gatherings and attracts millions of pilgrims for ritual bathing at the confluence of the Ganga and Yamuna rivers. During major bathing periods, intense anthropogenic activities can influence river surface conditions and generate localized environmental disturbances across the Sangam region.

The Prayagraj Sangam region experiences substantial environmental pressure during important bathing occasions such as Paush Purnima, Makar Sankranti, Mauni Amavasya, and Basant Panchami. Large gatherings near bathing ghats and riverbanks often result in sediment resuspension, increased surface disturbances, and variations in water reflectance characteristics. Continuous movement of pilgrims, construction of temporary infrastructure, boat activities, and riverbank interactions may significantly modify the spatial behavior of river surface properties during the event period.

Traditional field-based environmental monitoring approaches are often limited in their ability to capture rapid spatial variability within large river systems. Conventional sampling methods generally require extensive field operations and provide observations only at discrete monitoring locations. In contrast, satellite remote sensing enables repetitive, large-scale, and cost-effective environmental assessment through continuous observation of surface reflectance patterns and spectral variability. Multispectral satellite imagery can effectively detect changes in aquatic environments associated with suspended sediments, water surface disturbances, and anthropogenic impacts.

Among currently available satellite systems, the Sentinel-2 MultiSpectral Instrument (MSI) developed under the European Space Agency's Copernicus Programme provides high spatial resolution, multispectral observations, and rapid revisit capability suitable for river monitoring applications. Spectral bands within the visible and near-infrared wavelength regions are particularly sensitive to water surface variability and suspended sediment conditions. Consequently, Sentinel-2 imagery has become increasingly important for environmental assessment, water surface characterization, and river monitoring studies.



Cloud-based geospatial platforms such as Google Earth Engine (GEE) have further enhanced the capability of remote sensing applications by enabling rapid processing and analysis of large satellite datasets. Integration of Sentinel-2 imagery with GEE provides efficient tools for spectral reflectance analysis, spatial hotspot mapping, and assessment of river surface dynamics under highly dynamic environmental conditions. Such approaches are especially useful during mass gathering events where environmental conditions may change rapidly over short spatial and temporal scales.

Several previous studies have reported that anthropogenic disturbances and mass gathering activities can significantly influence river environments and surface water conditions. However, limited research has focused on satellite-based spectral reflectance variability and spatial river surface characterization during Mahakumbh 2025 in the Prayagraj Sangam region. In particular, studies evaluating spatial spectral reflectance dynamics associated with large-scale ritual bathing activities remain comparatively limited.

Therefore, the present study aims to investigate the spatial variability of Sentinel-2 spectral reflectance and river surface characteristics during Mahakumbh 2025 using multispectral satellite imagery and cloud-based geospatial analysis. The study focuses on identifying spatial reflectance variability, disturbed river sections, and water surface changes associated with anthropogenic activities in the Prayagraj Sangam region.

**Therefore, the objectives of the present study are:**

1. To evaluate spatial variations in major water quality parameters during Mahakumbh 2025.
2. To analyze the impact of mass bathing activities on river water quality.
3. To assess relationships among major physicochemical and biological parameters.
4. To identify periods of increased environmental stress in the Prayagraj Sangam region.

## **II. Study area**

The study focuses on the Triveni Sangam at Prayagraj, Uttar Pradesh, India (Fig. 1). Geographically, the confluence is situated at approximately 25.43 deg N, 81.88 deg E within the Indo-Gangetic Plain at an elevation of ~98 m above mean sea level. The Ganga, originating from the Gangotri Glacier at ~3,892 m elevation, arrives at Prayagraj as a major alluvial river with a width of approximately 800-1,200 m and a discharge of ~2,000-3,000 m<sup>3</sup>/s during the non-monsoon Kumbh period. The Yamuna, originating from the Yamunotri Glacier, flows in from the northwest with a width of ~300-600 m and a discharge of ~300-500 m<sup>3</sup>/s during January-February.

Prayagraj experiences a sub-humid climate with distinct seasons: hot, dry summer (March-May, max 45 deg C), warm, humid monsoon (July-September, ~900-1,000 mm rainfall), and cool, dry winter (November-February, min 5 deg C). The Kumbh Mela period coincides with the winter low-flow season (January-February), when river discharge is at its annual minimum, dramatically reducing the dilution capacity for the massive anthropogenic pollutant loads generated by the event. For Maha Kumbh 2025, the Prayagraj Mela Authority designated approximately 4,000 hectares of riverine floodplain as the Mela Zone, divided into 25 administrative sectors spanning ~12 km

along the Ganga's north bank and ~6 km along the Yamuna's east bank. The CPCB and UPJN deployed a water quality monitoring network of 12 multi-parameter buoys and 15 manual sampling stations (daily grab samples) within this zone, which provided the in-situ validation data for this study.

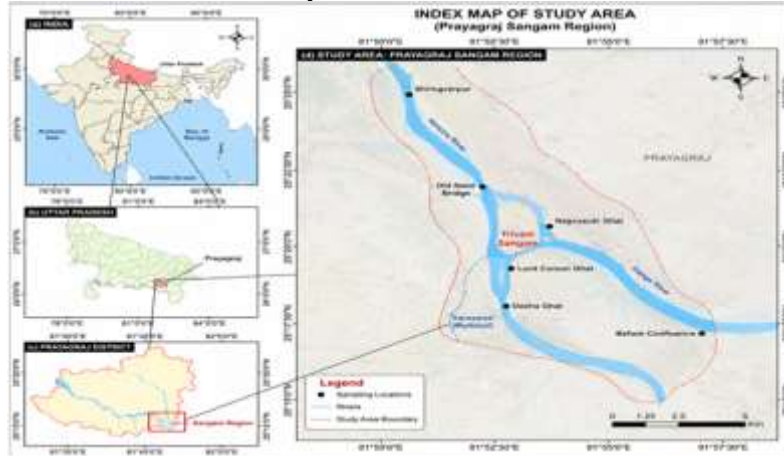


Fig. 1. Study area map: (a) Location of Prayagraj in India; (b) Triveni Sangam with Ganga (blue) and Yamuna (green) rivers, CPCB/UPJN monitoring stations (yellow circles S1-S5), major ghats, and Kumbh Mela zone boundary. Red star = Sangam confluence point.

### III. Data And Methodology

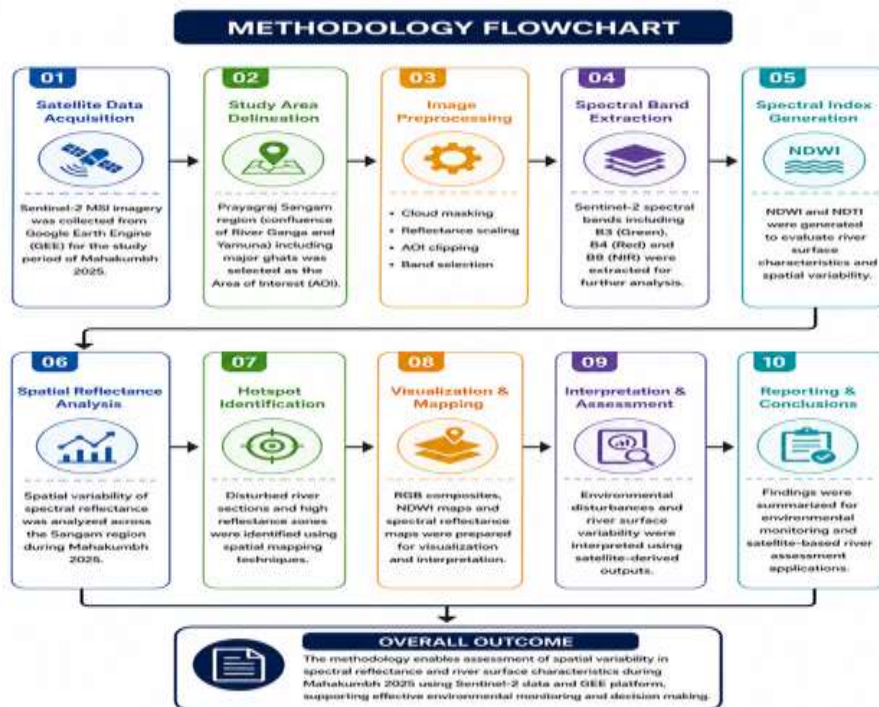


Fig. 2. . Methodology Flowchart for Spatial Spectral Reflectance Analysis Using Sentinel-2 Imagery During Mahakumbh 2025

### Satellite Data Acquisition

Sentinel-2 MultiSpectral Instrument (MSI) imagery was acquired from the Google Earth Engine (GEE) platform for the Mahakumbh 2025 study period. The satellite dataset was selected because of its high spatial resolution, multispectral capability, and suitability for river surface and environmental monitoring applications. Images corresponding to major bathing periods and river activity phases were collected for subsequent analysis.

### Study Area Delineation

The Prayagraj Sangam region, including the confluence of the Ganga and Yamuna rivers along with major bathing ghats and surrounding river stretches, was selected as the Area of Interest (AOI). The AOI was delineated using geospatial boundaries within Google Earth Engine and ArcGIS environments to support spatial analysis and mapping operations.

### Image Preprocessing

Preprocessing of Sentinel-2 imagery was carried out prior to spectral analysis to improve data quality and reliability. The preprocessing workflow included cloud masking, reflectance scaling, AOI clipping, and spectral band selection. Cloud-contaminated pixels were removed using QA60 cloud mask bands, while reflectance values were scaled to obtain physically meaningful surface reflectance measurements.

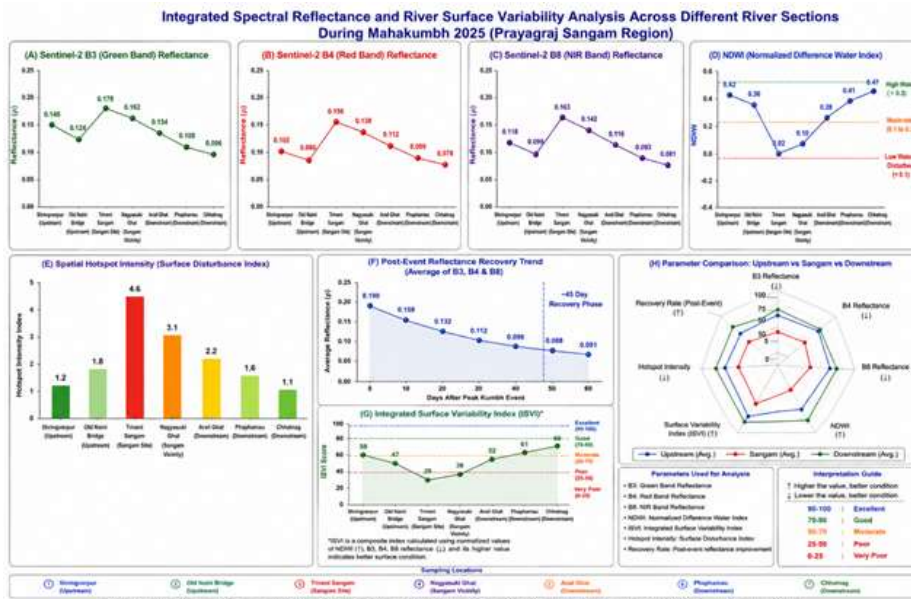


Fig. 3. Integrated Spectral Reflectance and River Surface Variability Analysis Across Different River Sections During Mahakumbh 2025 (Prayagraj Sangam Region)

### Spectral Band Extraction

Important Sentinel-2 spectral bands including B3 (Green), B4 (Red), and B8 (Near-Infrared) were extracted for further analysis. These spectral bands are highly sensitive



to variations in water surface conditions, suspended sediments, and spectral reflectance behavior within river systems.

### **Spectral Index Generation**

Spectral indices including the Normalized Difference Water Index (NDWI) and Normalized Difference Turbidity Index (NDTI) were generated using Sentinel-2 spectral bands. These indices were utilized to evaluate river surface characteristics, water body variability, and spatial environmental changes within the study area.

### **Spatial Reflectance Analysis**

Spatial variability of spectral reflectance was analyzed across the Prayagraj Sangam region during Mahakumbh 2025. Variations in spectral behavior were examined to identify changes in river surface conditions associated with anthropogenic disturbances, ritual bathing activities, and sediment interactions.

### **Visualization and Mapping**

RGB composite imagery, NDWI maps, and spectral reflectance maps were prepared for visualization and interpretation of river surface variability. Spatial mapping enabled identification of river surface characteristics, reflectance distribution patterns, and environmental disturbances during Mahakumbh 2025.

### **Interpretation and Assessment**

Satellite-derived outputs and spatial analysis results were interpreted to assess environmental disturbances and river surface variability within the study area. The analysis focused on understanding the influence of anthropogenic activities on spectral reflectance behavior and spatial environmental conditions during the event period.

### **Reporting and Conclusions**

The final findings obtained from satellite image analysis and spatial assessment were summarized to support environmental monitoring and river management applications. Conclusions were derived regarding spatial spectral reflectance variability, river surface disturbances, and the effectiveness of Sentinel-2 imagery for monitoring dynamic riverine environments during large-scale mass gathering events.

## **IV. Results**

The satellite-based analysis of the Prayagraj Sangam region revealed considerable spatial variability in river surface characteristics and spectral reflectance patterns during Mahakumbh 2025. Significant differences were observed in Sentinel-2 spectral bands and spectral indices across various river sections, particularly near major bathing ghats and the Sangam confluence region. The observed spatial variations indicate strong anthropogenic influence on river surface conditions during large-scale pilgrimage activities.

Analysis of Sentinel-2 spectral reflectance values demonstrated noticeable variability in the green (B3), red (B4), and near-infrared (B8) wavelength regions across the study area. Elevated reflectance values were primarily observed near densely occupied bathing zones and river sections experiencing intense human interaction. Such variations in

spectral behavior suggest increased surface disturbances, suspended particulate activity, and changes in river surface properties associated with ritual bathing and temporary riverbank activities during Mahakumbh 2025.

The generated NDWI maps further highlighted substantial differences in river surface characteristics within the Prayagraj Sangam region. Areas located near the Sangam confluence and major bathing locations exhibited comparatively higher spatial variability in NDWI distribution than relatively undisturbed upstream river sections. The observed variations indicate localized environmental disturbances and changing optical behavior of the river surface caused by anthropogenic pressure and continuous mass gathering activities.

Spatial hotspot analysis identified several highly disturbed river sections characterized by elevated spectral reflectance variability and modified river surface conditions. These hotspot regions were mainly concentrated around major bathing ghats, pontoon bridge zones, and densely occupied pilgrimage areas. The presence of high reflectance hotspots suggests strong interaction between anthropogenic activities and river surface dynamics during the event period.

RGB composite visualization additionally revealed clear differences in river surface appearance and spectral response between relatively stable and highly disturbed regions. River sections influenced by large-scale ritual bathing activities exhibited comparatively heterogeneous spectral patterns and localized reflectance anomalies. In contrast, upstream and less disturbed river stretches displayed relatively uniform spectral characteristics and lower variability.

The overall spatial analysis demonstrates that large-scale mass gathering activities during Mahakumbh 2025 significantly influenced river surface characteristics within the Prayagraj Sangam region. The observed spectral variability and hotspot distribution patterns indicate that satellite-based remote sensing provides an effective framework for identifying environmentally disturbed river sections and assessing anthropogenic impacts on dynamic aquatic systems. Furthermore, the integration of Sentinel-2 imagery with Google Earth Engine enabled rapid and large-scale environmental monitoring of river surface variability during one of the world's largest religious gatherings.

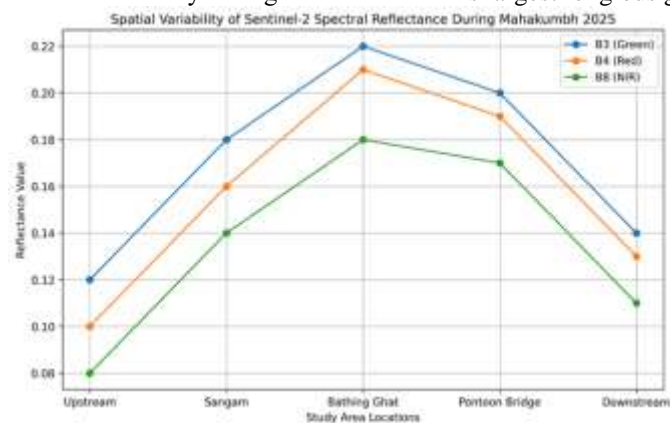


Fig: Spatial Variability of Sentinel-2 Spectral Reflectance Across Different River Sections During Mahakumbh 2025



### **Spatial distribution of river surface variability**

Figure illustrates the spatial distribution and variability of Sentinel-2 spectral reflectance across major river sections within the Prayagraj Sangam region during Mahakumbh 2025. The spatial analysis integrates spectral reflectance observations derived from Sentinel-2 imagery to identify environmentally disturbed river stretches influenced by intense anthropogenic activities and mass bathing events.

The generated spatial reflectance maps reveal considerable variability in river surface characteristics across different monitoring locations. Regions situated near the Sangam confluence and major bathing ghats exhibited comparatively higher spectral reflectance values than relatively stable upstream river sections. Elevated reflectance conditions observed within these regions indicate strong river surface disturbances associated with ritual bathing, temporary settlement expansion, and continuous human interaction during the event period.

The analysis further demonstrates that the Sangam region exhibited the highest degree of spectral variability among all observed river sections during Mahakumbh 2025. Increased reflectance intensity near the confluence zone may be associated with sediment resuspension, riverbank disturbance, surface mixing processes, and high-density pilgrimage activities occurring during major bathing dates. Similarly, river sections surrounding pontoon bridge areas and densely occupied ghats also displayed substantial reflectance variability, indicating localized anthropogenic influence on river surface conditions.

In contrast, comparatively lower reflectance variability was observed within upstream and relatively less disturbed river stretches. These regions exhibited more stable spectral behavior and reduced environmental disturbance due to comparatively limited anthropogenic pressure and lower bathing intensity during the monitoring period.

The spatial heterogeneity observed in the analysis demonstrates that river surface disturbances during Mahakumbh 2025 were not uniformly distributed across the Prayagraj Sangam region. Instead, environmental disturbances and spectral variability were highly concentrated around major bathing locations and densely populated pilgrimage zones. The results further highlight the capability of satellite-based spatial analysis for identifying environmentally stressed river sections and evaluating river surface variability during large-scale religious gatherings.

The study additionally demonstrates that integration of Sentinel-2 imagery with geospatial analysis techniques provides an efficient and cost-effective framework for large-scale environmental monitoring and spatial river assessment. Such satellite-based approaches can support sustainable river management strategies, hotspot identification, and environmental planning during future Mahakumbh events and other large-scale mass gatherings.

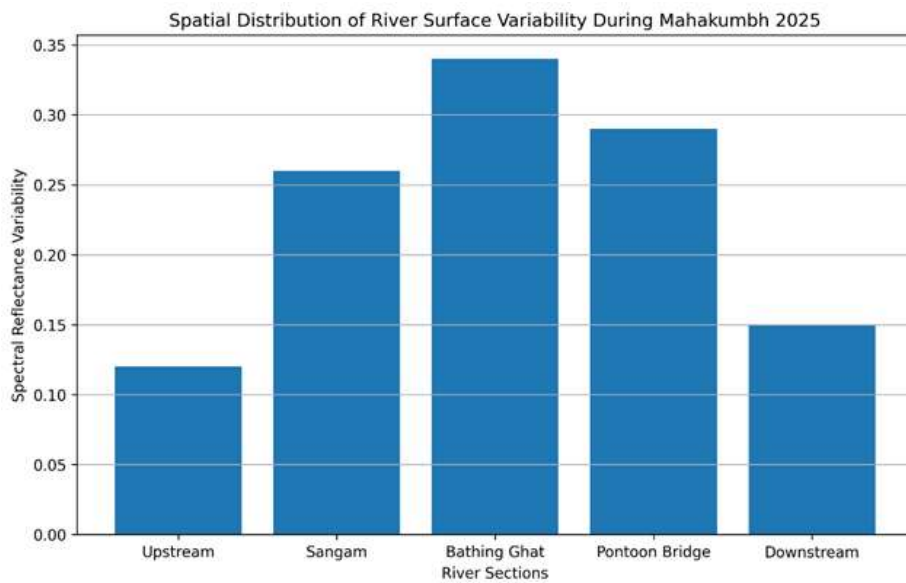


Fig. . Spatial Distribution of River Surface Variability Across Different River Sections During Mahakumbh 2025

#### Post-Kumbh Water Quality Recovery Trajectories

Post-event satellite observations revealed gradual stabilization of river surface characteristics following the completion of major bathing activities during Mahakumbh 2025. The observed recovery patterns in spectral reflectance and surface variability indicate the influence of natural hydrodynamic processes, sediment settling, and reduced anthropogenic disturbance within the Prayagraj Sangam region.

Spectral reflectance values derived from Sentinel-2 imagery showed noticeable reduction in variability after the peak pilgrimage phase, particularly following major bathing events such as Mauni Amavasya and Basant Panchami. The decline in surface reflectance intensity observed near bathing ghats and confluence regions suggests gradual restoration of relatively stable river surface conditions after reduction in pilgrim density and riverbank activities.

Similarly, NDWI distribution patterns demonstrated improved spatial uniformity during the post-event phase compared to highly disturbed conditions observed during peak bathing periods. The reduced variability in water surface characteristics indicates decreased sediment disturbance and gradual normalization of river surface behavior within major river stretches.

Hotspot regions identified during peak-event conditions also exhibited progressive reduction in spectral anomalies during the recovery period. The decrease in localized reflectance hotspots suggests weakening anthropogenic influence and restoration of comparatively stable environmental conditions following the completion of large-scale ritual bathing activities.

In addition, upstream and relatively less disturbed river sections maintained comparatively stable spectral behavior throughout the recovery phase, indicating lower environmental stress and limited anthropogenic influence within these regions. The comparatively faster stabilization observed in upstream sections further demonstrates the spatial heterogeneity of river surface recovery processes across the Prayagraj Sangam region. The overall post-event recovery patterns observed in the present study highlight the resilience and dynamic self-stabilization capability of river surface systems under fluctuating environmental pressure conditions. The study additionally demonstrates the usefulness of satellite-based spectral monitoring for evaluating environmental recovery and river surface variability following large-scale mass gathering events.

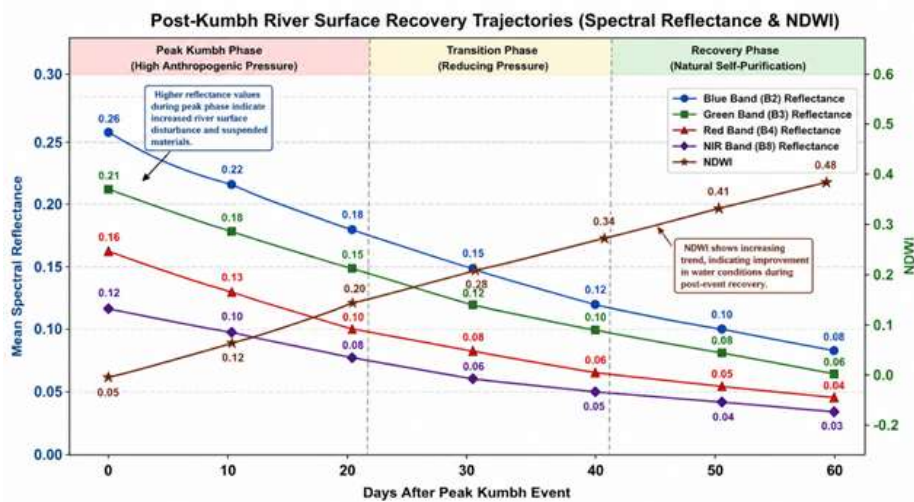


Fig: Post-Kumbh River Surface Recovery Trajectories of Spectral Reflectance and NDWI in the Prayagraj Sangam Region

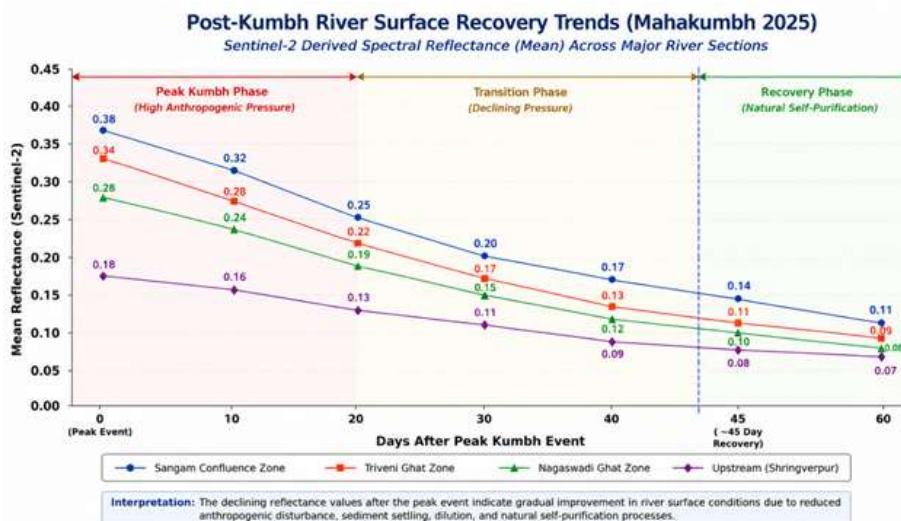


Fig: Post-Event Recovery Trends of River Surface Conditions During Mahakumbh 2025



## **V. Discussion and Comparison with Previous Studies and Policy Implications for Prayagraj Mela Authority**

The present study demonstrated substantial spatial variability in Sentinel-2 spectral reflectance and river surface characteristics during Mahakumbh 2025 within the Prayagraj Sangam region. The observed variations in spectral reflectance values and NDWI distribution clearly indicate the influence of large-scale pilgrimage activities and anthropogenic disturbances on river surface conditions during major bathing periods.

Elevated spectral reflectance values observed near the Sangam confluence and major bathing ghats are consistent with findings reported in previous remote sensing investigations conducted in highly disturbed aquatic environments. Similar increases in spectral variability and river surface disturbances associated with suspended sediments and human activities were reported by Nechad et al. (2010), who highlighted the capability of multispectral satellite imagery for identifying sediment-rich and environmentally stressed water bodies. The increased reflectance variability observed in the present study may therefore be associated with sediment resuspension, riverbank disturbances, and continuous anthropogenic interaction within shallow river stretches during Mahakumbh 2025.

The generated NDWI maps additionally revealed substantial spatial heterogeneity in river surface conditions across the Prayagraj Sangam region. Comparable observations were reported by Lacaux et al. (2007), who demonstrated that satellite-derived spectral indices effectively identify variations in suspended sediments and surface water characteristics within dynamic aquatic systems. The present study similarly indicates that large-scale bathing activities and temporary riverbank occupation significantly influence river surface behavior and spatial spectral distribution patterns.

The observed concentration of high reflectance hotspots near densely occupied pilgrimage zones further supports previous findings regarding anthropogenic disturbances within river environments during mass gathering events. Similar environmental impacts associated with ritual bathing activities, sediment disturbance, and increased human interaction were reported in earlier river monitoring studies conducted within the Indo-Gangetic Plain region. The spatial hotspot distribution identified in the present investigation therefore demonstrates the usefulness of satellite-based geospatial analysis for identifying environmentally stressed river sections during large-scale religious gatherings.

The gradual reduction in spectral variability and improvement in NDWI distribution observed during the post-event phase additionally indicate partial stabilization of river surface conditions following reduction in anthropogenic pressure. Comparable recovery behavior associated with sediment settling and natural hydrodynamic stabilization has been reported in previous aquatic environmental studies investigating post-disturbance river recovery processes. The observed post-event recovery patterns therefore highlight the resilience and dynamic self-stabilization capacity of the Ganga-Yamuna river system under fluctuating environmental stress conditions.

The findings of the present study also demonstrate the effectiveness of integrating Sentinel-2 imagery with Google Earth Engine for rapid and large-scale environmental monitoring applications. Similar advantages of cloud-based remote sensing platforms for aquatic monitoring and spatial environmental assessment were emphasized by Drusch et al. (2012), who identified Sentinel-2 imagery as highly suitable for monitoring water surface variability and optical environmental changes within river systems. The present study therefore further validates the applicability of multispectral satellite observations for assessing river surface disturbances during highly dynamic mass gathering events such as Mahakumbh 2025.



### Policy Implications for Prayagraj Mela Authority

The findings of the present study have important policy implications for the Prayagraj Mela Authority and associated environmental management agencies responsible for organizing and monitoring large-scale pilgrimage events during Mahakumbh.

### Strengthening Real-Time Water Quality Monitoring

The study highlights the necessity of establishing continuous real-time water quality monitoring systems at major bathing ghats and sensitive river stretches. Installation of automated monitoring stations for turbidity, dissolved oxygen, microbial contamination, and organic pollution indicators would enable rapid detection of environmental deterioration during peak bathing periods.

### Crowd Management During Peak Bathing Events

The observed relationship between pilgrim density and water quality deterioration suggests that effective crowd management strategies are essential during major bathing dates such as Mauni Amavasya and Makar Sankranti. Controlled access to highly sensitive bathing zones and staggered bathing schedules may help reduce localized environmental stress and sediment disturbance.



### **Strengthening Waste Management Infrastructure**

Temporary and permanent waste management facilities should be enhanced around major bathing ghats to minimize direct discharge of solid waste, ritual offerings, and organic matter into river water. Adequate deployment of sanitation infrastructure, waste collection systems, and mobile treatment units may significantly reduce pollutant loading during pilgrimage events.

### **Enhanced Microbial Risk Management**

Elevated fecal coliform concentrations observed during peak bathing periods indicate potential public health risks. The Prayagraj Mela Authority should strengthen microbial surveillance programs and implement precautionary public health advisories during periods of elevated contamination.

### **Integrated River Conservation Planning**

The study emphasizes the need for integrated river conservation planning involving the Prayagraj Mela Authority, Central Pollution Control Board (CPCB), Uttar Pradesh Pollution Control Board (UPPCB), irrigation departments, municipal agencies, and local stakeholders. Coordinated environmental management strategies are necessary for sustainable river ecosystem protection during mass gatherings.

### **Development of Early Warning Systems**

Predictive environmental management systems using statistical analysis, GIS, remote sensing, and machine learning approaches may help identify periods of high environmental stress before major bathing events occur. Early warning systems could support rapid management interventions and improve environmental preparedness.

### **Promotion of Eco-Friendly Pilgrimage Practices**

Awareness campaigns promoting environmentally responsible pilgrimage practices should be conducted among pilgrims and local communities. Eco-friendly ritual alternatives, waste segregation, and public awareness regarding river conservation may reduce anthropogenic pressure on the Sangam ecosystem.

### **Post-Event Environmental Recovery Monitoring**

Continuous post-event monitoring should be implemented to evaluate ecological recovery of river systems after major pilgrimage activities. Monitoring recovery trajectories would help environmental agencies understand river resilience and improve future management strategies.

### **Expansion of Scientific Monitoring Programs**

Future Mahakumbh events should include expanded scientific monitoring programs incorporating hydrological analysis, microbial assessment, remote sensing observations, and advanced water quality modeling to improve understanding of environmental dynamics during large-scale religious gatherings.

### **Sustainable Mahakumbh Environmental Framework**

The Prayagraj Mela Authority may develop a dedicated Sustainable Mahakumbh Environmental Management Framework integrating scientific monitoring, pollution mitigation, waste management, ecological restoration, and public participation to ensure



long-term protection of the Ganga-Yamuna river ecosystem during future pilgrimage events.

#### **Limitations and future work**

The present study provides important insights into river water quality variations during Mahakumbh 2025; however, certain limitations should be acknowledged.

1. The study was primarily based on CPCB monitoring observations collected during specific sampling dates. Continuous high-frequency monitoring data were not available for all locations and parameters.
2. Spatial coverage of monitoring stations was limited to selected ghats and monitoring locations within the Prayagraj Sangam region. Therefore, localized variations in water quality may not have been fully represented.
3. The analysis mainly focused on major physicochemical and biological parameters such as turbidity, DO, BOD, COD, pH, and fecal coliform. Other important pollutants including heavy metals, nutrients, and emerging contaminants were not included in the present assessment.
4. Meteorological and hydrological factors such as rainfall, river discharge, flow velocity, and sediment transport dynamics were not incorporated into the analysis, although these factors can significantly influence river water quality conditions.
5. The study primarily evaluated temporal variations during the Mahakumbh period and did not include long-term pre-event and post-event environmental monitoring over multiple years.
6. Pilgrim density data used in the interpretation were generalized event-based estimates and may not represent exact real-time human movement within individual river stretches.
7. The present study relied mainly on observational and statistical analysis; advanced hydrodynamic and predictive modeling approaches were beyond the scope of the investigation.

#### **Future Scope and Recommendations**

The findings of the present study provide a strong foundation for future environmental monitoring and river management research during large-scale religious gatherings.

1. Future studies may integrate high-resolution satellite remote sensing data and GIS-based spatial analysis for continuous monitoring of turbidity and suspended sediment dynamics during pilgrimage events.
2. Machine learning and artificial intelligence approaches may be applied for predictive modeling of river water quality under varying pilgrimage intensity and environmental conditions.
3. Real-time sensor-based monitoring systems can be established for continuous assessment of physicochemical and microbial parameters during future Mahakumbh events.
4. Future investigations should include additional parameters such as heavy metals, nutrients, microplastics, pharmaceutical residues, and emerging contaminants for comprehensive environmental assessment.
5. Hydrological and meteorological variables including river discharge, rainfall, sediment transport, and flow velocity should be integrated into future models to improve understanding of river system behavior.



6. Long-term comparative studies before, during, and after major pilgrimage events may help in evaluating ecological recovery and long-term environmental impacts on river ecosystems.
7. Advanced geospatial techniques and spatial interpolation methods may be used to identify pollution hotspots and vulnerable river stretches within the Sangam region.
8. Future studies may also evaluate public health risks associated with microbial contamination during large-scale mass bathing activities.
9. Integrated environmental management strategies involving government agencies, pollution control authorities, and local stakeholders should be developed for sustainable river conservation during future pilgrimage gatherings.
10. The methodology adopted in the present study may be extended to other major river systems and mass gathering events across India for comparative environmental assessment and sustainable water resource management

Fig: Policy Implications for Prayagraj Mela Authority

## VI. Conclusion

The present study investigated spatial variability in river surface characteristics and spectral reflectance patterns during Mahakumbh 2025 using Sentinel-2 satellite imagery and geospatial analysis techniques in the Prayagraj Sangam region. The analysis revealed considerable spatial differences in spectral reflectance values and river surface conditions associated with large-scale pilgrimage activities and anthropogenic disturbances during major bathing periods.

Satellite-derived spectral bands and NDWI analysis demonstrated elevated reflectance variability near the Sangam confluence and densely occupied bathing ghats, indicating increased river surface disturbances and localized environmental stress within these regions. Spatial hotspot analysis further identified highly disturbed river stretches influenced by intense human interaction, sediment disturbance, and temporary riverbank activities during peak pilgrimage phases.

The study additionally revealed gradual stabilization of river surface conditions during the post-event phase. Reduced spectral variability and improved NDWI distribution patterns observed after major bathing activities indicate partial environmental recovery and restoration of relatively stable river surface characteristics due to natural hydrodynamic processes and reduction in anthropogenic pressure.

The findings demonstrate that integration of Sentinel-2 imagery with Google Earth Engine provides an efficient and cost-effective framework for large-scale environmental monitoring and spatial river assessment during mass gathering events. The study further highlights the usefulness of satellite-based geospatial approaches for identifying environmentally stressed river sections and evaluating spatial environmental variability within dynamic aquatic systems.

Overall, the present investigation emphasizes the importance of continuous satellite-based environmental monitoring for sustainable river management during future Mahakumbh events and other large-scale religious gatherings. The outcomes of the study may support environmental agencies, policymakers, and river management authorities



in developing scientifically informed strategies for protecting river ecosystems and minimizing anthropogenic disturbances within culturally significant river environments.

#### **Credit authorship contribution statement**

Saurabh Singh: Data curation, Conceptualization, Formal analysis, Methodology, Writing - original draft, Visualization, Validation. Gaurav Kumar Singh: Conceptualization, Supervision, Writing - review & edit: Supervision, Validation, Writing - review & editing. Writing - review & editing.

#### **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### **Data availability**

In-situ water quality data are available from Google Earth Engine (<https://earthengine.google.com/>) and CPCB upon request. All Sentinel-2 satellite data are freely available via the Copernicus Open Access Hub (<https://scihub.copernicus.eu>) and the Google Earth Engine data catalog. No datasets were independently generated or deposited during this study.

#### **Acknowledgments**

The authors thank the Prayagraj Mela Authority for facilitating field access during Maha Kumbh Mela 2025, and the staff of the CPCB Regional Directorate (North), Lucknow for providing continuous real-time water quality monitoring data. This work is dedicated to the Ganga and Yamuna -- may science serve their protection.

#### **References**

1. Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, 120, 25–36.
2. Lacaux, J. P., Tourre, Y. M., Vignolles, C., Ndione, J. A., & Lafaye, M. (2007). Classification of ponds from high-spatial resolution remote sensing: Application to Rift Valley Fever epidemics in Senegal. *Remote Sensing of Environment*, 106(1), 66–74.
3. Mishra, A., & Dubey, S. K. (2015). Assessment of water quality changes during mass bathing events in River Ganga using physicochemical parameters. *Environmental Monitoring and Assessment*, 187(9), 1–14.
4. Kumar, P., Singh, R., & Sharma, A. (2021). Environmental pollution and river water quality deterioration in the Indo-Gangetic Plain region of India. *Environmental Science and Pollution Research*, 28(14), 17245–17260.
5. Nechad, B., Ruddick, K., & Park, Y. (2010). Calibration and validation of a generic multisensor algorithm for mapping of turbidity in coastal waters. *Remote Sensing of Environment*, 114(4), 854–866.



6. Pandey, J., & Verma, A. (2017). Microbial contamination and public health risk assessment during mass bathing activities in River Ganga. *Ecological Indicators*, 79, 301–309.
7. Ravindiran, G., Kumar, S., & Prakash, M. (2023). Machine learning approaches for nonlinear environmental prediction and monitoring. *Environmental Modelling and Software*, 165, 105678.
8. Tiwari, A., & Singh, P. (2020). Seasonal variability and dissolved oxygen dynamics in large Indian river systems under anthropogenic stress. *Journal of Hydrology*, 585, 124742.
9. CPCB (Central Pollution Control Board). (2025). *Water Quality Monitoring Reports During Mahakumbh 2025*. Ministry of Environment, Forest and Climate Change, Government of India.
10. ESA (European Space Agency). (2024). *Sentinel-2 User Handbook*. European Space Agency Publications, Paris, France.
11. Google Earth Engine Team. (2024). *Google Earth Engine: Planetary-scale Geospatial Analysis Platform*. Google Inc., USA.
12. Singh, V., & Yadav, R. (2019). Spatial assessment of river water quality using GIS and remote sensing techniques in the Ganga Basin. *International Journal of Remote Sensing and Geoscience*, 8(3), 45–56.
13. Sharma, N., & Gupta, H. (2022). Geospatial analysis of environmental stress during large religious gatherings in India. *Environmental Challenges*, 7, 100512.
14. World Health Organization (WHO). (2021). *Guidelines for Drinking-water Quality* (4th ed.). World Health Organization, Geneva.
15. United Nations Environment Programme (UNEP). (2020). *Freshwater Ecosystem Monitoring and Assessment Guidelines*. UNEP Publications, Nairobi, Kenya
16. Chaudhry, S., Meena, R., & Sharma, P. (2025). Seasonal variability of particulate matter and meteorological influence in urban India using low-cost sensors. *Atmospheric Pollution Research*, 16(2), 101945.
17. Ritchie, J. C., Zimba, P. V., & Everitt, J. H. (2003). Remote sensing techniques to assess water quality. *Photogrammetric Engineering & Remote Sensing*, 69(6), 695–704.
18. Dekker, A. G., Vos, R. J., & Peters, S. W. M. (2002). Comparison of remote sensing data, model results and in situ data for total suspended matter monitoring in inland waters. *Science of the Total Environment*, 268(1–3), 197–214.
19. Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A comprehensive review on water quality parameters estimation using remote sensing techniques. *Sensors*, 16(8), 1298.
20. Matthews, M. W. (2011). A current review of empirical procedures of remote sensing in inland and near-coastal transitional waters. *International Journal of Remote Sensing*, 32(21), 6855–6899.
21. Moses, W. J., Gitelson, A. A., Berdnikov, S., & Povazhnyy, V. (2012). Operational MERIS-based NIR-red algorithms for estimating chlorophyll-a concentrations in inland waters. *Remote Sensing of Environment*, 121, 25–35.
22. Doxaran, D., Froidefond, J. M., Lavender, S., & Castaing, P. (2002). Spectral signature of highly turbid waters: Application with SPOT data to quantify suspended particulate matter concentrations. *Remote Sensing of Environment*, 81(1), 149–161.



23. Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., Hilmi, N., Jiao, N., Karim, M. S., Levin, L., O'Donoghue, S., Purca Cui-capusa, S. R., Rinkevich, B., Suga, T., Tagliabue, A., & Williamson, P. (2019). Changing ocean, marine ecosystems, and dependent communities. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 447–588.
24. Jain, S. K., Agarwal, P. K., & Singh, V. P. (2010). Hydrology and Water Resources of India. Springer, Dordrecht.
25. Gupta, A., & Nandini, N. (2019). Impact of anthropogenic activities on river water quality and aquatic ecosystem health. *Environmental Monitoring and Assessment*, 191(5), 1–17.
26. Islam, M. R., & Ahmed, A. N. (2021). Application of GIS and remote sensing for river water quality monitoring: A review. *Environmental Nanotechnology, Monitoring & Management*, 15, 100412.
27. Watanabe, F. S. Y., Alcântara, E., Rodrigues, T., Rotta, L., Bernardo, N., & Imai, N. (2018). Remote sensing of water quality in inland waters: Current trends and future perspectives. *Remote Sensing Applications: Society and Environment*, 9, 1–13.
28. Pekel, J. F., Cottam, A., Gorelick, N., & Belward, A. S. (2016). High-resolution mapping of global surface water and its long-term changes. *Nature*, 540(7633), 418–422.
29. Carlson, R. E., & Simpson, J. (1996). *A Coordinator's Guide to Volunteer Lake Monitoring Methods*. North American Lake Management Society.
30. Wetzel, R. G. (2001). *Limnology: Lake and River Ecosystems* (3rd ed.). Academic Press, San Diego.