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From Monitoring to Meaning: Translating Long-Term River Water Quality Data and Earth Observation into SDG-Aligned Policy Intelligence

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Abstract

River water quality monitoring systems worldwide generate extensive long-term datasets, yet their use in policy and sustainability reporting remains largely limited to compliance-based assessments. Under the Sustainable Development Goals (SDGs), particularly SDG-6, there is a growing need to demonstrate spatially coherent, trend-based improvement in water quality and protection of aquatic ecosystems. This study presents an integrative framework that transforms routine river water quality monitoring data into SDG-aligned policy intelligence through systematic integration with satellite reflectance information. Using the Mahi River Basin as a representative medium-scale river system, long-term in-situ observations are combined with Earth observation data to reinterpret water quality in terms of signals, trajectories, and river-reach behavior rather than isolated parameters and stations. The analysis emphasizes temporal consistency, spatial coherence, and persistence of stress or recovery patterns, enabling differentiation between chronic degradation, transitional recovery, and emerging risk zones. Building on this synthesis, a policy translation framework links monitoring intelligence to interpretive diagnostics and action prioritization. The approach demonstrates how existing monitoring systems can be repurposed to support SDG-6 reporting, ecosystem-oriented governance, and targeted river basin management without new monitoring infrastructures, and is transferable to data-constrained river basins globally.

Keywords: Water Quality Governance, SDG-6 Implementation, Science–Policy Interface, Earth Observation Integration, River Basin Sustainability

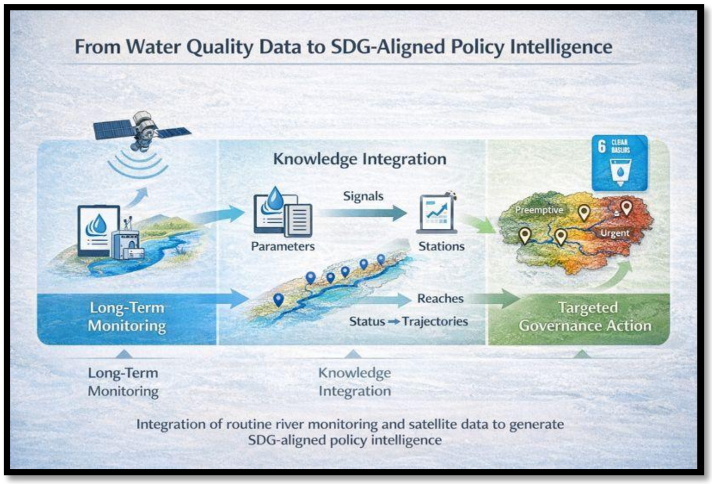

Figure 1: Graphical Abstract

(Integration of routine river monitoring and satellite data to generate SDG-aligned policy intelligence)

Highlights

- Long-term monitoring data are reframed into SDG-aligned policy intelligence
- Integration of in-situ and satellite data enables reach-scale water quality assessment
- Water quality is interpreted through signals and trajectories, not static compliance
- A three-tier framework links monitoring, diagnostics, and governance action
- Approach is scalable and transferable to data-constrained river basins globally

1. Introduction

River water quality monitoring systems have expanded globally over recent decades, generating extensive long-term datasets intended to support environmental protection and resource management [1,2]. Despite this growth, the use of monitoring data remains largely confined to compliance-based assessment, with limited translation into decision-oriented governance or sustainability planning [3,4]. The Sustainable Development Goals (SDGs), particularly SDG-6, represent a conceptual shift from static status reporting toward integrated, trajectory-based evaluation of water quality improvement and ecosystem protection [5,6]. Achieving SDG-6.3 and SDG-6.6 requires analytical approaches capable of capturing temporal trends, spatial heterogeneity, and cumulative pressures across river systems rather than isolated parameter exceedances [7,8]

At the same time, advances in satellite Earth observation have expanded opportunities for spatially continuous monitoring of surface water characteristics [9,10]. However, Earth observation products are frequently developed as parallel research tools rather than being systematically integrated into statutory monitoring and governance frameworks [11]. This separation limits their potential contribution to sustainability-oriented decision-making. This study addresses this gap by integrating long-term statutory water quality monitoring data with satellite reflectance information to generate SDG-aligned policy intelligence. Using the Mahi River Basin as a representative medium-scale river system, the analysis demonstrates how existing datasets can be reinterpreted to support sustainability governance without creating new monitoring infrastructures [12]

Across the world, rivers are increasingly recognized as integrative indicators of sustainability performance, reflecting cumulative pressures from land transformation, urbanization, industrialization, and climate variability. Global assessments consistently show that a large proportion of river systems exhibit declining water quality despite decades of monitoring and regulatory intervention, with the most pronounced deterioration occurring in rapidly developing regions of Asia, Africa, and Latin America. In India, this challenge is particularly acute: while an extensive statutory monitoring network exists and generates large volumes of water quality data annually, many major rivers and their tributaries continue to experience persistent or worsening degradation at basin and sub-basin scales. Similar patterns are evident at the state level, where river stretches often oscillate between seasonal compliance and chronic stress, masking long-term trajectories of decline or partial recovery.

Such disconnects between data availability and governance outcomes highlight a fundamental limitation of prevailing water quality assessment paradigms. Monitoring systems are typically designed for compliance verification rather than for diagnosing systemic stress, identifying cumulative impacts, or informing spatially differentiated interventions. As a result, rivers that are structurally degraded may appear intermittently compliant, while early warning signals of emerging stress remain undetected. In contrast, the Sustainable Development Goals, particularly SDG-6.3 and SDG-6.6, require countries to demonstrate sustained improvement in water quality and protection of water-related ecosystems over time, across space, and along entire river networks. Meeting these requirements demands analytical approaches that can translate routine monitoring data into knowledge about trajectories, persistence, vulnerability, and recovery potential.

Against this backdrop, the present study positions river water quality monitoring not as an endpoint, but as a starting point for sustainability-oriented knowledge translation. Using a representative Indian river system and long-term statutory monitoring data complemented by satellite Earth observation, the paper demonstrates how existing datasets can be reinterpreted to bridge the gap between measurement and meaning. The approach explicitly aligns empirical analysis with SDG expectations by reframing water quality assessment from static status checks to reach-scale, trajectory-based diagnosis. In doing so, the study provides a structured pathway from data to knowledge to policy, setting the foundation for the subsequent sections that detail the analytical framework, results synthesis, governance interpretation, and actionable policy insights presented in this paper.

2. Conceptual Framework: Monitoring Data to Policy Intelligence

2.1 Rethinking River Water Quality Assessment

Conventional river water quality assessment frameworks are largely designed around compliance verification, focusing on parameter-wise exceedances at individual monitoring stations. While such approaches are essential for regulatory oversight, they offer limited insight into the systemic behaviour of river basins, particularly in contexts where pressures accumulate gradually across space and time. As a result, rivers may appear intermittently compliant while undergoing long-term structural degradation, and early warning signals of emerging stress often remain undetected. Sustainability-oriented governance, however, requires analytical approaches that move beyond static status checks toward understanding how river systems evolve, respond to pressures, and recover, or fail to recover, over time. This necessitates a shift from snapshot-based assessment to trajectory-based interpretation, where the persistence, seasonality, and spatial propagation of stress signals become central to diagnosis and decision-making.

2.2 From Parameters to Signals

Individual water quality parameters, when interpreted in isolation, provide limited governance value. In contrast, sustainability-relevant insights emerge when parameters are examined collectively as signals that reflect underlying processes and pressures. Signals such as seasonal amplification, downstream persistence, and multi-parameter coherence indicate systemic stress regimes rather than isolated anomalies. In this framework, parameters related to organic pollution, salinity, nutrients, and sediments are not treated as independent indicators but as interrelated expressions of land use change, hydrological connectivity, and anthropogenic loading. Translating parameters into signals enables differentiation between transient perturbations and structurally embedded degradation, thereby strengthening the interpretive power of routine monitoring data.

2.3 From Monitoring Stations to River Reaches

Most monitoring networks are station-centric by design, producing point-based observations that are often difficult to translate into basin-scale governance action. However, river management decisions, such as pollution control, restoration, or conservation, are typically implemented at reach or segment scales, where upstream–downstream interactions and cumulative effects become operationally relevant. Accordingly, this study adopts a reach-based framing, aggregating station-level observations into analytically meaningful river segments. This approach enables assessment of cumulative pressures, spatial continuity of stress, and differential vulnerability across the river network. By shifting the analytical unit from stations to reaches, the framework aligns scientific assessment more closely with planning, regulation, and SDG reporting requirements.

2.4 From Status to Trajectories

A central element of the framework is the transition from static status assessment to trajectory analysis. Rather than asking whether a river reach meets prescribed standards at a given point in time, the framework examines how water quality evolves across seasons and years. Trajectories capture whether conditions are persistently degraded, seasonally vulnerable with partial recovery, or relatively stable despite external pressures. This distinction is critical for sustainability governance. Persistent degradation signals the need for structural intervention, seasonal vulnerability highlights opportunities for targeted preventive action, and relative stability points to conservation priorities. Trajectory-based interpretation thus provides a basis for differentiated governance responses, avoiding one-size-fits-all management strategies.

2.5 From Knowledge to SDG-Oriented Policy Action

The final step of the conceptual framework explicitly links scientific interpretation to policy-relevant action in alignment with the Sustainable Development Goals. In particular, SDG-6.3 and SDG-6.6 require evidence of sustained improvement in water quality and protection of water-related ecosystems across entire river systems, rather than isolated compliance at monitoring points. Meeting these targets depends not only on the availability of monitoring data, but on the capacity to translate routine observations into actionable governance intelligence.

Operationalizing this framework, river reaches in the present study were classified according to dominant water quality trajectories rather than isolated observations or station-level compliance. Figure 2 synthesizes these spatio-temporal trajectories across the Mahi River Basin, offering a system-level perspective that distinguishes persistently degraded reaches, seasonally vulnerable segments, and relatively stable zones. This trajectory-based synthesis provides the empirical foundation for moving from measurement to interpretation. Complementing this results-oriented view, Figure 2 articulates the conceptual integration pathway through which satellite reflectance spatially amplifies statutory ground-based monitoring. It illustrates how parameters are translated into signals, monitoring stations into analytically meaningful river reaches, and static status assessments into dynamic trajectories that support reach-scale diagnosis and policy prioritization. Anchored in sustainability science and SDG-6 frameworks, this integrative approach repurposes routine datasets into actionable governance intelligence, enabling identification of priority reaches, timing of interventions, and evaluation of long-term progress.

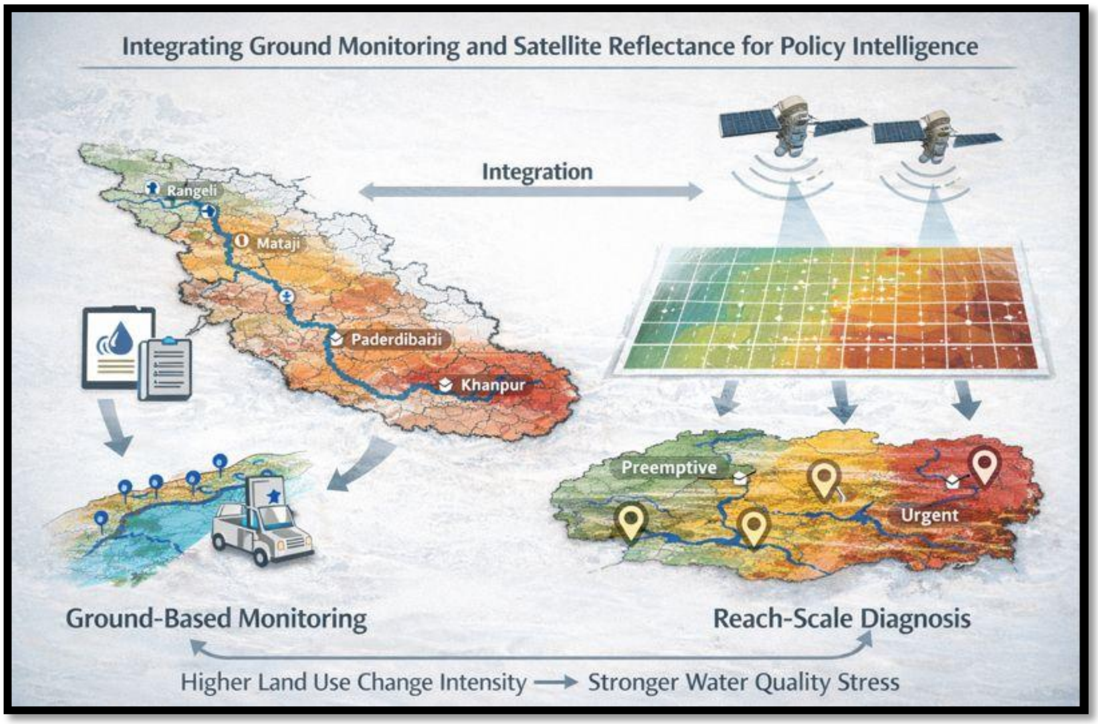

Figure 2: Conceptual Framework for Integrating Ground-Based Monitoring and Satellite Reflectance into Reach-Scale Policy Intelligence

3. Materials, Data Architecture, and Methods

3.1 Study System and Analytical Framing

The Mahi River Basin in western India was selected as a representative medium-scale river system exhibiting multi-sectoral pressures typical of semi-arid and sub-humid regions of the Global South. The basin traverses diverse physiographic, land-use, and socio-economic settings, including agricultural command areas, urban–industrial clusters, forested uplands, and ecologically sensitive downstream reaches. To enable spatial differentiation and policy-relevant interpretation, the basin was analytically partitioned into four nested units, Angeli, Mataji, Paderdibadi, and Khanpur, representing upstream to downstream transitions within the river network. Rather than treating these units as isolated sub-basins, the analysis conceptualizes them as linked river reaches, allowing assessment of cumulative impacts, upstream–downstream interactions, and reach-specific stress trajectories. This reach-based framing aligns more closely with river basin governance and SDG reporting requirements than conventional station-centric analysis. The reach-based analytical framing adopted in this study aligns with integrated water resources management and sustainability science perspectives that emphasize system behaviour and cross-scale interactions [13,4]

3.2 Ground-Based Water Quality Data

The use of long-term statutory monitoring data in this study aligns with established practices in river water quality assessment and environmental governance, where continuity, comparability, and regulatory legitimacy are critical [14,2]. Such datasets are particularly valuable for diagnosing systemic trends and cumulative pressures that are not evident from short-term or event-based observations. Long-term river water quality data were obtained from the statutory monitoring network of the Central Water Commission (CWC), Government of India. Monthly observations spanning a ten-year period (2006–2016) were analyzed, providing sufficient temporal depth to examine seasonal patterns, inter-annual variability, and longer-term trajectories. This dataset constitutes one of the few systematically generated and quality-controlled water quality archives available for a medium-scale river basin in India, thereby offering a robust empirical foundation for trajectory-based interpretation.

Eighteen key water quality parameters were selected to capture the physical, chemical, and biological dimensions of river health. These include indicators of organic pollution (BOD, COD, DO), salinity and ionic composition (EC, Na, K, TDS), nutrients (NO_3-N, NO_3, P), sediment and turbidity dynamics (suspended solids, turbidity, Secchi depth), alkalinity and hardness (APT, TA), temperature, and microbiological contamination (total coliforms). Together, this parameter set provides a comprehensive representation of river water quality relevant to ecosystem integrity, agricultural use, and pollution management. To explicitly account for monsoon-driven hydrological variability, the dataset was structured into two analytically meaningful seasonal periods: a Dry season (January–June) and a Wet season (July–December). This seasonal framing facilitates interpretation of dilution effects, runoff-driven pollutant loading, and seasonal stress windows, and is directly relevant to river management and SDG-6 reporting. Seasonal differentiation of water quality responses is widely recognized as essential for understanding hydrological and pollution dynamics in monsoon-dominated river systems [15,16]

3.3 Land Use and Land Cover (LULC) Data

The influence of land-use change as a dominant driver of river water quality outcomes is well established in basin-scale studies across diverse hydro-climatic settings [17-19]. Changes in land cover alter runoff pathways, pollutant mobilization, and sediment delivery, thereby shaping cumulative water quality responses along river networks.

In this study, land use and land cover (LULC) information was derived from multi-temporal Landsat imagery (Landsat-7 ETM+ and Landsat-8 OLI/TIRS), processed at five-year intervals between 2006 and 2016. Standard supervised classification techniques were applied to delineate major LULC categories, including agricultural land, forest cover, surface water bodies, bare land, and urban or built-up areas. Classification outputs were cross-validated using ancillary thematic datasets and available ground reference information to ensure consistency across time periods. Rather than treating LULC as a static background descriptor, land-use transitions were explicitly incorporated as explanatory stressors influencing river water quality trajectories. Quantified changes in landscape composition were examined alongside long-term water quality patterns to identify plausible linkages between land transformation, pollutant loading, and river system response. This approach enables interpretation of water quality degradation as an emergent outcome of cumulative land-use dynamics rather than isolated point-source effects. Satellite reflectance data were integrated to extend this analysis spatially. Satellite-based approaches have been widely used to infer water quality characteristics, particularly for optically active constituents such as sediments and organic matter [21,22,9].Consistent with a sustainability-oriented perspective, the present study adopts an integration-focused approach that prioritizes spatial amplification, screening, and prioritization over precise parameter prediction. This integration supports reach-scale diagnosis of water quality stress and strengthens the linkage between empirical observation and governance-relevant interpretation.

3.4 Earth Observation Data

Satellite-based surface reflectance data were derived from Landsat imagery corresponding to the study period. Reflectance values were extracted for river surface pixels co-located with Central Water Commission (CWC) monitoring stations and extended spatially along river reaches to enable reach-scale interpretation. Standard atmospheric correction and reflectance conversion procedures were applied to ensure temporal consistency across images and seasons. Satellite reflectance was not employed as a substitute for in-situ measurements but as a spatial amplifier of point-based monitoring data [23]. The integration philosophy emphasizes coherence between ground-measured water quality signals and satellite-observed reflectance patterns, allowing station-limited observations to be interpreted in a spatially continuous manner. Empirical relationships between reflectance values and selected water quality parameters were explored using multiple linear regression analysis. Rather than prioritizing individual predictive equations, the analysis focused on demonstrating the feasibility and indicative strength of satellite-enabled estimation, particularly for extending diagnostic capability to ungauged or sparsely monitored river segments [24].

3.5 Data Synthesis and Analytical Approach

The analytical strategy was deliberately oriented toward knowledge translation rather than parameter optimization, consistent with the study's governance-focused objectives. Monthly observations were aggregated to reveal inter-annual and seasonal water quality trajectories, while comparative analysis across upstream–downstream river reaches enabled identification of cumulative and spatially differentiated stress patterns [25]. Water quality signals were further interpreted to distinguish persistent degradation, emerging vulnerabilities, and transient perturbations in relation to land-use transitions and monsoon-driven hydrological seasonality. To characterize variability and persistence, statistical summaries including ranges, medians, and interquartile spreads were emphasized over simple mean values. This approach facilitates differentiation between episodic exceedances and structurally degraded conditions—an essential distinction for policy-relevant diagnosis, prioritization of interventions, and sustainability-oriented river governance.

3.6 Methodological Scope and Limitations

The study relies on routinely collected monitoring data and open-access satellite products, which ensures scalability and transferability but also imposes certain constraints. Spatial sparsity of monitoring stations, indirect nature of satellite proxies, and parameter-specific variability in predictive strength are acknowledged limitations. These constraints are addressed not by methodological complexity but through integrative interpretation, emphasizing robustness of trends and coherence of signals over exact point prediction [26].

4. Results

The results presented in this section move beyond parameter-wise reporting to synthesize river water quality behaviour as an integrated spatio-temporal system. Rather than interpreting observations as isolated exceedances or seasonal fluctuations, the analysis aggregates long-term monitoring data across space, season, and river reaches to reveal dominant trajectories and persistent stress signals. This synthesis approach enables identification of patterns that are not evident through conventional station-based or annual-average assessments, including cumulative degradation, seasonal vulnerability, and relative stability across different segments of river network.

By structuring results around trajectories instead of snapshots, the analysis distinguishes between transient perturbations and structurally fixed stress regimes. Seasonal amplification during monsoon periods, downstream persistence of multiple stress indicators, and coherence across physical, chemical, and biological parameters together point to underlying drivers linked to land-use transitions, hydrological connectivity, and anthropogenic pressure. These patterns provide a more policy-relevant understanding of river water quality, highlighting where degradation is chronic, where systems remain resilient, and early warning signals of emerging stress are detectable.

In this sense, the Results section functions as a knowledge translation layer, converting long-term empirical observations into interpretable signals that can inform governance decisions and SDG-oriented assessment. The subsections that follow present this synthesis progressively, first by establishing the spatio-temporal structure of water quality variability, then by examining key stress domains, and finally by integrating these insights into reach-scale trajectories that form the basis for subsequent discussion on governance and policy implications.

4.1 Spatio-Temporal Structure of River Water Quality

Analysis of the ten-year monthly dataset (2006–2016) reveals that river water quality in the Mahi Basin is characterized by strong spatial differentiation and pronounced seasonal structuring, rather than uniform basin-wide behaviour. Across the four analytically defined river reaches, variability in water quality parameters consistently exceeded short-term fluctuations, indicating the dominance of structural drivers over episodic events. Seasonal separation into Dry (January–June) and Wet (July–December) periods highlighted systematic contrasts in parameter behaviour. Several parameters exhibited amplified dispersion during the Wet period, reflecting the combined influence of monsoon runoff, land-surface flushing, and effluent transport. Importantly, these seasonal patterns were spatially non-uniform, with downstream reaches exhibiting higher persistence of stress signals compared to upstream segments.

This spatio-temporal heterogeneity underscores the limitations of basin-averaged reporting and reinforces the relevance of a reach-based interpretation for governance and SDG-oriented assessment. Above seasonal dispersion and upstream–downstream differentiation of organic pollution, salinity, and turbidity parameters were suitably compared and analysed for a long-time span (Table 1) highlighting the persistence of stress signals during the Wet period. The aim was to synthesize long-term variability into governance-relevant signals, seasonal and spatial dispersion of key water quality indicators across upstream and downstream river reaches. Summarized representative ranges and dominant stress signals (Dry and Wet periods) over the study decade are reflected in below given table which are self-explanatory towards policy domains.

Parameter	Season	Upstream Reaches	Downstream Reaches	Dominant Signal
BOD (mg/L)	Dry	Low–Moderate	Moderate	Background load
	Wet	Moderate	High	Runoff + effluent transport
COD (mg/L)	Dry	Moderate	High	Structural pollution
	Wet	High	Very High	Load-driven stress
EC (µS/cm)	Dry	Moderate	Moderate	Base salinity
	Wet	High	Very High	Catchment flushing
Turbidity (NTU)	Dry	Low	Moderate	Stable
	Wet	Very High	Very High	Erosion + runoff

Table 1: Seasonal and Spatial Dispersion of Key River Water Quality Indicators (2006–2016)

Note : Representative ranges synthesized from CWC monthly data (Source CWC Govt of India)

AboThe above outcomes in terms of dry versus wet seasonal contrast, upstream vs downstream differentiation, focused dispersion and persistence (no single values) and best possible identification of dominant stress behaviour may considered as an implicit support to relevant policy experts. Results herein amicably demonstrates that water quality degradation in the Mahi River Basin is governed primarily by seasonal amplification and downstream persistence, rather than isolated exceedances. Across multiple indicators, organic pollution, salinity, and turbidity, the Wet period exhibits systematically higher dispersion, particularly in downstream reaches. This pattern indicates load-driven stress associated with monsoon runoff and effluent transport, contradicting assumptions of dilution-led improvement during high-flow conditions. The persistence of elevated stress across seasons in downstream reaches further suggests structural degradation linked to cumulative upstream pressures. From a governance perspective, these findings highlight the inadequacy of annual-average or station-centric reporting and reinforce the need for trajectory-based assessment aligned with SDG-6.3 objectives.

4.2 Organic Pollution and Oxygen Regime Dynamics

Indicators associated with organic pollution, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Dissolved

Oxygen (DO),displayed coherent seasonal and spatial patterns. COD and BOD values were generally higher during the Wet period across all reaches, with peak values frequently observed during late monsoon months. This pattern suggests enhanced mobilization of organic matter and industrial or urban effluents during high-flow conditions rather than effective dilution alone. Contrary to expectations of improved water quality under higher discharge, the persistence of elevated COD and BOD during the Wet period indicates load-driven degradation, particularly in middle and downstream reaches. Dissolved oxygen exhibited inverse responses in several instances, reflecting oxygen stress during periods of heightened organic loading. These findings indicate that monsoon flows act as transport mechanisms for accumulated pollutants, rather than as simple dilution agents, emphasizing the need for season-specific pollution control strategies.

4.3 Salinity, Ionic Composition, and Conductivity Signals

Electrical Conductivity (EC), salinity-related parameters, and major ions (Na^+, K^+) exhibited distinct seasonal asymmetry. EC values were frequently higher during the Wet period, with peak conductivity often occurring shortly after monsoon onset. This counter-intuitive behaviour suggests the flushing of accumulated salts and dissolved solids from catchment surfaces and anthropogenically altered landscapes. The persistence of elevated EC and ionic concentrations in downstream reaches indicates cumulative effects of land use change, irrigation return flows, and industrial activity. Importantly, temperature exhibited relatively limited seasonal dispersion, suggesting that observed salinity and conductivity patterns are anthropogenically mediated rather than climatically driven. From a governance perspective, these results highlight salinity and EC as early warning indicators of basin-scale stress, particularly relevant for agricultural water use and ecosystem health.

4.4 Nutrients, Sediments, and Turbidity Responses

Nutrient indicators (NO_3-N, NO_3, P) and sediment-related parameters (Suspended Solids, Turbidity, Secchi depth) demonstrated pronounced sensitivity to land-surface processes. Nutrient concentrations showed mixed seasonal responses, with nitrate levels often increasing during the Wet period, consistent with agricultural runoff and soil nutrient mobilization. Sediment and turbidity parameters exhibited sharp seasonal amplification, particularly during early and peak monsoon months. Reduced Secchi depth during these periods reflects high particulate loads and reduced light penetration, with implications for aquatic productivity and habitat quality. The spatial persistence of high turbidity and suspended solids in certain reaches suggests chronic erosion and land degradation, rather than transient storm effects alone.

4.5 Land Use Transitions as Dominant Stress Drivers

Land use and land cover analysis revealed substantial landscape transformation across the basin over the study period. Agricultural land and surface water bodies declined markedly, while bare land and urban/built-up areas expanded significantly. These transitions were most pronounced in downstream and mid-basin reaches. By linking land-use transitions to persistent water quality stress, Table 2 reframes landscape change as a decisive governance lever rather than a background correlation, with direct relevance to SDG-6.6. Importantly, temporal alignment between LULC change trajectories and water quality deterioration indicates that land transition intensity, rather than land use type alone, governs water quality responses. Reaches experiencing rapid conversion to bare land or urban use exhibited stronger and more persistent degradation signals across multiple parameters. This result elevates LULC change from a correlational background variable to a primary governance lever, directly linking landscape planning decisions to river water quality outcomes and SDG-6.6 objectives.

LULC Class	Change (%)	Spatial Concentration	Water Quality Implication
Agricultural land	−25 to −33	Mid and downstream	Nutrient + runoff stress
Water bodies	−79 to −86	Basin-wide	Reduced dilution capacity
Bare land	+76 to +170	Downstream	Sediment and EC increase
Urban/Built-up	+200 to +2500	Localized clusters	COD, BOD spikes

Table 2: Major Land-Use Transitions and Corresponding Water Quality Stress

To examine the role of landscape transformation in shaping river water quality outcomes, land-use transition intensity was analysed alongside spatial patterns of water quality stress. Figure 3 illustrates the alignment between land-use transitions and associated water quality stress across river reaches. It shows that river reaches experiencing more intense land-use transitions, particularly urban expansion, growth of bare land, and loss of surface water bodies, exhibit progressively higher and more persistent water quality stress, underscoring landscape transformation as a dominant driver of river degradation.

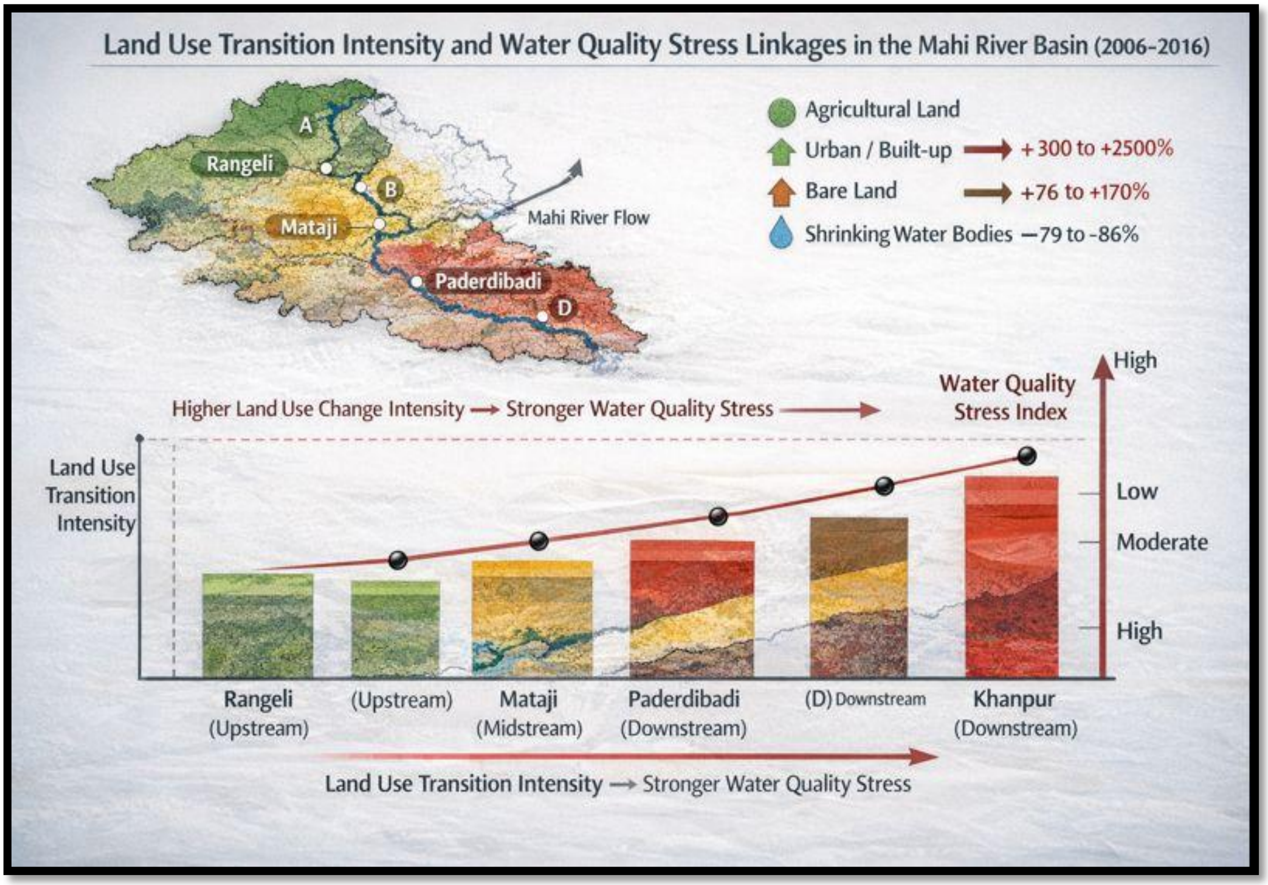

Figure 3: Relationship Between Land-Use Transition Intensity and Water Quality Stress Along the Mahi River Basin

Results and trends illustrated in above figure demonstrate that water quality degradation closely tracks the intensity of land-use transitions, rather than land-use type alone. Upstream reaches, characterized by relatively stable land-use patterns, exhibit lower water quality stress, whereas downstream reaches experiencing rapid urbanization, expansion of bare land, and severe reduction in surface water bodies show markedly higher stress levels. The near-linear increase in stress with transition intensity highlights the cumulative impact of fragmented land governance on river systems. This figure elevates land-use planning from a background contextual factor to a central governance lever for river water quality management. It provides empirical support for integrating water quality considerations into land-use decision-making, urban development controls, and watershed restoration strategies. From an SDG-6.6 perspective, the loss of surface water bodies evident in downstream reaches represents a critical ecosystem risk that cannot be addressed through water-sector interventions alone

4.6 Satellite Reflectance as a Spatial Amplifier of Ground Signals

Satellite-derived reflectance patterns exhibited meaningful coherence with ground-measured water quality variability. While individual parameter predictability varied, the collective results demonstrate that satellite data can effectively extend point-based observations across river reaches, enabling spatial diagnosis of stress zones beyond monitoring stations. The strength of reflectance-parameter relationships differed by season, with Wet-period models generally exhibiting higher explanatory power, consistent with enhanced optical expression of sediment and organic matter loads. Rather than emphasizing individual predictive equations, these results validate the feasibility of satellite-enabled screening and prioritization, particularly for ungauged or sparsely monitored reaches. In this line the Table 3 synthesizes the policy-relevant coherence between satellite reflectance and ground-based water quality indicators, positioning Earth observation as a spatial screening and prioritization tool rather than a precision predictor.

Parameter Group	Seasonal Strength	Policy Utility
Sediment / Turbidity	High (Wet)	Hotspot detection
Organic matter (COD/BOD)	Moderate	Screening
Salinity / EC	Moderate	Early warning
Nutrients	Low–Moderate	Contextual

Table 3: Governance-Relevant Coherence between Satellite Reflectance and River Water

Note: It indicated strength and governance relevance of satellite–water quality relationships.

4.7 From Results to Knowledge: Emergent Trajectories

This trajectory-based interpretation marks a fundamental shift in river governance logic. Rather than treating all river reaches uniformly, Figure 4 supports differentiated management responses aligned with observed system behaviour: conservation-oriented protection for relatively stable upstream reaches, seasonal risk mitigation for vulnerable midstream segments, and targeted corrective interventions for persistently degraded downstream reaches. Such spatial and temporal differentiation is critical for SDG-6.3 reporting, which requires evidence of sustained improvement across river systems rather than reliance on isolated or episodic compliance snapshots.

The conceptually synthesized water quality trajectories presented in Figure 4 capture how river systems actually behave under real-world conditions, integrating persistent, seasonal, and stable responses into a coherent diagnostic framework. The figure demonstrates that water quality dynamics in the Mahi Basin are best interpreted through trajectory classes, not individual parameter values. Upstream reaches exhibit low variability and relative stability, indicating buffering capacity and lower cumulative stress. Midstream reaches show pronounced seasonal oscillations, reflecting vulnerability to monsoon-driven pollutant loading with partial dry-season recovery. In contrast, downstream reaches display consistently elevated stress across seasons and years, signalling structural degradation driven by cumulative upstream pressures and land-use transformation.

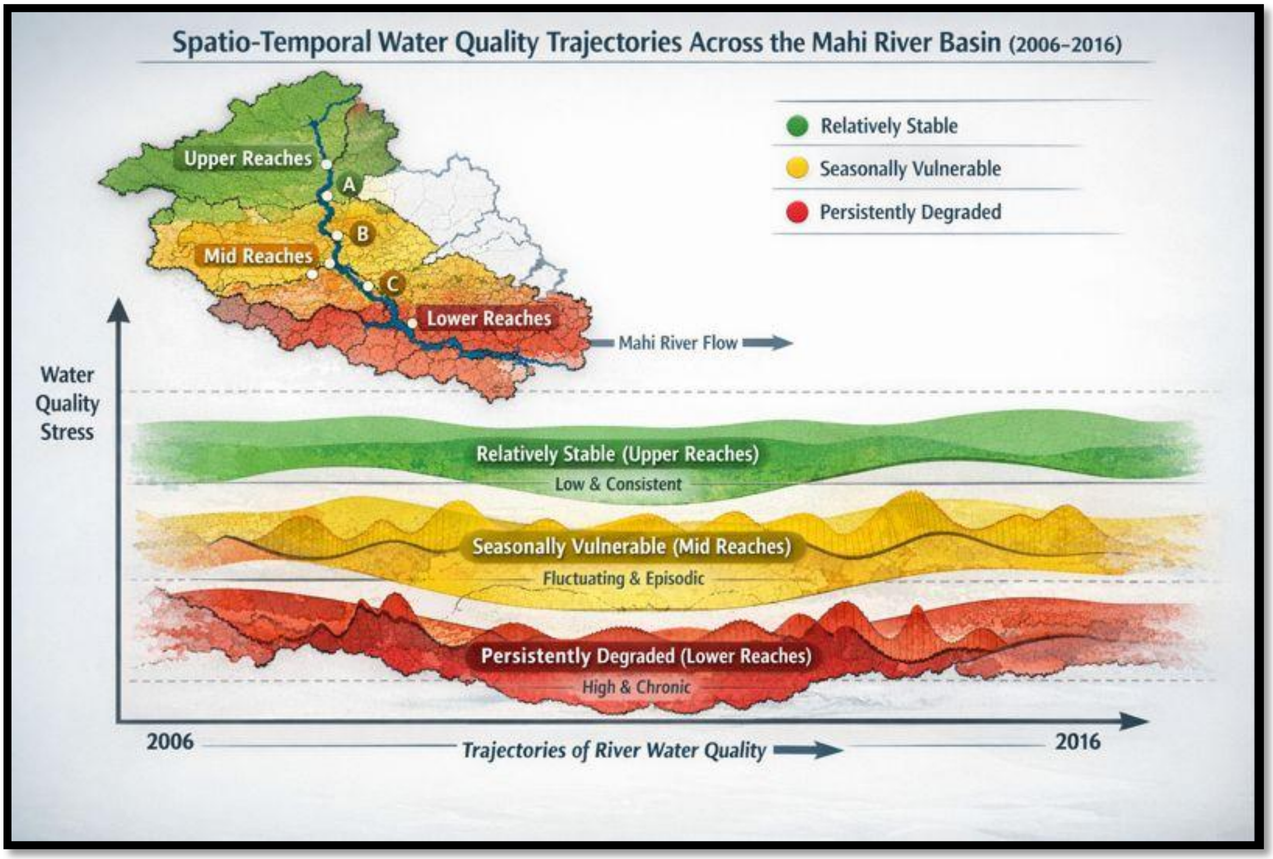

Figure 4: Conceptual Spatio-Temporal Water Quality Trajectories Across River Reaches (2006–2016)

Above figure illustrates how integration, rather than replacement, of monitoring systems enhances governance relevance. Ground-based observations provide regulatory legitimacy and temporal depth, while satellite reflectance extends spatial coverage and enables identification of unmonitored stress zones. The integrated framework converts fragmented measurements into reach-scale diagnosis, categorizing river segments into pre-emptive, preventive, and urgent intervention zones. The figure underscores that the principal value of satellite data lies in screening, prioritization, and early warning, not in precise parameter substitution. By translating scientific measurements into spatially explicit action categories, this integration framework bridges the long-standing gap between environmental monitoring and decision-making. Such boundary knowledge is particularly critical for sustainability-oriented governance and SDG reporting in data-scarce or institutionally fragmented contexts.

5. Discussion

Reframing river water quality assessment from static compliance checks to trajectory-based interpretation reflects a broader evolution within sustainability science toward system-level diagnosis and solution-oriented knowledge. The findings of this study underscore that persistent water quality degradation is less a consequence of data scarcity than of fragmented interpretation and governance misalignment, patterns consistent with global assessments of river system stress. By revealing how land-use transitions act as dominant drivers of cumulative degradation and how satellite-derived information can function as boundary knowledge, the study highlights the need for coherent integration across water, land, and urban governance domains. Together, these insights provide a practical foundation for strengthening SDG-6 implementation by grounding policy action in long-term trends, spatial differentiation, and ecosystem-relevant evidence rather than isolated compliance snapshots.

5.1 Reinterpreting River Water Quality Beyond Compliance

The results demonstrate that river water quality in the Mahi Basin cannot be adequately understood through conventional compliance-based reporting alone. Parameter-wise exceedances, when viewed in isolation, obscure the more critical patterns revealed by spatio-temporal synthesis, namely, the persistence, seasonality, and spatial propagation of stress signals. This distinction is central to sustainability science, which emphasizes system behaviour and trajectories over static states. The observed coherence across multiple parameters, organic pollution indicators, salinity and conductivity, nutrients, and sediments, suggests that degradation in several reaches is structural rather than episodic. Such conditions are unlikely to be resolved through short-term regulatory actions or post-factum mitigation. Instead, they point to deeper linkages between land transformation, hydrological processes, and governance gaps. This finding reinforces the need to reposition river water quality assessment as a diagnostic tool for sustainability transitions, rather than a narrow environmental compliance exercise.

5.2 Seasonal Dynamics as Governance Signals, Not Variability Noise

A critical insight from the synthesis is the role of monsoon-driven seasonality as a governance signal rather than a confounding factor. Elevated COD, BOD, turbidity, and nutrient concentrations during the Wet period contradict the common assumption that increased flows necessarily improve water quality through dilution. Instead, monsoon flows function as transport vectors, mobilizing accumulated pollutants from agricultural fields, urban surfaces, and degraded landscapes. This interpretation has direct implications for water policy. Regulatory frameworks and monitoring strategies that emphasize annual averages or dry-season benchmarks risk underestimating the cumulative impacts of wet-season loading. From an SDG perspective, particularly SDG-6.3, such underestimation can lead to overly optimistic assessments of water quality improvement. Recognizing wet-season stress windows enables more precise targeting of pollution control measures, land management interventions, and industrial discharge regulation.

5.3 Land Use Transitions as Primary Levers of Water Quality Outcomes

The alignment between land use transitions and water quality trajectories elevates LULC change from a contextual variable to a primary governance lever. Declines in agricultural land and surface water bodies, combined with expansion of bare land and urban areas, were consistently associated with intensified water quality stress, particularly in downstream reaches. These patterns suggest that the rate and direction of land transformation, rather than land use categories alone, determine river system response. This insight resonates strongly with sustainability science literature emphasizing cross-sectoral interactions and unintended consequences of development pathways. In the context of the Mahi Basin, water quality degradation emerges as an emergent property of fragmented land, water, and urban governance. Addressing such degradation therefore requires policy coherence across sectors, agriculture, urban planning, industry, and watershed management, rather than isolated water quality regulations.

5.4 Satellite–Ground Integration as Boundary Knowledge

The integration of satellite reflectance data with statutory monitoring illustrates how Earth observation can function as boundary knowledge, bridging scientific assessment and governance needs. While satellite-based estimation cannot replace in-situ measurements, its ability to spatially extend point observations and highlight reach-scale patterns offers significant governance value, particularly in data-constrained contexts. Importantly, the study demonstrates that the utility of satellite data lies less in precise parameter prediction and more in screening, prioritization, and early warning. This reframing aligns with sustainability science's emphasis on usability and decision relevance over methodological sophistication. By enabling identification of stress hotspots and vulnerable reaches, satellite–ground integration supports proactive intervention strategies consistent with SDG monitoring and reporting requirements.

5.5 Implications for SDG-6 Implementation

The findings have direct implications for operationalizing SDG-6, particularly targets 6.3 and 6.6. The trajectory-based interpretation adopted in this study offers a pathway to demonstrate progress or stagnation in water quality improvement, moving beyond binary compliance metrics. Persistent degradation signals identified in specific reaches indicate where SDG-6.3 objectives are unlikely to be met without structural intervention. Similarly, the linkage between land transformation and water quality trajectories informs SDG-6.6 by identifying river segments where ecosystem protection and restoration efforts are most urgently needed. The reach-based framing provides a practical unit for aligning monitoring, reporting, and intervention, enhancing the credibility and transparency of SDG assessments. Crucially, the study shows that SDG-aligned assessment does not require new monitoring infrastructures. Instead, it depends on reinterpretation and integration of existing datasets,an insight with broad relevance for countries facing resource constraints but committed to sustainability reporting.

5.6 Policy Translation: From Knowledge to Actionable Pathways

Building on the empirical synthesis, the three-tier policy translation framework proposed earlier gains concrete grounding. Monitoring intelligence derived from integrated datasets enables identification of where stress is occurring, interpretive diagnostics explain why it persists, and action prioritization guides where and how interventions should be deployed. This structured progression addresses a common gap in environmental governance, the absence of a clear pathway from scientific evidence to policy action. In practical terms, the results suggest differentiated management strategies across river reaches: immediate corrective measures in persistently degraded zones, preventive interventions in seasonally vulnerable reaches, and conservation-oriented protection in relatively stable segments. Such differentiation enhances the efficiency and efficacy of investments in pollution control, watershed management, and ecosystem restoration.

5.7 Broader Contributions to Sustainability Science

Beyond the Mahi Basin, this study contributes to sustainability science by demonstrating how long-term environmental monitoring can be transformed into actionable sustainability intelligence. It exemplifies a shift from data accumulation to knowledge translation, emphasizing interpretive structures, cross-scale integration, and governance relevance. The approach aligns with emerging calls for solution-oriented, transdisciplinary research that supports real-world sustainability transitions. Synthesizing across parameters, seasons, and river reaches (Fig 2) reveals three dominant water quality trajectories in the Mahi Basin: persistently degraded reaches with sustained multi-parameter stress, seasonally vulnerable reaches marked by wet-period degradation and partial dry-season recovery, and relatively stable reaches that maintain acceptable conditions despite hydrological variability. Together, these trajectories translate empirical observations into governance-relevant knowledge, enabling prioritization of interventions based on persistence, vulnerability, and recovery potential rather than isolated exceedances.

6. Conclusion

This study provides a comprehensive assessment of seasonal and sub-basin controls on nutrient, organic, and sediment pollution in a monsoon-driven river system using a decade of field monitoring integrated with remote sensing–based modelling. The results demonstrate that water quality variability in the Mahi River Basin is structured, predictable, and strongly governed by monsoon hydrology, rather than random or episodic in nature. Seasonal stratification reveals pronounced wet–dry contrasts, with monsoon periods driving elevated sediment loads, organic pollution, and nutrient transport, while dry seasons are characterised by more stable, baseflow-dominated conditions. Spatial analysis shows gradual downstream integration of water quality signals, reflecting cumulative basin-scale processes rather than isolated point-source effects.

Land-use dynamics further modulate these patterns, with agricultural expansion and forest decline increasing catchment susceptibility to runoff-driven pollution during wet periods. Reflectance-based empirical models demonstrate satisfactory predictive performance for several key parameters, particularly when calibrated separately for seasonal and spatial contexts, confirming their value as complementary tools for basin-scale assessment. The study highlights the importance of seasonally informed analysis, long-term consistency in monitoring, and hybrid ground–satellite approaches for effective river water quality management. By combining field realism with scalable analytical tools, the proposed framework offers a transferable methodology for improving monitoring efficiency and decision support in monsoon-dominated, data-limited river basins.

Limitations and Pathways for Next-Generation River Governance

While this study provides robust, policy-relevant insights into spatio-temporal water quality dynamics, it also highlights important limitations that invite reflection rather than methodological caution alone. The analysis relies on long-term monthly monitoring data, which are well suited for identifying dominant seasonal patterns and persistent stress trajectories but may not fully capture short-duration pollution pulses associated with extreme rainfall events. Similarly, the satellite-based empirical relationships explored here prioritize interpretive coherence over predictive precision and therefore do not attempt to resolve highly non-linear or episodic processes under rapidly changing monsoon conditions.

These limitations, however, are not merely technical constraints, they reflect a deeper reality of river systems themselves. Rivers are not laboratory experiments governed by controlled inputs and outputs, but living socio-ecological systems shaped by hydrology, chemistry, biology, land-use history, and cumulative governance choices. In such contexts, excessive emphasis on increasingly complex algorithms or narrowly optimized models may obscure rather than illuminate the broader signals that rivers express. This study deliberately adopts an alternative stance: listening to the river through long-term patterns, spatial continuity, and coherence across indicators, allowing the underlying "river logic" to speak more clearly than isolated statistical fits.

Looking ahead, future work can build on this foundation by integrating higher-frequency observations, non-linear and machine-learning approaches, real-time discharge data, erosion metrics, and finer-resolution land-use products to enhance diagnostic depth where data availability permits. Equally important, however, is the expansion of river studies beyond biophysical variables alone. Integrating socio-economic indicators, institutional arrangements, and governance responses with water quality trajectories would enable a more complete understanding of why certain river reaches degrade, stabilize, or recover under similar environmental conditions.

For next-generation policy planners, ground-level executors, and researchers, the broader message is clear: meaningful river governance does not emerge solely from better models, denser data, or more sophisticated experiments. It emerges from interpretive wisdom, the ability to see patterns across time and space, to recognize cumulative stress, and to align scientific insight with practical decision-making. By positioning rivers as narrators of integrated environmental change rather than as mere repositories of parameters, studies such as this can help reshape how evidence is generated, interpreted, and used on journal pages and in policy arenas alike.

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References

1. Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., et al. (2010). Global threats to human water security and river biodiversity. *Nature, 467*, 555–561.
2. OECD. (2015). *Water resources governance in OECD countries: A multi-level approach*. OECD Publishing.
3. Gupta, J., and Vegelin, C. (2016). Sustainable development goals and inclusive development. *International Environmental Agreements, 16*, 433–448.
4. Clark, W. C., and Harley, A. G. (2020). Sustainability science: Toward a synthesis. *Annual Review of Environment and Resources, 45,* 331–386.
5. United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development.* UN General Assembly.
6. UN-Water. (2018). *Sustainable Development Goal 6 synthesis report 2018 on water and sanitation*. United Nations.
7. Stafford-Smith, M., Griggs, D., Gaffney, O., et al. (2017). Integration: The key to implementing the SDGs. *Sustainability Science, 12*, 911–919.
8. Bhaduri, A., Bogardi, J., Siddiqi, A., Voigt, H., Vörösmarty, C., Pahl-Wostl, C., ... and Osuna, V. R. (2016). Achieving sustainable development goals from a water perspective. *Frontiers in Environmental Science, 4,* 64.
9. Tyler, A. N., Hunter, P. D., Spyrakos, E., et al. (2016). Developments in Earth observation for water quality. *Remote Sensing of Environment, 173,* 1–13.
10. Topp, S. N., Pavelsky, T. M., Jensen, D., Simard, M., and Ross, M. R. V. (2020). Research trends in river remote sensing. *Remote Sensing of Environment, 239*, 111611.
11. Vollmer, D., Pribadi, D. O., Remondi, F., et al. (2022). Adaptive water governance and sustainability transitions. *Sustainability Science, 17*, 353–368.
12. Parmar, U. (2022). *Reconnoitering water quality disparities in selected reaches of Mahi River by exploiting blended ground and satellite data* (Unpublished M.Tech thesis). Anand Agricultural University, India.
13. Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., ... and Svedin, U. (2001). Sustainability science. *Science, 292*(5517), 641-642.
14. Simeonov, V., Stratis, J. A., Samara, C., et al. (2003). Assessment of surface water quality using multivariate statistical methods. *Water Research, 37*(17), 4119–4124.
15. Ouyang, Y., Nkedi-Kizza, P., Wu, Q. T., Shinde, D., and Huang, C. H. (2006). Assessment of seasonal variations in surface water quality. *Journal of Environmental Monitoring, 8,* 840–849.
16. Bhuiyan, M. A. H., Suruvi, N. I., Dampare, S. B., et al. (2011). Investigation of surface water quality in Bangladesh. *Environmental Monitoring and Assessment, 180,* 183–197.
17. Huang, J., Zhan, J., Yan, H., Wu, F., and Deng, X. (2013). Evaluation of land-use change impacts on water quality. *Science of the Total Environment, 437*, 359–367.
18. Bonansea, M., Ledesma, C., Rodríguez, C., and Pinotti, L. (2016). Assessing land use–water quality relationships.

Environmental Monitoring and Assessment, 188, 423.

19. de Mello, K., Valente, R. A., Randhir, T. O., et al. (2020). Effects of land use on water quality. *Environmental Management, 66*, 789–806.
20. Dekker, A. G., Malthus, T. J., Wijnen, M. M., and Seyhan, E. (1996). The effect of spectral band width on water quality retrieval. *Remote Sensing of Environment, 58*, 559–572.
21. Kloiber, S. M., Brezonik, P. L., Olmanson, L. G., and Bauer, M. E. (2002). Satellite estimation of lake water quality. *Remote Sensing of Environment, 82,* 381–392.
22. Griggs, D., Nilsson, M., Stevance, A., and McCollum, D. (2017). A guide to SDG interactions: From science to implementation. *International Council for Science.*
23. Mirzaei, M., Zare-Mehran, M., and Roozbahani, A. (2018). Landscape metrics and river water quality. *Environmental Earth Sciences, 77,* 410.
24. Rockström, J., Gupta, J., Qin, D., et al. (2023). Safe and just Earth system boundaries. *Nature, 619,* 102–111.
25. UNESCO WWAP. (2023). *United Nations World Water Development Report 2023: Partnerships and cooperation for water.* UNESCO.
26. Zilioli, E., and Brivio, P. A. (1997). Lake water quality mapping using Landsat TM data. *Remote Sensing of Environment, 61*, 375–386.