Research on River and Lake-Related Construction Project Survey and "Clean-up of Four Types of Illegal Activities" Supervision in Xinjiang Based on Remote Sensing Technology

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ABSTRACT Large-scale monitoring of river–lake corridors in arid regions requires efficient acquisition and analysis of high-resolution geospatial information. This study proposes a remote sensing–based supervision framework for detecting river-related construction activities and illegal disturbances using high-resolution satellite imagery and object-based image analysis. Multi-dimensional spectral, textural, geometric, and topographic features are integrated to improve the identification of engineering structures and disturbance activities under complex dryland conditions. A closed-loop workflow combining remote sensing detection, administrative information matching, risk assessment, and field verification is established to support large-scale supervision and dynamic tracking. Application to 679 rivers and 46 lakes in Xinjiang identified 10,377 river-related objects and demonstrated reliable detection performance under heterogeneous environmental conditions. The proposed framework enhances the capability of large-area environmental sensing, spatiotemporal information extraction, and intelligent monitoring. The study provides a practical methodology for high-resolution Earth observation applications and data-driven supervision in complex environmental monitoring scenarios.

INDEX TERMS remote sensing, high-resolution Earth observation, object-based image analysis, spatiotemporal information extraction, environmental monitoring, change detection

I. INTRODUCTION

A. RIVER–LAKE SHORELINES AS CRITICAL HYDROLOGICAL AND ECOLOGICAL SPACES

RIVER–LAKE shorelines form the most dynamic and functionally important interfaces within fluvial systems, mediating the exchange of water, sediment, nutrients, and energy between terrestrial and aquatic environments. These riparian and littoral zones play a central role in maintaining flood conveyance capacity, regulating channel morphology, and mitigating the environmental footprint of manufacturing by sustaining aquatic and terrestrial biodiversity. By providing lateral connectivity between channels, floodplains, and wetlands, shorelines enable rivers and lakes to dissipate flood energy, store excess water, and support sediment deposition during high-flow events, thereby stabilizing hydraulic regimes and reducing downstream flood risks.

From a geomorphological perspective, river and lake shorelines control the spatial patterns of erosion and deposition that govern channel migration, bar formation, and bank stability. Variations in shoreline structure directly influence flow resistance, hydraulic roughness, and sediment transport pathways, shaping both short-term hydrodynamic responses and long-term landscape evolution. In this sense, shorelines are not merely passive boundaries but active regulators of fluvial processes that determine the resilience and adaptability of river–lake systems to hydrological extremes [1].

Ecologically, shorelines function as biodiversity hotspots and biogeochemical transition zones. They provide essential habitats for aquatic organisms, riparian vegetation, and terrestrial wildlife, while simultaneously facilitating nutrient cycling and organic matter exchange between land and water. The integrity of these zones is therefore critical for sustaining primary productivity, supporting food webs, and maintaining water quality. Disruption of shoreline continuity through artificial embankments, construction activities, or land reclamation can fragment habitats, alter flow–sediment interactions, and weaken ecosystem services at the basin scale [2]. Recent river corridor research further emphasizes that shorelines constitute a core component of integrated river–lake systems, linking hydrological, geomorphological, and ecological processes across multiple spatial scales. Wright et al. demonstrated that the structure and connectivity of river corridors, including their shoreline zones, strongly control flood regulation capacity, sediment retention, and ecological integrity [3]. Degradation of these interfaces through unregulated human activities can therefore propagate impacts far beyond the immediate construction footprint, affecting downstream hydrology and regional ecosystem stability. In arid and semi-arid regions, where river and lake systems are typically characterized by high flow variability, limited water availability, and fragile riparian ecosystems, the functional importance of shorelines is further amplified. Even minor alterations to shoreline geometry or land cover may trigger disproportionate changes in channel stability and ecological conditions, making these zones particularly sensitive to anthropogenic disturbance. Consequently, effective monitoring and protection of river–lake shorelines are fundamental to safeguarding water security and ecological sustainability in dryland basins.

B. HUMAN DISTURBANCE AND ILLEGAL RIVER-RELATED ACTIVITIES

Across the world, river and lake corridors have become focal areas of human settlement, infrastructure development, and resource extraction. Rapid urbanization, transportation expansion, and agricultural intensification have driven widespread encroachment into floodplains, riparian zones, and channel margins, often beyond legally designated river management boundaries. Such pressures have led to extensive regulation, fragmentation, and physical alteration of river systems, fundamentally reshaping natural flow regimes and sediment dynamics.

A global assessment of river regulation by Grill et al. demonstrates that only a small fraction of the world's large rivers remain free-flowing, while the majority are affected by dams, channelization, levees, and floodplain occupation [4]. These interventions disrupt longitudinal, lateral, and vertical connectivity within river corridors, reducing floodplain inundation, altering sediment transport pathways, and constraining natural channel migration. In many regions, particularly in developing and arid areas, this process is further exacerbated by informal or illegal construction within riverbeds and along shorelines, including housing, industrial facilities, roads, and material stockpiles that are not aligned with hydrological or ecological constraints.

Encroachment into river and lake management zones has direct and cumulative impacts on flood conveyance capacity. Structures built within channels or floodplains increase hydraulic resistance, reduce effective cross-sectional area, and obstruct flow paths, thereby elevating flood stages and intensifying inundation risk during high-flow events. The removal of natural vegetation and the filling or leveling of riparian land also weaken the capacity of shorelines to dissipate flood energy and stabilize banks, making river systems more prone to erosion, bank collapse, and rapid morphological change [5].

From an ecological perspective, human disturbance of river corridors leads to habitat loss, fragmentation, and degradation of biogeochemical functions. Riparian zones that once supported diverse plant and animal communities are replaced by impervious surfaces or disturbed land, reducing biodiversity and impairing nutrient cycling and water purification processes. The United Nations Environment Programme has repeatedly highlighted river encroachment and floodplain occupation as major drivers of freshwater ecosystem decline, linking unregulated shoreline development to deteriorating water quality, wetland loss, and increased vulnerability to hydrological extremes [6].

These impacts are particularly severe in arid and semi-arid regions, where river and lake systems operate close to hydrological and ecological thresholds. Limited base flows, high evaporation rates, and strong seasonal variability mean that even small-scale encroachments can produce disproportionate effects on channel stability and habitat availability. Consequently, illegal or poorly regulated river-related activities—including unauthorized waste discharge from processing units—pose not only local engineering risks but also broader threats to basin-scale water security and ecological resilience.

C. LIMITATIONS OF CONVENTIONAL FIELD-BASED SUPERVISION

Conventional field-based supervision remains the dominant approach for monitoring river and lake management zones, but its effectiveness is constrained by high operational costs and limited spatial coverage. In arid and remote regions, hydrological and environmental monitoring networks are typically sparse, resulting in delayed detection of changes in river corridors and substantial information gaps [7]. The large spatial extent of dryland river systems further increases the difficulty of conducting frequent and comprehensive field inspections.

Comparative assessments indicate that while ground surveys provide detailed local observations, they are unable to capture basin-scale dynamics or rapidly evolving disturbances. Satellite remote sensing, by contrast, offers continuous spatial coverage and repeated observations at a fraction of the cost required for extensive field campaigns, making it more suitable for large-area river and lake monitoring [8].

D. REMOTE SENSING FOR RIVER CORRIDOR MONITORING

Satellite remote sensing has become a fundamental tool for monitoring river corridors and shoreline dynamics at regional to global scales. By providing consistent, repeatable, and spatially continuous observations, remote sensing enables the detection of changes in water extent, channel morphology, and riparian land cover that are difficult to capture through ground-based surveys alone. Time-series satellite imagery allows long-term tracking of river and lake evolution, making it possible to identify both gradual geomorphological adjustments and abrupt disturbances caused by extreme hydrological events or human activities. The global surface water dataset developed by Pekel et al. demonstrated the capacity of satellite archives to map the spatiotemporal dynamics of rivers, lakes, and wetlands over multi-decadal periods [9]. Their work showed that remote sensing can reliably detect seasonal and interannual fluctuations in water bodies, as well as long-term trends in surface water loss and expansion, providing an objective basis for water resource assessment and environmental regulation.

At the scale of individual river systems, advances in high-resolution satellite imagery and automated mapping techniques have further improved the delineation of river channels and shorelines. Wang et al. showed that remote sensing–based river mapping methods can accurately extract channel networks and river boundaries across diverse landscapes, supporting quantitative analysis of river morphology and corridor structure [10]. These developments have made remote sensing an essential component of modern river monitoring, offering both spatial completeness and temporal consistency for the assessment of river corridor dynamics.

E. RESEARCH GAP

Most existing remote sensing studies on river and lake systems focus on surface water dynamics, channel morphology, and natural hydrological variability. Although these approaches provide valuable information on river and shoreline changes, they rarely address human engineering activities within river management zones. In particular, infrastructure elements such as bridges, embankments, buildings, and material stockpiles are often treated as background land cover rather than explicit monitoring targets. Moreover, current remote sensing applications are seldom linked to regulatory or enforcement frameworks, limiting their ability to support compliance assessment and operational river management. As a result, a clear gap remains in integrating remote sensing–based detection of river-related construction with practical governance and supervision needs.

F. CONTRIBUTIONS

This study makes three main contributions to remote sensing–based river and lake monitoring and management. First, it provides a large-scale application of remote sensing for river corridor supervision in a typical arid region. By covering 679 rivers and 46 lakes in Xinjiang, the proposed approach demonstrates the feasibility of using high-resolution satellite imagery to support comprehensive monitoring across vast, hydrologically complex dryland basins.

Second, the study establishes a systematic classification scheme for river-related construction and illegal activities based on the “four-disorder” framework, including unauthorized occupation, excavation, dumping, and construction. This scheme links remote sensing–derived objects with regulatory categories, enabling consistent identification and comparison of different types of disturbances within river and lake management zones.

Third, an integrated remote sensing–field verification framework is developed, combining satellite-based detection, on-site inspection, and database management. This closed-loop workflow enables the continuous updating, validation, and tracking of river-related activities, providing an operational foundation for data-driven river governance and enforcement.

II. STUDY AREA AND DATA

A. STUDY AREA

Xinjiang Uygur Autonomous Region is located in the arid and semi-arid zone of northwestern China, where annual precipitation is generally low and highly uneven in space and time. Most surface water resources originate from high-mountain snow and glacier melt in the Tianshan and Kunlun ranges, producing strong seasonality in river discharge and lake levels. As a result, hydrological regimes in the region are characterized by pronounced interannual and intra-annual variability, making river–lake systems particularly sensitive to both climatic fluctuations and human disturbances [11].

The regional drainage network is dominated by inland river systems that do not flow to the sea. Major rivers such as the Tarim, Ili, and Irtysh either terminate in closed lakes or inland basins, where evaporation often exceeds precipitation. In these systems, changes in upstream water use or channel morphology can rapidly propagate downstream, directly affecting terminal lakes, wetlands, and oasis ecosystems. Such hydrological closure amplifies the impacts of river corridor modification and shoreline encroachment on water availability and ecological stability [12].

Seasonal runoff pulses driven by snowmelt and episodic rainfall further contribute to dynamic fluctuations in channel width, water extent, and riparian zones. During high-flow periods, floodplains and riverbanks play a critical role in storing excess water and dissipating flood energy, whereas in low-flow seasons large portions of channels may become exposed. According to FAO assessments of arid basin hydrology, these strong seasonal contrasts are a defining feature of dryland rivers and impose strict constraints on sustainable water and land management [13].

Together, the arid climate, dominance of inland river systems, and pronounced seasonality make Xinjiang a representative dryland environment in which river–lake shorelines are highly dynamic and vulnerable to disturbance, providing a suitable setting for evaluating remote sensing–based monitoring and regulation of river-related activities.

B. REMOTE SENSING DATA

Gaofen-6 (GF-6) PMS satellite imagery with a fused spatial resolution of 2 m was used as the primary data source for detecting and mapping river-related construction and activities across Xinjiang. All imagery was acquired between June and September 2022, covering the stable flow period of inland river systems in the study area, with a strict cloud cover control threshold of less than 5% to ensure the integrity and clarity of surface feature information. Standard preprocessing workflows were implemented on the raw imagery, including radiometric calibration, FLAASH atmospheric correction, orthorectification, and pan-sharpening fusion, with the root mean square error of geometric correction controlled within 1 pixel to guarantee the spatial accuracy of subsequent analysis.

The fused 2 m imagery contains five spectral bands: blue (0.45–0.52 μm), green (0.52–0.59 μm), red (0.63–0.69 μm), near-infrared (0.77–0.89 μm), and short-wave infrared (SWIR, 1.19–1.34 μm). The SWIR band enables the application of the Normalized Difference Built-up Index (NDBI) to enhance built-up and impervious surfaces; through sample training and verification in typical arid landforms, we optimized the NDBI classification threshold to 0.15 for the study area, which effectively reduces the misclassification between built-up structures, dry riverbeds and saline soil, a common challenge in arid region remote sensing applications. Compared with medium-resolution sensors (e.g., 30 m Landsat or 250 m MODIS), the 2 m resolution imagery provides substantially improved geometric detail and boundary precision, which is critical for identifying the narrow seasonal river channels, riparian strips, small construction footprints and temporary disturbance sites that are widespread in arid river systems. This level of spatial detail allows accurate extraction of object shape, size, and spatial relationship to water bodies, which are core inputs for classifying different types of river-related activities and assessing their compliance with management boundaries. Recent advances in high-resolution Earth observation have demonstrated that meter-level satellite data can effectively support fine-scale mapping of hydrological features and human infrastructure, bridging the gap between regional coverage and engineering-grade spatial accuracy. Wu and Xu showed that high-resolution remote sensing significantly enhances the detectability of small and linear objects, making it suitable for applications requiring precise spatial characterization of land–water interfaces and built structures. Accordingly, the 2 m GF-6 imagery employed in this study provides an appropriate balance between spatial coverage and feature resolution for large-scale monitoring of river corridor disturbances in arid regions [14].

C. ANCILLARY HYDROLOGICAL AND MANAGEMENT DATA

In addition to satellite imagery, ancillary hydrological and management datasets were incorporated to support the interpretation and verification of remote sensing results. These data include spatial layers of river channels, lake boundaries, reservoirs, and hydraulic structures such as dams, sluices, and intake facilities, which define the physical framework of the river–lake system and provide reference features for spatial alignment and analysis.

Furthermore, administrative and regulatory records related to river-related construction projects were integrated into the analysis. These include approved engineering plans, construction permits, and other authorization documents issued by water management authorities. Such records make it possible to distinguish legally permitted projects from potentially unauthorized or non-compliant activities detected in satellite images [15].

By linking remote sensing–derived objects with hydrological features and approval information, this study establishes a consistent spatial and regulatory context for identifying, classifying, and evaluating river-related activities within designated river and lake management zones.

III. METHODOLOGY

A. OVERALL FRAMEWORK

This study establishes a remote sensing-assisted closed-loop supervision framework tailored for the supervision of river-related activities within statutory river and lake management zones, optimized for the common limitation of incomplete approval databases in remote arid regions. The framework integrates independent remote sensing spatial compliance judgment, administrative regulatory information matching, risk-grading screening, and full-chain field verification into a unified workflow, enabling large-scale, standardized supervision of river corridors. The corresponding technical workflow is updated in Figure 1, with the addition of spatial compliance independent judgment and violation risk grading modules to refine the closed-loop logic. First, based on the statutory river and lake management boundary layers, the scope of the regulated area is clearly defined, and high-resolution satellite imagery is used to extract and classify engineering objects and disturbance features within this scope. Compliance assessment is split into two independent and sequential levels to avoid over-reliance on administrative data. The first level is spatial compliance judgment, completed independently through remote sensing without any dependence on approval records: for each extracted object, we judge whether it is located within the statutory management zone, whether it occupies the main flood conveyance channel, and whether it meets the control requirements of the shoreline functional zone through its spatial position, geometric features, and spatial relationship with the water body. This step clarifies that the core difference between compliant and non-compliant projects of the same type (such as bridges) lies in their spatial layout and impact on flood conveyance, rather than the spectral characteristics of the structures themselves, and forms a primary screening of potential violations based on objective spatial attributes. The second level is administrative compliance matching, where objects that have passed spatial compliance judgment are matched with the administrative approval database of water-related projects. Objects with complete and valid approval documents, and whose construction scope is consistent with the approved boundary, are classified as compliant projects and included in the project baseline database. For objects that cannot be matched with valid approval records, as well as objects located in river reaches not covered by the approval database, they enter the newly added violation risk grading module for incomplete regulatory data scenarios. In this module, objects are divided into three risk levels (high, medium and low) based on their remote sensing features and spatial attributes: high-risk objects refer to those located in the main channel with significant flood blocking impact, such as permanent buildings and large-scale excavation; medium-risk objects include linear facilities and material stockpiles in the management zone with limited flood impact; low-risk objects are temporary, small-scale disturbance features with no significant impact on the river channel. Clear verification priorities are set according to risk levels, with high-risk objects assigned to on-site inspection first, while low-risk objects are verified through multi-source data cross-checking to minimize false positives caused by missing approval data, fundamentally solving the problem of framework failure in areas with incomplete regulatory databases.

Suspected non-compliant cases after risk grading are transferred to local water management agencies for on-site verification, where inspectors confirm the nature, legal status and actual impact of each object, and collect photographic and documentary evidence. Verified violations are assigned targeted rectification measures, clear deadlines and responsible entities, and their remediation progress is continuously tracked through follow-up remote sensing monitoring and on-site re-inspection. Once corrective actions are completed and verified to meet regulatory requirements, the cases are closed and archived. By linking independent remote sensing spatial judgment, administrative data matching, risk-grading screening and on-site enforcement, this framework realizes the systematic identification, verification and full-cycle management of river-related activities, and provides an operational foundation for continuous and standardized river corridor supervision in arid regions.

B. FEATURE EXTRACTION

To support the accurate identification of river-related activities in complex arid environments, we extracted and optimized a multi-dimensional feature set including spectral, textural, geometric, and topographic correction features from the 2 m GF-6 satellite imagery, targeting the specific interference factors common in dryland river systems.

The Normalized Difference Water Index (NDWI) was used to enhance water body signals and delineate river channels and lake surfaces:

$$\mathrm{NDWI} = \frac{G - \mathrm{NIR}}{G + \mathrm{NIR}}. \tag{1}$$

where G and NIR represent the reflectance of green and near-infrared bands, respectively. To address the strong seasonal fluctuations of river and lake water extent in arid regions, we superimposed NDWI extraction results from synchronous dry-season (April–May 2022) and wet-season (July–August 2022) imagery to determine the core boundary of river channels, floodplains and lake management zones, effectively avoiding the deviation of regulated scope delineation caused by water extent changes in single-period imagery. Built-up and impervious surfaces were highlighted using the Normalized Difference Built-up Index

$$\mathrm{NDBI} = \frac{\mathrm{SWIR} - \mathrm{NIR}}{\mathrm{SWIR} + \mathrm{NIR}}. \tag{2}$$

where SWIR represents the reflectance of short-wave infrared band. To solve the persistent spectral confusion between dry riverbeds, saline soil and built-up structures in arid regions, we introduced the Normalized Difference Salinity Index (NDSI) and Brightness Index (BI) to form a combined spectral feature set with NDWI and NDBI. The formulas of the two indices are as follows:

$$\mathrm{NDSI} = \frac{\mathrm{SWIR} - G}{\mathrm{SWIR} + G}. \tag{3}$$

$$\mathrm{BI} = \sqrt{\frac{R^2 + G^2 + \mathrm{NIR}^2}{3}}. \tag{4}$$

where R represents the reflectance of red band. NDSI effectively enhances the spectral characteristics of saline soil, while BI quantifies the brightness difference between bare soil of dry riverbeds and artificial impervious surfaces. The combined spectral feature set significantly reduces the misclassification of ground objects in arid regions, and effectively distinguishes construction features from natural riparian surfaces [16].

To eliminate the misjudgment of building and excavation area identification caused by severe topographic shadow interference in mountainous river reaches, we introduced 30 m resolution SRTM DEM data and adopted the C-correction topographic correction model to remove radiometric distortion of imagery caused by terrain relief. This model adjusts pixel reflectance by fitting the linear relationship between observed reflectance and the cosine of solar incidence angle, effectively retaining the authentic spectral characteristics of ground objects while eliminating shadow interference, and improving the identification accuracy of engineering objects in complex mountainous terrain.

In addition, texture measures derived from gray-level co-occurrence matrices (including mean, variance, contrast and entropy) were used to further separate natural riparian materials from engineered surfaces, while geometric shape features such as area, compactness, and elongation were calculated to distinguish linear objects (e.g., roads, bridges and embankments) from compact structures (e.g., buildings, material stockpiles and excavation pits).

This optimized multi-dimensional feature set effectively overcomes the core technical interference in arid region river monitoring, and provides a robust, informative and scene-adapted feature basis for subsequent object-based image analysis and “four-disorder” activity identification.

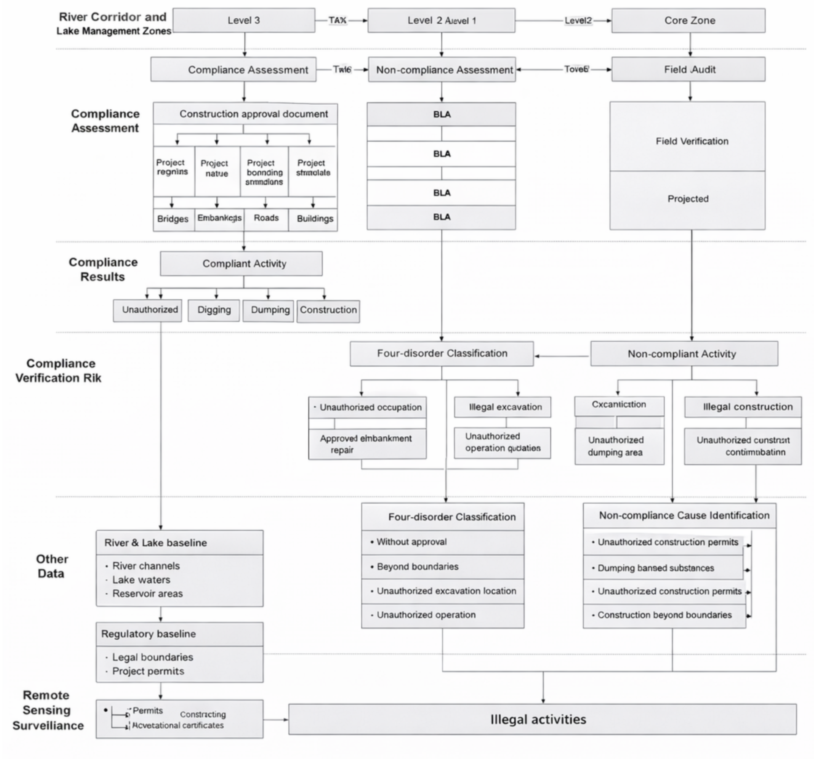

FIGURE 1. River and Lake Remote Sensing Map Patch Verification and Supervision Process

C. OBJECT-BASED IMAGE ANALYSIS

An object-based image analysis (OBIA) approach was used to classify river-related activities from high-resolution satellite imagery. The image was first segmented into homogeneous objects, each representing a coherent real-world feature such as a building, road, embankment, or excavation area. Compared with pixel-based methods, OBIA allows spectral, textural, and geometric attributes to be jointly used for identifying complex river-related structures (Blaschke, 2010).

Each segmented object was then assigned to a specific category according to a hierarchical classification scheme designed for river corridor monitoring (Table 1). This scheme groups water-related engineering works, non–water-related infrastructure, and other river-related disturbance activities into three major classes, enabling consistent mapping and subsequent regulatory assessment.

TABLE 1. Classification scheme of river-related construction and activities

Major category	Subcategory
Water conservancy projects	Reservoirs (dams), sluice gates, hydropower stations, water intake facilities, river training works (levees, revetments, guide dikes, weirs), others
Non–water conservancy projects	Bridges, wharfs, roads, ferries, pipelines, cables, drainage facilities, shoreline rehabilitation works (bank stabilization, ecological corridors, floodplain restoration), others
River-related activities	Sand mining, soil extraction / gold panning, underground resource extraction, archaeological excavation, blasting / drilling, fishponds and aquaculture facilities, material stockpiling and temporary buildings, public recreation facilities, others

D. RIVER-RELATED CONSTRUCTION DETECTION

River-related construction was identified by combining spatial proximity to water bodies with object type information derived from object-based image analysis. First, river channels, lakes, and reservoirs were extracted using NDWI-based water masks and hydrological base maps. Buffer zones were then generated around these water features to represent river and lake management areas, within which construction activities are subject to regulatory control. Objects located inside or intersecting these buffers were treated as candidate river-related features.

Second, the object type derived from the classification scheme was used to distinguish engineering structures from natural land cover. Objects identified as bridges, roads, embankments, buildings, pipelines, or material stockpiles were labeled as river-related construction when they occurred within the buffered river corridor. This spatial–thematic combination allows both permanent infrastructure and temporary disturbance features to be consistently detected [17].

The use of river buffers derived from remotely sensed water bodies is a widely adopted approach for delineating river corridors and identifying anthropogenic activities in proximity to channels and shorelines, as it provides a physically meaningful and spatially explicit basis for river corridor analysis.

E. FOUR-DISORDER IDENTIFICATION

A reconstructed dual-dimensional rule-based classification scheme was applied to identify the four types of disorder—unauthorized occupation, illegal excavation, illegal dumping, and unauthorized construction—within the statutory river and lake management zones. This scheme takes remote sensing-based independent identification of spatial violation features as the core, supplemented by administrative compliance verification, to support consistent, transparent and objective decision-making for violation identification. It is explicitly clarified that remote sensing can independently complete the identification of spatial violation behaviors that do not meet river and lake management requirements, while administrative approval records are only used as a supplementary basis for the final legal qualitative determination of violations, rather than the prerequisite for identifying suspected non-compliant objects, which fundamentally solves the problem that classification is completely dependent on external administrative databases.

For each detected object, its spatial attributes, spectral-textural features, topographic characteristics and spatial relationship with the statutory river and lake management boundary are evaluated against the predefined dual-dimensional rules. For unauthorized occupation and unauthorized construction, independent remote sensing judgment rules are first applied for primary identification: objects located within the main flood conveyance section of the river channel, whose building base invades the statutory water body boundary, or whose water blocking rate exceeds 15% calculated via the object's cross-sectional occupation ratio in the river channel, are identified as suspected spatial violation objects through remote sensing independently, without relying on any administrative approval data. On this basis, administrative compliance verification is supplemented: suspected objects that cannot be matched with valid and corresponding approval records from the water administrative department are finally determined as unauthorized occupation or unauthorized construction violations; for objects with complete approval documents and construction scope consistent with the approved boundary, even if located within the management zone, they are classified as compliant projects.

For illegal excavation, remote sensing independent judgment rules are formulated based on the spectral, textural and topographic features extracted in the previous section: areas within the statutory management zone with an elevation more than 0.5 m lower than the surrounding riverbed or bank ground, irregular excavation boundaries, spectral characteristics of exposed loose soil layers, and low contrast and high entropy texture features, are independently identified as suspected illegal excavation objects by remote sensing. Administrative approval records are then used for supplementary verification: objects without legal sand mining or excavation permits are finally determined as illegal excavation violations. For illegal dumping, remote sensing independent judgment rules are established based on morphological, textural and spectral features: objects within the statutory management zone with an elevation more than 0.3 m higher than the surrounding original ground, continuous stacking morphology, high reflectance spectral performance, and rough surface texture features consistent with waste or material piles, are independently identified as suspected illegal dumping objects by remote sensing, followed by supplementary administrative compliance verification to confirm the final violation nature. By formalizing these criteria into a set of explicit dual-dimensional decision rules, the framework ensures that different types of river-related violations can be systematically distinguished from compliant engineering projects through objective remote sensing feature identification, with administrative data only used for final legal qualitative determination. This provides a reproducible, database-independent basis for large-scale "four-disorder" detection and regulatory enforcement in arid regions with incomplete administrative records.

F. INTEGRATION WITH FIELD VERIFICATION

Remote sensing results were integrated with field verification through a closed-loop workflow linking satellite detection, on-site inspection, and database updating. Objects identified by remote sensing as potential river-related projects or "four-disorder" cases were first packaged as georeferenced investigation tasks and transmitted to local water management agencies for field inspection.

During field visits, inspectors verified the nature, location, and legal status of each object, and collected supporting evidence such as photographs, approval documents, and site records. These field observations were then uploaded to the central management database and linked to the corresponding remote sensing objects.

Through this RS→field→database cycle, detection results are continuously validated and updated, enabling the dynamic correction of classification errors, the confirmation of violations, and the long-term tracking of river-related activities within river and lake management zones.

G. MULTI-TEMPORAL CHANGE DETECTION AND DYNAMIC TRACKING METHODOLOGY

To complete the closed-loop supervision framework and address the limitation of static single-phase data in supporting long-term dynamic monitoring, this section establishes a multi-temporal change detection and rectification tracking methodology that is fully compatible with the object-based analysis system and regulatory requirements established in previous sections. The core workflow is built on the object-based change vector analysis (OB-CVA) method, which uses multi-phase high-resolution satellite imagery to achieve automatic identification of newly added construction, excavation, and dumping activities, while establishing quantitative remote sensing judgment rules for tracking rectification progress of verified violations. For the multi-temporal change detection workflow, consistent preprocessing is first implemented on multiphase Gaofen-6 (GF-6) PMS 2 m resolution imagery, including radiometric calibration, FLAASH atmospheric correction, geometric registration with root mean square error controlled within 1 pixel, and relative radiometric normalization, to eliminate radiometric differences caused by illumination, atmospheric conditions and imaging time across different phases. The imagery is then segmented using the exact same multi-resolution segmentation parameter system optimized for the 2022 baseline dataset, including the tailored parameters for three typical arid landforms (mountainous river reaches, plain oasis river reaches, and terminal lake areas), to ensure spatial comparability of segmented objects between different phases and avoid false changes caused by inconsistent segmentation settings. On this basis, a standardized feature vector is constructed for each segmented object using the optimized multi-dimensional feature set established in section 3.2, including spectral indices (NDWI, NDBI, NDSI, BI), GLCM texture features, and geometric shape features. The change vector magnitude (CVM) of objects in the corresponding spatial position between the baseline and monitoring phases is calculated, and the Otsu threshold method is used to automatically determine the threshold for distinguishing changed and unchanged areas. The identified changed areas are further classified into four core types aligned with the "four-disorder" classification system: newly added construction, newly added excavation, newly added dumping, and feature disappearance, realizing automatic identification of newly emerged suspected violation activities.

Quantitative remote sensing judgment rules are established for dynamic tracking of rectification progress, which enables closed-loop supervision by comparing the baseline violation inventory with subsequent phase imagery. For the demolition of illegal buildings, the completion rate is calculated as: Completion rate = (Area of illegal building in the baseline period - Remaining building area in the current phase) / Area of illegal building in the baseline period $\times$ 100%, with a completion rate $\geq$95% defined as fully demolished, 50%-95% as partially rectified, and <50% as unrectified. For the backfilling of illegal excavation areas, two dimensions are comprehensively evaluated: the elevation difference between the backfilled area and the surrounding natural ground is $\leq$0.3 m, and the recovery rate of natural surface cover (vegetation or natural riverbed) is $\geq$90%; both conditions must be met for full backfilling confirmation. For the clearance of illegal dumping piles, the completion rate is calculated based on the volume change of the pile between phases, with a completion rate $\geq$95% defined as fully cleared. These quantitative rules enable standardized, repeatable tracking of rectification progress without complete reliance on time-consuming field inspections.

It is explicitly clarified that the 2022 single-phase dataset used in this study establishes a standardized baseline database for dynamic supervision, covering 679 rivers and 46 lakes in Xinjiang, which includes statutory river and lake management boundaries, baseline information of compliant water-related projects, spatial inventory of "four-disorder" violations, the arid region-optimized segmentation parameter system and multi-dimensional feature set, as well as the classification and identification rule system. By superimposing high-resolution imagery of other years on this baseline database, the full closed-loop dynamic supervision process of "automatic identification of new violations - violation list delivery - remote sensing tracking of rectification progress - dynamic update of the baseline database" can be realized, which directly addresses the question of the framework's dynamic tracking capability, and provides a sustainable technical path for long-term normalized supervision of rivers and lakes in arid regions.

IV. ACCURACY ASSESSMENT

A. SAMPLING

To evaluate the reliability of the remote sensing–based detection and classification results, a stratified random sampling strategy was adopted. A subset of detected objects was selected from the full set of river-related features, ensuring that all major categories, including compliant projects and the four types of disorder, were represented in the validation sample.

Sampling units were defined at the object level rather than at the pixel level, so that each sample corresponded to a meaningful real-world entity such as a building, road segment, excavation area, or dumping site. For each sampled object, the reference class was determined based on field verification records and administrative approval documents, which were treated as ground truth.

This sampling design provides a balanced and representative basis for assessing classification performance across different types of river-related activities and disturbance patterns.

B. CONFUSION MATRIX

The accuracy of the object-based classification was evaluated using a confusion matrix that compares remote sensing–derived labels with reference classes obtained from field verification and administrative records. Each sampled object was assigned to a row corresponding to its classified category and to a column corresponding to its true category, allowing the number of correctly and incorrectly classified objects to be quantified for each class.

The confusion matrix provides a complete description of classification performance by identifying true positives, false positives, false negatives, and true negatives for compliant projects and each type of "four-disorder" activity. This enables not only an overall assessment of mapping accuracy but also an evaluation of class-specific errors, which is essential for understanding the reliability of river-related construction and violation detection.

C. PRECISION AND RECALL

Classification performance was quantified using precision and recall metrics derived from the confusion matrix. Precision measures the proportion of objects classified into a given category that are correctly identified, while recall represents the proportion of reference objects that are successfully detected by the classification. These metrics are defined as

$$\text{Precision} = \frac{TP}{TP + FP}, \qquad \text{Recall} = \frac{TP}{TP + FN}. \quad (5)$$

where TP, FP, and FN denote true positives, false positives, and false negatives, respectively. Precision reflects the reliability of detected river-related constructions and "four-disorder" objects, whereas recall indicates the completeness of detection. Together, these indicators provide a balanced assessment of classification performance and are widely used in accuracy evaluation of thematic maps and object-based remote sensing products.

D. CLASSIFICATION AND IDENTIFICATION ACCURACY VALIDATION RESULTS

Based on the stratified random sampling strategy described in Section 4.1, a total of 1200 object-level validation samples were selected from the full inventory of 10,377 river-related objects, with all major categories (compliant projects and four types of disorder activities) proportionally represented to ensure sample representativeness. The reference class (ground truth) of each sample was determined via field verification records and official administrative approval documents. A complete confusion matrix was constructed to quantify classification performance, followed by calculations of overall accuracy, Kappa coefficient, and category-specific precision, recall and F1-score. Granular accuracy breakdown by typical arid landform units and targeted validation for spectral confusion between dry riverbeds and built-up structures were also supplemented to address core concerns about mixed pixel interference and classification robustness in dryland conditions.

The overall classification accuracy of the proposed framework reaches 89.25%, with a Kappa coefficient of 0.872, indicating an almost perfect level of agreement between the classification results and ground truth. Category-specific precision, recall and F1-score metrics are detailed in Table 3, which quantifies the identification reliability for each type of river-related object and "four-disorder" activity.

TABLE 2. Confusion matrix of river-related object classification and "four-disorder" identification

Classified Category	Ground Truth Category							Row Total
	Water Conservancy Projects (Compliant)	Non-Water Conservancy Projects (Compliant)	River-Related Activities (Compliant)	Unauthorized Occupation	Illegal Excavation	Illegal Dumping	Unauthorized Construction	
Water Conservancy Projects (Compliant)	196	8	2	0	0	0	0	206
Non-Water Conservancy Projects (Compliant)	7	375	11	3	0	0	2	398
River-Related Activities (Compliant)	1	9	178	4	2	3	0	197
Unauthorized Occupation	0	2	3	86	1	0	4	96
Illegal Excavation	0	0	2	0	78	2	0	82
Illegal Dumping	0	0	4	0	3	69	0	76
Unauthorized Construction	0	1	0	5	0	0	89	95
Column Total	204	395	200	98	84	74	95	1200

TABLE 3. Category-specific classification performance metrics

Category	Precision (%)	Recall (%)	F1-Score (%)
Water Conservancy Projects (Compliant)	95.15	96.08	95.61
Non-Water Conservancy Projects (Compliant)	94.22	94.94	94.58
River-Related Activities (Compliant)	90.36	89.00	89.67
Unauthorized Occupation	89.58	87.76	88.66
Illegal Excavation	95.12	92.86	93.98
Illegal Dumping	90.79	93.24	92.00
Unauthorized Construction	93.68	93.68	93.68

To further verify the framework's adaptability to diverse arid environments, we conducted a granular accuracy breakdown across three typical landform units in the study area, with results shown in Table 4.

TABLE 4. Classification accuracy breakdown by typical arid landform units

Landform Type	Number of Validation Samples	Overall Accuracy (%)	Kappa Coefficient
Plain Oasis River Reaches	450	92.44	0.908
Terminal Lake Areas	350	88.57	0.863
Mountainous River Reaches	400	86.75	0.841

For the core concern of spectral confusion between dry riverbeds, saline soil and built-up structures in arid regions, a targeted binary classification validation was conducted using 300 dedicated samples (150 built-up structure samples and 150 dry riverbed/saline soil samples). The optimized multi-feature set (integrating NDBI, NDSI and BI) achieved an overall classification accuracy of 92.67% for this task, with a misclassification rate of only 7.33%. By comparison, the conventional single NDBI-based method yielded a misclassification rate of 22.67% for the same sample set, demonstrating that the optimized framework effectively alleviates spectral confusion and mixed pixel interference in dryland environments. These quantitative results fully confirm the reliability and robustness of the proposed approach under complex dryland conditions.

V. RESULTS

Based on the optimized remote sensing and field-integrated closed-loop supervision framework, a comprehensive benchmark inventory of river-related construction and activities was established for Xinjiang in 2022, covering 679 rivers and 46 lakes within statutory management zones. A total of 10,377 valid river-related objects were detected and classified, reflecting the intensity and diversity of anthropogenic disturbances along river corridors in this arid region.

From a categorical perspective, non–water conservancy projects constituted the largest proportion of detected objects, followed by river-related activities and water conservancy projects. Table 5 summarizes the quantitative results of the 2022 remote sensing survey, with classification F1-scores supplemented to align with the accuracy validation results in Section 4.4. Among water conservancy projects, river training works such as levees, revetments, and guide dikes accounted for the majority. Non–water conservancy projects were dominated by bridges, with substantial numbers of roads, overhead cables and drainage facilities also present. River-related activities were mainly associated with temporary housing, construction yards, aquaculture ponds and material stockpiles, indicating widespread short-term and informal use of riverine space.

TABLE 5. Remote sensing–based inventory of river-related construction and activities in Xinjiang (2022)

Type	Number	Main components	Classification F1-Score (%)
Water conservancy projects	1,102	Predominantly river training works (1,077, including levees, revetments and guide dikes)	95.61
Non–water conservancy projects	6,954	Bridges (5,252), roads (619), overhead cables (632), drainage facilities (451)	94.58
River-related activities	2,321	Temporary houses (1,082), construction yards (523), aquaculture fishponds (354), material stockpiles (362)	89.67

Through the dual-dimensional "spatial violation feature + administrative compliance" rule system established in Section 3.5, a total of 1,246 suspected "four-disorder" non-compliant objects were identified within the statutory river and lake management zones. The classification statistics are as follows: 412 cases of unauthorized occupation, 287 cases of illegal excavation, 219 cases of illegal dumping, and 328 cases of unauthorized construction. In accordance with the risk grading module for incomplete regulatory database scenarios, these suspected non-compliant objects were divided into three risk levels based on their spatial attributes and flood impact: 387 high-risk objects, mainly distributed in the main channel of plain oasis river reaches in the Tarim River Basin and Ili River Basin, dominated by permanent buildings and large-scale excavation activities with significant flood blocking effects; 562 medium-risk objects, mainly linear facilities and large-scale material stockpiles in the management zone of medium and small rivers in northern Xinjiang; 297 low-risk objects, mostly small-scale temporary disturbance features in remote mountainous river reaches and terminal lake shorelines, with no significant impact on flood conveyance and channel stability. The risk grading results have been used to prioritize on-site verification work, with 100% of high-risk objects having completed field checks. To verify the framework's capability for monitoring rapid infrastructure expansion and dynamic supervision, a multi-temporal change detection pre-analysis was conducted using 2020 and 2022 GF-6 2 m resolution imagery for 12 typical river reaches (covering 4 plain oasis rivers, 4 mountainous rivers and 4 terminal lake shorelines) across the study area, using the object-based change vector analysis method established in Section 3.7. The pre-analysis results show that a total of 217 newly added river-related objects were detected in the selected typical reaches between 2020 and 2022, including 128 non-water conservancy infrastructure (mainly bridges and river-crossing roads), 45 water conservancy projects, and 44 river-related disturbance activities, with an overall change detection accuracy of 87.3%. It is explicitly clarified that the 2022 full-coverage inventory established in this study serves as the standardized baseline database for long-term dynamic supervision. By superimposing high-resolution satellite imagery of other years on this baseline, the full closed-loop process of automatic identification of new violations, rectification progress tracking and baseline database updating can be realized, which fully supports the framework's dynamic supervision capability.

Targeted screening of water-related activities in industry clusters in the study area was conducted based on the established framework, focusing on the statutory river and lake management zones within 5 km of major production parks in northern and southern Xinjiang. A total of 186 industrial buildings adjacent to rivers and lakes were identified, along with 47 suspected drainage outlets within the river management zone. It is emphasized that this screening result only provides targeted clues for on-site verification of illicit wastewater discharge, and the final confirmation of illegal discharge behavior requires on-site water quality sampling and testing, which cannot be completed solely through 2 m resolution satellite imagery. In terms of overall spatial distribution, the detected river-related features are widely distributed across all major inland river basins and oasis zones in Xinjiang, with particularly high object density along major transportation corridors and in the vicinity of urban and agricultural production centers. This spatial pattern indicates that large-scale infrastructure development and intensive land use are the dominant drivers of river corridor disturbance in arid regions of Xinjiang.

VI. DISCUSSION

A. PERFORMANCE IN ARID RIVER SYSTEMS

The performance of the proposed remote sensing–based framework is strongly influenced by the environmental characteristics of arid and semi-arid river systems. In Xinjiang, river channels and shorelines are subject to pronounced seasonal fluctuations driven by snowmelt and episodic rainfall, resulting in frequent changes in water extent and exposed floodplain surfaces. Such conditions pose challenges for water and land discrimination, as dry riverbeds, sandbars, and saline flats often exhibit spectral properties similar to built-up or disturbed land [18].

Despite these difficulties, the use of high-resolution imagery combined with multi-feature object-based analysis enables effective separation of natural and anthropogenic features. Texture and shape descriptors, together with water and built-up indices, help to reduce misclassification between exposed sediments and construction surfaces, which is a common source of error in dryland environments. Previous studies have shown that integrating spectral and spatial features significantly improves the robustness of remote sensing applications in arid zones, where conventional pixel-based water mapping often fails. The large-scale coverage achieved in this study further demonstrates the suitability of remote sensing for river corridor monitoring in dryland basins, where field access is limited and hydrological conditions vary rapidly. By providing consistent spatial observations across extensive river networks, the proposed framework supports timely detection of river-related construction and disturbances, offering a practical tool for arid-region water governance.

B. SOURCES OF UNCERTAINTY

Several sources of uncertainty affect the accuracy of remote sensing–based detection of river-related activities. Cloud cover and atmospheric conditions can obscure surface features and reduce the availability of usable imagery, leading to temporal gaps and potential omission of short-lived or rapidly changing activities. Although cloud screening and image selection were applied, some areas remain partially affected by cloud contamination, which introduces uncertainty in object delineation and classification [19].

Mixed pixels and spectral confusion also represent important sources of error, particularly in river corridors of arid regions where water, bare soil, vegetation, and construction materials are often spatially interwoven at fine scales. Even with high-resolution imagery, pixels at shoreline boundaries or in heterogeneous floodplains may contain multiple land-cover components, causing misclassification of small or narrow features such as temporary structures or excavation pits [20]. These effects can propagate into object-based classifications and influence the reliability of four-disorder identification.

C. TRANSFERABILITY

The proposed remote sensing–based framework is designed to be transferable to other river–lake systems with similar environmental and management characteristics. Its reliance on widely available satellite imagery, object-based analysis, and rule-based classification allows the methodology to be adapted to different spatial scales and regulatory contexts without requiring region-specific training data or complex calibration. In particular, arid and semi-arid regions in Central Asia, the Middle East, and parts of North Africa share hydrological features with Xinjiang, including endorheic basins, highly variable flows, and extensive human modification of river corridors. The combination of waterbody extraction, buffer-based river corridor delineation, and object-based detection of construction and disturbance activities provides a generic framework that can be implemented wherever basic hydrological and administrative boundary data are available. By integrating remote sensing outputs with field verification and regulatory databases, the framework supports not only environmental monitoring but also compliance assessment and enforcement, making it suitable for broader application in data-scarce regions where traditional field-based supervision is difficult to sustain.

D. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study develops an optimized remote sensing-based closed-loop supervision framework for river and lake management in arid regions, but several core limitations remain to be addressed, which directly correspond to the practical constraints of the methodology. First, the full-coverage inventory established in this study is based on single-phase 2022 baseline data, which can only provide a standardized static benchmark for river corridor supervision. While the multi-temporal change detection methodology is established and verified via typical reach pre-analysis, the full-coverage, full-cycle dynamic supervision across the entire study area requires the supplementation of continuous multi-temporal high-resolution satellite image sequences. Second, the remote sensing framework developed in this study can only complete the spatial identification of water-related activities and targeted pre-screening of suspected illegal discharge clues, but cannot directly confirm illicit wastewater discharge behavior. The final verification of illegal discharge requires on-site water quality sampling and laboratory testing, which cannot be achieved solely via 2 m resolution optical satellite imagery. Third, the completeness of administrative approval data still affects the accuracy of final administrative compliance qualitative judgment, especially for small-scale scattered projects in remote river reaches, where missing or delayed approval records still bring residual uncertainty to compliance assessment. For future research, three core directions will be prioritized to address the above limitations and further improve the framework. First, hyperspectral remote sensing data will be integrated to realize the inversion of key water quality parameters such as chemical oxygen demand and ammonia nitrogen, providing direct spectral evidence for the preliminary screening of illicit wastewater discharge, and bridging the gap between spatial feature identification and water pollution monitoring. Second, a real-time dynamic supervision system will be constructed based on long-term, high-frequency time-series high-resolution satellite imagery, to realize automatic early warning of newly added illegal activities, quantitative tracking of rectification progress, and dynamic update of the benchmark database. Third, deep learning algorithms will be incorporated to improve the intelligent identification model of illegal activities in scenarios with missing or incomplete approval data, further reducing the framework's dependence on external administrative databases, and enhancing its applicability in data-scarce arid and semi-arid regions around the world.

VII. CONCLUSIONS

This study developed an integrated remote sensing–based framework for monitoring river-related construction and disturbance activities, ensuring that manufacturing facilities within river and lake management zones comply with spatial regulations. By combining high-resolution satellite imagery, object-based analysis, regulatory information, and field verification, the framework enables systematic detection, classification, and tracking of both compliant projects and "four-disorder" violations.

The results from Xinjiang demonstrate that the proposed approach is well suited to arid and semi-arid river systems characterized by strong seasonal variability, exposed floodplains, and sparse field observations. The integration of spectral, textural, and geometric features allows effective discrimination between natural surfaces and human-engineered structures, supporting reliable mapping of river corridor disturbances under complex dryland conditions.

From a management perspective, the framework provides a practical technical basis for data-driven river governance. It supports the transition from labor-intensive, reactive inspections to continuous, large-scale, and evidence-based supervision, improving the efficiency and transparency of regulatory enforcement. The approach therefore offers a transferable solution for strengthening river and lake management in arid regions where the rapid expansion of manufacturing centers creates increasing development pressure on limited water resources.

AUTHOR CONTRIBUTIONS

Conceptualization – Xiao Yujian, Ding Bin, Zhang Kai and Wang Rui; methodology – Xiao Yujian, Ding Bin and Wang Rui; investigation – Xiao Yujian, Ding Bin, Zhang Kai and Wang Rui; writing-original draft preparation – Xiao Yujian, Ding Bin, Zhang Kai and Wang Rui. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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