

RESEARCH ARTICLE

ASSESSMENT OF THE MORPHO-DYNAMIC CHANGES OF THE QORADARYO RIVERBANKS BASED ON SENTINEL-2 SATELLITE IMAGERY

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ABSTRACT

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This article analyzes the morphological changes, erosion, and accumulation processes occurring in the Qoradaryo River. The study is dedicated to one of the major issues, bank erosion, under the influence of river flow, sediment deposition, and alterations in the shape of the riverbed. The authors used Sentinel-2 satellite imagery obtained from 2018 to 2024, along with hydraulic and hydrological data collected under field conditions. These datasets were analyzed using the ArcGIS software and the NDWI index to identify changes in water level and flow direction. Within the framework of the study, hydraulic parameters of the flow were measured at 12 characteristic cross-sections using a Doppler device, and turbidity was analyzed in laboratory conditions using a spectrophotometric method. Additionally, the fractional composition of suspended sediment particles was studied using the aerometric method. Based on geomorphological analyses, the surface area and volumetric indicators of eroded and accumulated zones were calculated. According to the study results, zones with high erosion risk and relatively stable areas were identified, and corresponding protective measures- biologically and engineering approaches were recommended. The article highlights the advantages of an integrated analysis approach combining remote sensing and field data.

KEYWORDS

river morphology, erosion processes, turbidity level, NDWI index, sediment fraction, remote sensing, riverbank protection

1. INTRODUCTION

The river channel represents a fundamental element in the geological and hydrological development of river systems. Its formation is governed by a complex interplay of environmental factors such as geological framework, climatic variability, the chemical composition of the water, and topographic features of the surrounding landscape (Khosronejad et al., 2022). Throughout its course, the river actively modifies its own channel through processes of lateral and vertical erosion, sediment transport, and deposition, all of which contribute to the reconfiguration of the riverbank. Flow velocity and hydraulic pressure are among the principal hydrodynamic forces shaping the morphology of the riverbed and banks (Vu et al., 2024). In this context, turbidity - defined as the presence of suspended materials such as sand, silt, and clay - emerges as a critical factor influencing both riverine structure and ecological balance. Increased turbidity impacts flow characteristics, alters sediment transport capacity, and can either stabilize or destabilize bank formations. High - energy flows, characterized by elevated velocity, exert intensified erosive force on riverbeds and banks, facilitating the downstream transport of coarse materials like gravel and sand (Chohan et al. 2022). Erosional activity typically occurs in two dominant forms:

Horizontal erosion: high-velocity flows erode riverbanks, altering the riverbank line and leading to the formation of new channels and landscape features.

Vertical erosion: As the hydraulic force of the flow increases, the riverbed deepens, resulting in changes to the overall morphological structure of the channel (Mallick et al., 2023; Qin et al., 2024).

In contrast, low-velocity flows have less energy and contribute to the accumulation of sediment materials within the river channel (Andualem et al., 2024). Under such conditions, the following processes are observed:

Sediment deposition: Low-velocity flows promote the accumulation of sediment along the channel, leading to modifications in its shape and the formation of new geological layers.

Basin stability: such flows help maintain ecological balance within the river basin, reservoirs, and other aquatic systems (Langhorst and Pavelsky, 2023; Niyonsenga and Uwingeneye, 2024).

Changes in turbidity levels - whether increasing or decreasing - significantly influence the formation of riverbeds and riverbank outlines. Increased turbidity, characterized by a higher concentration of suspended particles in the flow, tends to reduce the intensity of erosion processes, which in turn leads to the formation of sediment layers along the banks (Tha et al., 2022). Decreased turbidity, on the other hand, enhances erosional activity, resulting in notable transformations of the river channel and bank structure. In general, flow velocity, turbidity levels, and erosion processes are interrelated and play a decisive role in the formation of river morphology and ecosystems (Hayes et al., 2023). These factors form the

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foundational knowledge base required to understand the complex structure of river systems and to manage them scientifically. In the formation of riverbed morphology, the particle size of suspended sediments plays a critical role (Nath and Ghosh, 2024). Coarser particles, such as stones and gravel, require greater flow energy to be transported and are thus less mobile within the current. In contrast, finer particles, including sand and silt, are more easily transported by the flow. This affects the distribution of flow energy and consequently alters the shape of the riverbed and the alignment of the riverbank.

Morphological changes in river systems primarily occur through deformational processes, namely erosion and sediment deposition. These processes are driven by a combination of natural climatic conditions, geological characteristics, and anthropogenic activities (Abbass et al., 2023; Nones, 2020). Climate change - particularly fluctuations in precipitation - directly impacts flow velocity, which in turn intensifies or reduces riverbank erosion.

Human activity plays a major role in shaping river ecosystems. Construction projects, hydraulic structures, and various water management systems often lead to noticeable changes in the shape of riverbeds and their banks. These changes can disturb the natural balance of river systems and influence their long-term stability (Chadwick et al., 2023; Islam and Mitra, 2024). To manage water resources effectively and protect the environment, it is important to study how riverbeds and banks form and change over time. These processes are also central to developing practical solutions for reducing ecological risks, preventing erosion, and maintaining healthy riverbank zones (Zhou et al., 2023; Shahin, 2007). Today, with the help of satellite images, GIS technologies, and remote sensing tools, it is possible to observe changes in rivers more precisely and in real time. These methods allow researchers to track erosion, sediment buildup, and shifts in river shape, as well as to predict how these patterns might continue. Many studies around the world have applied such technologies to monitor the condition of river systems more deeply, both ecologically and physically (Payne et al., 2018; Smith et al., 2018). The findings from these studies help in planning protection measures for riverbanks, setting up long-term strategies, and responding quickly to flood risks. This approach also helps preserve the balance of local ecosystems and encourages better use of natural resources (Bogoni et al., 2017).

According to the 2023 report by Uzbekistan's Hydrometeorology Service under the Ministry of Ecology, heavy rainfall during the spring season caused the water level of the Qoradaryo River in the Andijan region to rise sharply (Gazeta, 2023). In some places, the water overflowed the banks by 3 - 4 meters, and the river's discharge nearly doubled compared to normal levels. This led to severe erosion along the riverbanks. Local residents, who rely heavily on fishing, rice farming, and horticulture, were directly affected. Since the river passes through populated areas, flooding poses a serious threat to people's safety and their livelihoods. For this reason, urgent reinforcement of the embankments has begun (Kun, 2022).

Given these risks, it is vital to keep monitoring the river and its behavior. Developing quick and reliable responses will be essential for protecting both local communities and farmlands from potential flooding in the future.

2. METHODS AND MATERIALS

2.1 Study Area

To systematically study the aforementioned issues, the Qoradaryo River was selected as the object of this research. Qoradaryo is one of the main tributaries of the Syrdarya River, with a total length of 180 kilometers. The total area of its watershed is 30,100 km². According to long-term observations, during particularly high-water years, the maximum discharge in the Qoradaryo River has reached up to 1500 m³/s. The main tributaries of the river are the Qorako'lcha and Tar rivers. The river's water source primarily depends on the melting of snow and glaciers, with 55 percent of the annual runoff forming between March and July.

2.2 Selection of Observation Points and Field Measurements

To analyze the ongoing erosion and accumulation (sediment deposition) processes in the riverbed, 12 characteristic cross-sections were selected along the Qoradaryo River. These cross-sections were determined at 500-meter intervals within the segments of the river passing through populated areas. At each selected cross-section, morphometric parameters of the riverbed and hydraulic elements of the flow, such as flow velocity, cross-sectional area of flow, and average depth, were measured. For this purpose,

the modern SonTek RS5 Acoustic Doppler Current Profiler (ADCP) was used (Figure 1). This device enables high-accuracy and high-repeatability measurements of flow velocity, direction, and depth. The RS5 is a compact and advanced instrument equipped with SmartPulse+ technology. This system automatically selects between BroadBand and Pulse-Coherent signal transmission modes depending on the surrounding environmental conditions during measurements.

The device is equipped with the following components:

- GNSS module for accurate coordinate acquisition;
- Bluetooth Low Energy (BLE5) for mobile connectivity and data transfer;
- Compass, pitch, and roll sensors to monitor movement direction and device stability;
- Temperature sensor for detecting water temperature.

The measurement range of the instrument covers water layers with depths from 0.2 meters to 5 meters, and the velocity measurement error margin is $\pm 0.25\% \pm 0.0025$ m/s.



Figure 1: Measurement of hydraulic parameters of river flow using the SonTek RS5 Doppler device (based on fieldwork conducted between May and August 2024)

2.3 Turbidity and Particle Size Analysis

Within the scope of the study, water samples were collected from both the left and right banks at the selected cross-sections to determine the turbidity levels in the river flow. For this purpose, a rod-mounted bathometer device was used. This tool made it possible to collect water samples precisely from designated depths, helping ensure accurate measurements during fieldwork. Each sampling location's coordinates were logged using a Garmin GPS device, and the data were systematically saved in digital format. This method not only supports the reliability of the collected samples but also provides a solid foundation for later physical and chemical analyses in the laboratory.

The turbidity level in the collected water samples was determined using a UV755 spectrophotometer. The UV755 is a high-precision laboratory device operating in the ultraviolet and visible light spectrum (UV-Vis). It is widely used for measuring turbidity levels in water samples by assessing their optical density. This device is based on a spectral analysis method that enables accurate quantification of particle concentrations within a sample, providing high repeatability and reliability in laboratory research. The method allows for the quantitative evaluation of turbidity and offers important insights into the physical properties of river water.

Before measuring turbidity in the water samples, each one must be mixed thoroughly. This step helps prevent larger particles from settling at the bottom of the container and ensures that they are evenly distributed throughout the sample. Proper mixing is essential for producing reliable and consistent measurement results. Once the sample is well-mixed, it is carefully poured into a prepared cuvette. The cuvette is then sealed tightly with a special lid to block any external light, which helps improve the accuracy of the spectrophotometric reading. After sealing, the cuvette is

placed into the UV755 spectrophotometer. When the device is turned on, it sends light beams through the sample in a darkened chamber. These beams interact with the suspended particles, some of which absorb or scatter the light. Based on these physical interactions, the device determines the turbidity level. The measurement results are displayed on the digital screen of the instrument, providing the researcher with accurate quantitative information on the turbidity level in the water.

The particle size distribution of suspended sediments in the flow - i.e., the fractional composition - was also separately investigated. For this purpose, sediment samples were collected from the vicinity of the riverbanks at the selected cross-sections, specifically from zones where turbidity had settled over a given time interval. These samples were analyzed in a specialized laboratory to determine the physical-granulometric composition of the sediments. The aerometric method was used during the analysis. This method enables the determination of the particle size distribution within the sediment, i.e., the granulometric (fractional) composition. Aerometry is based on physical laws and classifies particles into compositional categories by measuring their settling velocity in water, which depends on their density and diameter. The resulting data serve as an important source of information for understanding how transported and deposited particles influence the morphological development processes of the river flow.

2.4 Remote Sensing and GIS Analysis

As part of this research, Sentinel-2 satellite imagery was used to evaluate changes in the Qoradaryo River channel between 2018 and 2024. Sentinel-2, developed under the European Union's Copernicus program, captures high-resolution multispectral images with a spatial resolution of 10 meters. Thanks to its imaging capabilities, the satellite is commonly used for monitoring environmental conditions and tracking land surface changes. For this study, the necessary images were downloaded from the Copernicus Open Access Hub. The data was processed using ArcMap, a component of the ArcGIS software suite. First, the images were georeferenced to align them accurately with real-world coordinates. After

that, a temporal comparison was carried out to highlight changes between different years. The analysis revealed several morphological transformations in the Qoradaryo River channel, including bank erosion, shifts in flow direction, and areas where sediment had accumulated. This remote sensing approach made it possible to observe how the river system evolved over time and provided useful insights for regional planning, environmental monitoring, and identifying high-risk zones.

3. RESULTS AND DISCUSSION

3.1 Hydrological Dynamics and Turbidity Trends in the Qoradaryo River

Initially, the area of interest was extracted from the general multispectral images downloaded from the Sentinel-2 satellite. Based on these images, maps reflecting the presence and distribution of water were generated using the NDWI (Normalized Difference Water Index) model (Figure. 2). The NDWI model is one of the most effective remote sensing indicators used to distinguish between water bodies and land surfaces. Using the satellite images obtained for the period 2018–2024, water index maps were produced, which revealed changes in the river flow direction, particularly shifts in the riverbank line, erosion-induced degradation, and areas where sediment particles had accumulated. These analyses allowed for the spatial and temporal evaluation of morphological changes occurring in the Qoradaryo River channel. For the analysis, images from May were selected, as water discharge typically reaches its maximum during this time. The primary reason for this increase is the rapid melting of snow and glaciers due to rising temperatures, along with intensified seasonal precipitation. As a result, the river experiences an increase in water volume, leading to intensified hydrodynamic activity within the channel, including accelerated erosion and sedimentation processes. The findings obtained from the NDWI-based maps provided a significant scientific and practical foundation for detecting variability within the river system, identifying hazardous zones, and developing effective ecological monitoring frameworks.

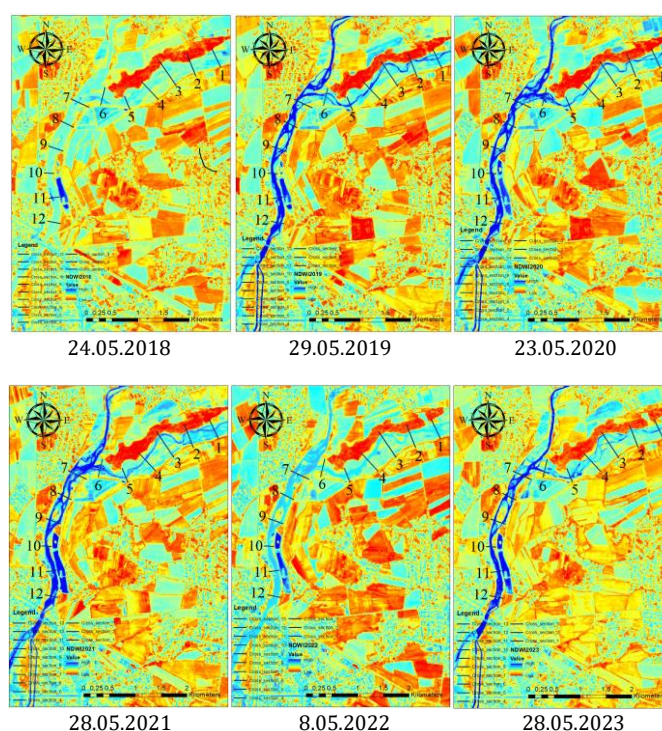


Figure 2: Water index maps generated based on the NDWI model (Qoradaryo River, 2018–2023 period)

Selected cross-sections 1 to 6 are located in the upper reaches of the Qoradaryo River, where water from the Fergana Canal enters the river. In contrast, cross-sections 7 to 12 are situated in the lower reaches, downstream of the canal's confluence with the river. The previously generated maps were analyzed in comparison with field-obtained natural observation data - namely, river discharge and turbidity levels within the flow. This approach enabled an in-depth investigation of the deformational

processes that occurred in the Qoradaryo River channel between 2018 and 2024.

Correlations were identified between spatial data extracted from NDWI maps generated from satellite imagery and field-based measurements. Based on this, zones of bank erosion associated with rising water levels, as well as areas of sediment accumulation, were precisely identified. The

analyses showed that with increased water discharge, the hydrodynamic regime of the river channel undergoes substantial changes, resulting in a gradual shift in the riverbank line and channel shape over time.

Long-term dynamic observations have revealed that the Qoradaryo River channel is significantly altering its geometric morphology over time. These changes are particularly evident during periods of intensive flow. According to field observations conducted on May 27, 2024, the river

discharge was recorded at 447 m³/s. On the same day, turbidity levels measured across various cross-sections ranged from 0.52 to 2.05 kg/m³. Due to the high turbidity values, a low NDWI index was observed, even under conditions of high water discharge. This phenomenon is reflected in spectral analysis maps as darker or duller shades of blue (Figure. 3). In other words, when turbidity is high, the spectral reflectance properties of water decrease, which leads to a reduction in the NDWI value.

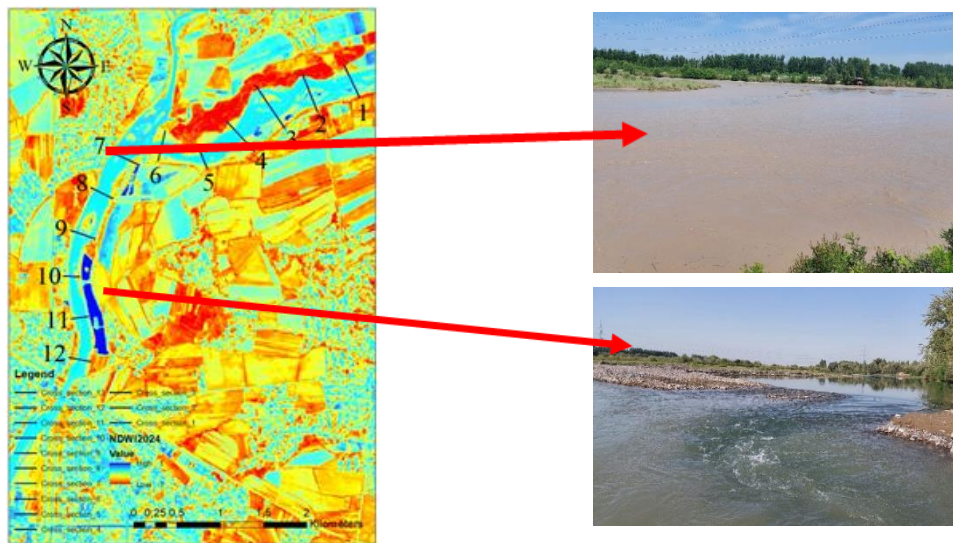


Figure 3: NDWI map and actual field conditions under high discharge and elevated turbidity levels (Qoradaryo River, May 27, 2024)

The research findings revealed that a large-scale erosion zone had formed along the left bank of the Qoradaryo River, particularly near cross-sections 10 and 11. Due to the low flow velocity in this area, suspended sediment particles were unable to continue moving with the current and consequently settled in the form of deposits. In contrast, the water near the outflow zone was relatively clear, which was reflected on the NDWI maps as bright blue coloration. This indicates low turbidity levels in the water and high spectral reflectance properties.

The next phase of field research was carried out on August 20, 2024, during a period when water discharge had decreased and turbidity levels were reduced. According to measurement results, the river discharge at that time was 97 m³/s, and the turbidity levels across different cross-sections ranged between 0.22 and 1.03 kg/m³. During this period, the significant decrease in turbidity led to a rise in NDWI values. In the spectral imagery, the river flow appeared bright and clear, represented by light blue tones (Figure. 4). This reflects an improvement in water quality and a reduction in sediment concentration.

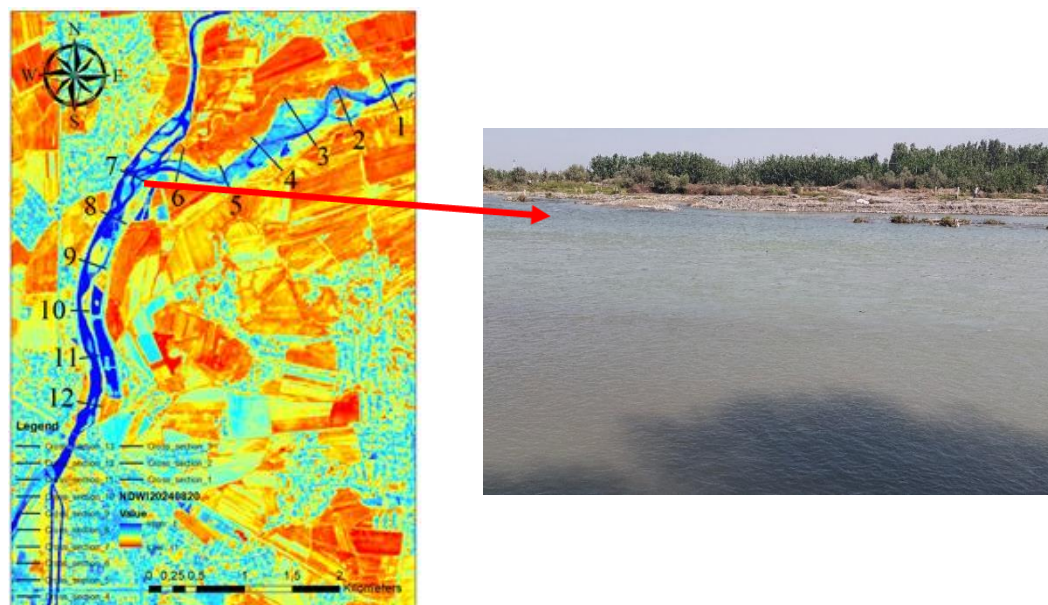


Figure 4: NDWI map view and actual conditions under low discharge and reduced turbidity levels (Qoradaryo River, August 20, 2024)

Based on the developed thematic maps, the relationship between NDWI index values and measured turbidity levels (S_0) obtained through field observations under natural conditions was analyzed. This assessment enabled the identification of a statistical correlation between the optical properties of river water (derived from satellite imagery) and its physico-chemical characteristics (measured in situ). The conducted correlation

analysis showed that a decrease in NDWI values is directly associated with increased turbidity levels. This phenomenon is linked to the light-absorbing and scattering properties of suspended particles in water, which reduce spectral reflectance under high turbidity conditions, thus lowering the NDWI index.

Based on the statistical analysis results, a correlation diagram (Figure. 5) was developed to represent the relationship between NDWI and S_0 values graphically. This graph makes it possible to predict the spectral

characteristics of water in satellite imagery based on changes in turbidity levels. Consequently, it serves as a practical tool for assessing the physical state of river water using remote sensing techniques.

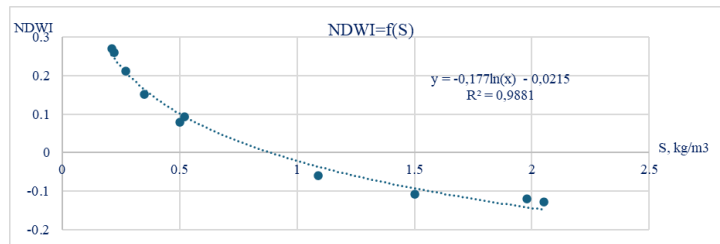


Figure 5: Graphical representation of the correlation between the NDWI index and turbidity concentration (S_0) in river water

The constructed correlation graph demonstrates that when the turbidity concentration in the water exceeds 0.5 kg/m³, there is a noticeable decrease in NDWI index values. This observation, in turn, indicates that there are certain limitations in assessing the physical condition of water using the NDWI index alone. The results show that the NDWI model can accurately detect the presence of water under low-turbidity conditions (≤ 0.5 kg/m³). However, when turbidity increases, the spectral reflectance properties of the water deteriorate, leading to a decline in NDWI values and, consequently, a reduction in the reliability of the model's output. Therefore, in such cases, it is advisable to supplement NDWI-based assessments with additional models or alternative remote sensing methods. Based on these observations, the study proposes a new empirical formula representing the relationship between NDWI values and turbidity concentration (S_0). This formula allows for the estimation of river water turbidity based on NDWI index values and facilitates the integration of remote sensing results with physico-chemical characteristics obtained from field measurements.

$$\text{NDWI} = -0.177\ln(S_0) - 0.0215 \quad (1)$$

The mathematical, statistical, and graphical analyses conducted during the study revealed that the relationship between NDWI index values and turbidity concentration (S_0) follows a logarithmic pattern. According to the results, as the NDWI value increases, a sharp decrease in turbidity levels is observed. However, once the NDWI reaches a certain threshold, the rate of change in turbidity slows down. This behavior is characteristic of classical logarithmic regression models, which express a non-linear yet stable relationship between the variables.

Regression analysis based on this logarithmic trend model yielded a correlation coefficient of $R^2 = 0.9881$, indicating a very strong relationship between NDWI and turbidity concentration. This high R-value scientifically validates the reliability of the proposed model. However, the practical application of the model is limited to specific ranges, meaning that it provides accurate results only within the following intervals:

- Turbidity concentration (S_0): 0 – 0.5 kg/m³
- NDWI index values: 0.00 – 0.30

Within these specified ranges, the model can reliably predict turbidity levels. However, outside of the indicated intervals - particularly under conditions of high turbidity or elevated NDWI values - the model's predictions may lack sufficient accuracy. Therefore, for such cases, it is necessary to implement additional field studies, physico-chemical measurements, and alternative modeling approaches. The proposed logarithmic model serves as an important theoretical foundation for the remote monitoring of river water quality. Moreover, this approach contributes to the expansion of remote sensing applications in the assessment of turbidity dynamics. Over the past three years, the morphological changes observed in the Qoradaryo River channel have been systematically investigated and thoroughly analyzed. The results of these studies indicate that the changes have primarily been influenced by hydrological factors (such as water discharge, flow velocity, and turbidity levels) and geomorphological conditions (including topography, bank material composition, and the stability of soil masses).

3.2 Remote Sensing-Based Analysis of River Morphology

During the analysis, bank erosion, the accumulation of suspended sediment transported by the flow, and notable shifts in the channel's shape were recorded as key deformation processes. These phenomena significantly impact the ecological and physical-geographical stability of the river system (Figure. 6). The identified changes are largely the result of the complex interaction between seasonal variability in river discharge, climatic influences, and human activities, such as irrigation canals, dams, and periodic water releases.

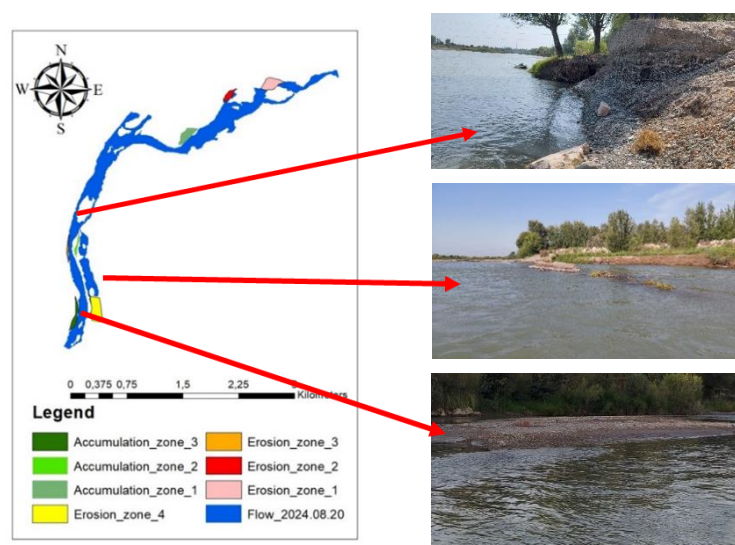


Figure 6: Deformational processes observed in the Qoradaryo River channel over the past three years: erosion, sediment accumulation, and channel morphology changes (2021–2024)

According to the analysis results, intensive bank erosion was observed in certain segments of the Qoradaryo River. These processes have led to the widening of the river channel and alterations in the natural direction of the water flow. In addition, the accumulation of suspended sediment transported by the current has resulted in blockages in some areas of the channel, causing the formation of new flow paths. These geomorphological changes are primarily driven by seasonal precipitation, rising water levels, and human activities such as construction and hydraulic infrastructure development. The study also assessed the negative impacts of these changes on the ecosystem and the surrounding environment. As a result of bank erosion, agricultural lands, natural vegetation zones, and aquatic biodiversity are increasingly at risk.

In cross-sections 2 and 3, active erosion processes were identified along

the right riverbank. Notably, erosion in these areas has intensified significantly over the past two years, largely due to seasonal rainfall, spring flooding, and anthropogenic influences. In cross-section 5, an increase in accumulation processes was observed on the right bank, resulting from the deposition of fine sediment particles. This has led to a relative shallowing of the channel and a change in the hydrodynamic characteristics of the flow.

Moreover, in cross-section 10, bank mass erosion continues on the right side, while sediment accumulation persists on the left bank. These changes were analyzed in comparison with flow velocity, direction, and depth data collected using Doppler instrumentation, forming a comprehensive analysis (Figure. 7).

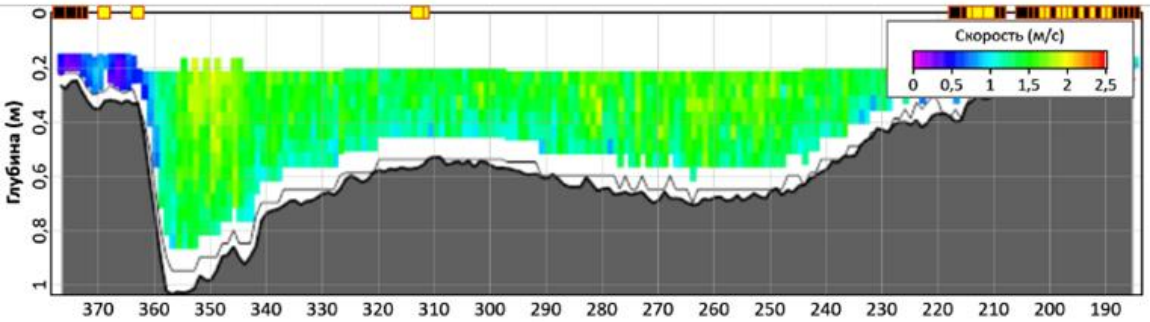


Figure 7: Erosion and accumulation processes observed at cross-section 10 of the Qoradaryo River

According to the analysis of data obtained using the Doppler device, both vertical (depth-related) and horizontal (lateral expansion) erosion processes are occurring along the right bank of the river. Notably, these erosion processes are continuing even under relatively low water discharge conditions, indicating low bank stability in these areas. In contrast, an opposite pattern was observed at cross-section 11: sediment accumulation is active on the right bank, while large-scale bank erosion is taking place on the left bank, highlighting a geomorphological asymmetry. Although such changes were recorded at various points along the river channel, analysis revealed that the most significant zones of deformation, erosion, and ecological risk are concentrated in seven key areas. These zones represent the main threats to the morphological stability of the river and are the result of complex interactions between high hydrodynamic loading, fluctuations in flow velocity, loose bank material structures, and anthropogenic influences. Such unevenly distributed hydrodynamic forces

and physical-geomorphological conditions confirm the complex and multifaceted nature of deformation processes occurring throughout the river channel. This underlines the critical importance of continuous monitoring of the Qoradaryo system, the development of protection strategies, and the implementation of engineering-ecological assessments.

3.3 Sediment Composition and Flow Energy Relationship

To gain a deeper understanding of the hydrodynamic changes discussed above and to determine the granulometric characteristics of the suspended sediment, an analysis of the average fractional distribution of particles in water samples was conducted (Tab. 1). This analysis allows for the identification of sediment transport behavior and the assessment of its relationship to observed morphological changes. The following results are based on investigations carried out within this specific research direction.

Table 1: Average granulometric (fractional) composition of sediment particles in Qoradaryo River water, % (as of May 27 and August 20, 2024)

Date	Granulometric composition, %									Total fraction, %
	10,0-5,0 mm	5,0-2,0 mm	2,0-1,0 mm	1,0-0,5 mm	0,5-0,25 mm	0,25-0,10 mm	0,1-0,05 mm	0,05-0,01 mm	0,01-0,005 mm	
	1	2	3	4	5	6	7	8	9	
27.05.2024				0,40	0,57	25,04	36,58	34,37	3,04	100,00
20.08.2024	18,28	7,94	2,00	0,41	1,53	16,64	30,63	20,51	2,06	100,00

The granulometric analysis of sediment samples collected on May 27 and August 20, 2024, revealed significant differences in the particle size distribution across sediment fractions.

Results from May 27, 2024: During this period, the river discharge was relatively high (447 m³/s), and the turbidity level ranged between 0.52 and 2.05 kg/m³. According to the granulometric analysis, the sediment composition was dominated by medium and fine sand particles within the 0.25–0.05 mm range: 0.25 - 0.10 mm - 25.04%, 0.10 - 0.05 mm - 36.58%, 0.05 - 0.01 mm - 34.37%, Very fine particles (0.01 - 0.005 mm) - 3.04%. Coarse fractions larger than 1 mm were not detected.

These results indicate that during high-discharge periods, the increased flow velocity is sufficient to transport even coarse particles, preventing them from settling. As a result, the sediment accumulated along the riverbanks and bed primarily consists of fine particles that were either not

mobile or only slowly settling within the flow. In strong hydrodynamic conditions, coarse particles do not have enough time to settle, and the sediment observed in place mainly comprises residual fine fractions. This finding highlights the physical relationship between flow velocity and particle diameter.

Results from August 20, 2024: At this time, the discharge had significantly decreased (97 m³/s), and turbidity ranged between 0.22 and 1.03 kg/m³. The analysis showed a much more diversified particle distribution, with a wider range of sizes: Coarse particles (10.0 - 5.0 mm) - 18.28 %, 5.0 - 2.0 mm - 7.94%, 2.0 - 1.0 mm - 2.00%, Medium sand (0.25 - 0.10 mm) - 16.64%, Fine sand and silt (0.10 - 0.01 mm) - total of 53.20%, Very fine particles (0.01–0.005 mm) - 2.06%.

These results confirm that slower flow conditions allowed even larger particles to settle, and under low discharge, sediment material is deposited

in a wider range of particle sizes. During high-flow conditions (May), primarily fine fractions are deposited, while during low-flow periods (August), coarser particles also settle and become part of the sediment layer. This demonstrates that flow velocity and hydraulic energy are key factors governing the transport and deposition of sediment fractions. The findings reflect a direct correlation between hydrodynamic forces and sediment particle size. In the riverbed formation process, coarse fractions accumulate in slower-flowing zones, which serve as a key indicator for identifying areas of sediment accumulation.

3.4 Spatial Assessment of Erosion and Accumulation Zones

Furthermore, an assessment of total surface area and volume was conducted for eroded zones and areas covered with sediment deposits along the river channel. Based on satellite monitoring and field observations, the geometric dimensions of these zones were calculated, and their volumetric indicators were determined. Erosion surfaces were delineated using developed maps, and depth values were derived from Doppler measurements. The results of these calculations were systematized into a table (Tab. 2), detailing eroded and accumulation-prone areas at each cross-section. This approach enables a spatial and quantitative assessment of the morphological changes occurring in the river system.

Table 2: Total surface area and volumetric indicators of zones affected by erosion and accumulation processes in the Qoradaryo River channel (as of 2024)				
№	Characteristic cross-section/bank	Deformation zones	Deformation area m ²	Deformation volume m ³
1	2 / Right bank	Erosion zone 1	30754	23065
2	3 / Right bank	Erosion zone 2	11258	6191
3	10 / Right bank	Erosion zone 3	4311	5302
4	11 / Left bank	Erosion zone 4	42416	36053
5	5 / Right bank	Accumulation zone 1	28268	16960
6	10 / Left bank	Accumulation zone 2	8780	2195
7	11 / Right bank	Accumulation zone 3	16761	8873

This table presents a quantitative assessment of geomorphological changes identified through spatial analysis and field observations conducted along the Qoradaryo River channel. Specifically, it includes measurements related to bankline shifts, soil erosion, and sediment accumulation. For each cross-section, the areas affected by erosion (m²), the accumulated sediment areas (m²), and their volumes (m³) were calculated and are presented in the table.

The data summarized in this table serve as a valuable resource for future hydrological and geomorphological studies. Moreover, the obtained indicators can be used to develop strategic recommendations in practical fields such as sustainable basin management, riverbank protection, and the

identification of ecologically vulnerable zones.

In the remaining investigated areas, no significant bank erosion or notable geomorphological transformations were recorded (Figure. 8). In these cross-sections, the river flow predominantly follows a central path, and the hydrodynamic pressure on the banks is not sufficient to trigger active erosion processes. Observations at each cross-section were compared with flow velocity, depth, and direction data measured using the Doppler device, and analytical conclusions were drawn accordingly. This approach made it possible to clearly distinguish between stable zones and active deformation zones along the river channel.

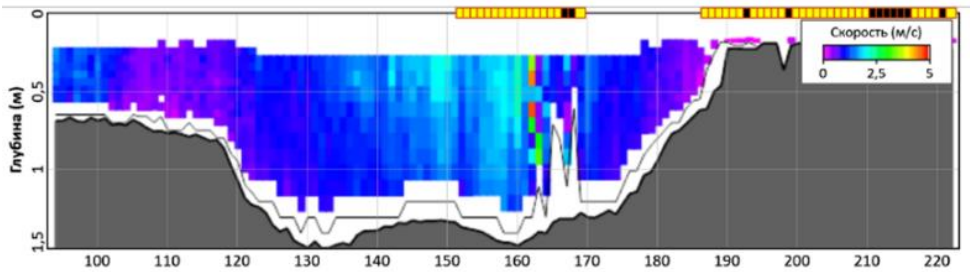


Figure 8: Centralized flow direction of the river and areas with no observed bank erosion (based on Doppler data)

Comprehensive analyses based on field observations and remote sensing data indicate that the riverbank zones along the Qoradaryo River can be divided into two main categories:

- Relatively stable areas;
- Actively forming areas with a high risk of erosion.

Based on the geomorphological characteristics of these zones, two protection strategies are proposed for riverbank stabilization:

1. Biological Reinforcement (for low-erosion, stable areas):

In zones with a relatively low erosion risk, biological reinforcement through vegetation adapted to local ecological conditions, such as willow, reed, oleaster, and other riparian plant species, is recommended.

This approach:

- Enhances the natural stability of the soil layer
- Provides soil cohesion through the root systems of plants
- Reduces the hydraulic pressure exerted on the banks
- Contributes to the preservation of ecological balance

It is recommended as an environmentally friendly, cost-effective, and long-term sustainable protection measure.

2. Engineering Structures (for high-erosion, actively eroding zones):

In areas where erosion rates reach 10–25 meters per year, plant-based methods alone are insufficient, as vegetation cannot establish quickly enough to counteract the erosion. In such high-energy and flood-prone zones, engineering solutions are necessary.

Recommended structures include:

- Gabion walls
- Concrete or stone barriers
- Hydraulic screens and levees

These structures serve to:

- Reduce the velocity of river flow
- Stabilize the bank zones
- Slow down erosion processes
- Ensure safety in vulnerable areas

In summary, the proposed strategies are tailored to the varying morphodynamic and hydrodynamic conditions of the river system. These measures are both scientifically grounded and practically effective, playing a crucial role in:

- Preserving the ecological integrity of the river,
- Ensuring the safety of infrastructure, and
- Enabling the sustainable management of water resources.

4. CONCLUSION

In this research, the morpho-dynamic evolution of the Qoradaryo Riverbanks was analyzed utilizing multi-temporal Sentinel-2 satellite imagery. By employing a combination of remote sensing tools and GIS-based spatial analysis, the study successfully detected notable alterations in riverbank outlines, including zones of accretion and erosion. These transformations were particularly evident in highly dynamic segments of the river and are likely the result of both natural hydrological processes and human-induced influences.

The use of Sentinel-2 data across different time intervals has demonstrated its efficiency in tracking fluvial changes with considerable spatial and temporal precision. The outcomes highlight the necessity of regular monitoring to support effective river management strategies, particularly in regions susceptible to land degradation and bank instability.

This methodology serves as a scalable model for similar fluvial systems in environmentally sensitive or inaccessible areas. For more comprehensive understanding, future investigations should integrate climatic variables and hydrological measurements to explore causal relationships and forecast future morphological trends.

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