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Multi-Temporal GIS Analysis of River Channel Migration Near a Pipeline Crossing: The Kura River, Azerbaijan

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Abstract

River crossings of linear infrastructure are often interpreted as fixed engineering locations, although the surrounding channel may undergo significant spatial reconfiguration over time. This study presents a multi-temporal GIS-based analysis of river channel migration near a pipeline crossing on the Kura River, Azerbaijan. The research focuses on the spatial interaction between channel migration, island development, flow redistribution, and the changing geomorphic context of the crossing corridor. Watercourse and exposed in-channel ground polygons were delineated from satellite imagery for 2001, 2007, 2009, 2010, 2012, and 2013 within a fixed geomorphic area of interest. A separate localized pipeline area of interest was used to assess spatial exposure indicators near the crossing corridor. Temporal overlay, area comparison, island fragmentation assessment, and proximity-based GIS interpretation were applied to evaluate morphodynamic change. The results indicate substantial reconfiguration of the active river corridor. The watercourse area increased from 16.41 ha in 2001 to 48.17 ha in 2010 and then decreased to 27.05 ha in 2013, while the exposed in-channel ground increased from 3.16 ha to 30.76 ha during the study period. The island fraction increased from 0.16 to 0.53, indicating a growing dominance of exposed alluvial surfaces within the mapped corridor. Pipeline-related spatial indicators also changed markedly, with the total pipeline length located within the 50 m near-bank zone increasing from 410 m in 2001 to 821 m in 2013. These changes show that the crossing should be considered part of a dynamic river interaction corridor rather than a static point. The proposed approach provides a reproducible GIS framework for spatial screening of riverine infrastructure exposure and for identifying crossing zones that may require field verification or closer monitoring. The findings represent GIS-based spatial indicators and should not be interpreted as direct measurements of pipeline exposure depth, scour, damage, or structural integrity.

Keywords: multi-temporal GIS; river corridor evolution; channel migration; alluvial island development; fluvial morphodynamics; spatial exposure indicators; geomorphic exposure screening; Kura River; Azerbaijan

Introduction

River channels are dynamic geomorphic systems whose spatial configuration may change considerably over time. In alluvial river environments, channel migration, bank erosion, sediment deposition, island formation, and flow redistribution can gradually reshape the active river corridor. Such behaviour is characteristic of actively adjusting alluvial river systems (Church, 2006; Fryirs & Brierley, 2013). These processes are especially important where rivers intersect linear infrastructure, because the crossing is often treated as a fixed engineering location, while the surrounding river morphology may continue to evolve. Studies of active meandering rivers show that channel instability is commonly spatially variable and may be expressed through localized erosion, deposition, widening, narrowing, or bend adjustment (Hooke, 2007).

Remote sensing and GIS provide an effective basis for detecting and interpreting such changes. Multi-temporal satellite images, aerial photographs, and vector-based spatial analysis allow researchers to compare watercourse footprints, identify erosion and deposition zones, map in-channel landforms, and quantify changes in river planform through time. These methods are widely used in fluvial geomorphology because they make it possible to reconstruct river corridor evolution where continuous field measurements are unavailable or limited (Gilvear & Bryant, 2016; Piégay et al., 2020). In this context, GIS analysis is not only a mapping tool, but also a methodological framework for interpreting spatial relationships between geomorphic processes and exposed elements of the landscape.

The problem becomes more specific near pipeline crossings. A buried pipeline crossing a river may remain fixed in its designed position, but the channel may migrate toward or away from it, split into branches, develop islands, or redistribute flow across the crossing corridor. Similar multi-thread and island-dominated configurations are widely documented in large alluvial river systems (Gurnell et al., 2001; Makaske, 2001). Therefore, the crossing should not be considered only as a static point or line. It may be more appropriately interpreted as a dynamic morphodynamic interaction corridor, where changes in river morphology influence the spatial context of infrastructure exposure. From a GIS and geoecological perspective, this does not imply direct assessment of pipeline damage, exposure depth, or structural integrity. Rather, it refers to spatial indicators that may help identify zones requiring closer monitoring or field verification.

The Kura River is the largest river system in Azerbaijan and represents an important fluvial corridor characterized by active lowland reaches, alluvial banks, meandering segments, and local channel reconfiguration. Spatial variability of such channel adjustment processes is typical for dynamically evolving river corridors (Hooke, 2007; Surian et al., 2009). In such conditions, pipeline crossings located near active river bends or island-forming zones may be affected by gradual changes in the spatial structure of the river corridor. This makes the Kura River a suitable case for applying multi-temporal GIS analysis to assess channel migration and corridor evolution change near critical infrastructure.

This study examines a pipeline crossing area on the Kura River using satellite image interpretation and GIS vector analysis for 2001, 2007, 2009, 2010, 2012, and 2013. Within a fixed geomorphic area of interest, watercourse polygons and exposed in-channel ground polygons were delineated and compared over time. A separate localized pipeline area of interest, hereafter referred to as the pipeline AOI, was used to assess spatial exposure indicators near the crossing corridor. This distinction is important because the broader geomorphic area describes river wide dynamics, while the pipeline AOI focuses on the local crossing environment.

In this methodological framework, the main dynamic processes described above were represented through measurable GIS indicators. Channel migration and bank adjustment were assessed by comparing annual watercourse footprints and their derived boundary proxies. Island development was evaluated through exposed in-channel ground polygons, island area, island fraction, and the number of island parts. Flow redistribution was interpreted from temporal changes in the spatial arrangement of watercourse and island polygons, including repeated transitions between water-covered and exposed states. The pipeline AOI was then used to relate these river-corridor changes to the crossing corridor through proximity, buffer-based, and intersection-based indicators. In this way, the GIS analysis reconstructs river corridor evolution not as a single mapped displacement, but as a sequence of planimetric changes in watercourse position, island structure, channel-thread distribution, and near-bank relationships.

The objective of the study is to develop a GIS-based interpretation of channel migration, island development, and river corridor reconfiguration near a pipeline crossing. The scientific contribution of the work lies in treating the crossing not as a fixed engineering point, but as part of a changing alluvial corridor. The proposed approach remains within GIS, fluvial geomorphology, geoecology, and spatial analysis. It is intended to support spatial monitoring and preliminary exposure screening, without replacing hydrodynamic modelling, geotechnical surveys, or engineering integrity assessment.

Methods and Materials

Study area

The study area shown in Figure 1 is located along the Kura River near Poylu, Azerbaijan. The analysed reach includes a river crossing corridor where the river channel interacts spatially with a pipeline alignment. The local planform is characterized by an active watercourse, an alluvial island, and changes in channel-thread distribution observed in multi-temporal satellite imagery. A fixed geomorphic area of interest, hereafter referred to as the geomorphic AOI, was used for all mapped years. This methodological decision ensures that watercourse and island footprint areas are calculated within the same spatial frame, making temporal comparisons consistent. As a result, changes in watercourse area, island area, and island fraction can be interpreted as relative indicators of river corridor reconfiguration rather than as artefacts of changing analysis boundaries.

The study corridor represents an actively evolving river environment where local sediment accumulation, island development, and flow redistribution are visible in satellite imagery. The alluvial island is a key geomorphic element because it may divide the flow into separate channel threads and modify the position of active banks. Island-related redistribution of flow is recognized as an important component of large-river corridor evolution (Gurnell et al., 2001). As the island expands, fragments, or merges with smaller bars, it may contribute to narrowing of active flow paths and redistribution of hydraulic energy toward one or both banks.

The study area is therefore suitable for examining how channel migration and island development influence the spatial context of a pipeline crossing. In this study, the crossing is not treated as a fixed engineering point only, but as part of a dynamic river interaction corridor. This interpretation supports GIS-based monitoring of riverine infrastructure exposure while remaining distinct from direct engineering assessment of pipeline condition or structural integrity

Figure 1. Location of the study area along the Kura River near Poylu, Azerbaijan. Source: compiled by the author based on GIS data and satellite imagery

Satellite Data and GIS Vector Preparation

Satellite imagery was used as the primary source for reconstructing the spatial configuration of the Kura River channel within the analysed reach. Multi-temporal image interpretation was carried out for six observation years: 2001, 2007, 2009, 2010, 2012, and 2013. These years were selected because they provide the most usable available historical sequence for identifying changes in the watercourse footprint, exposed in-channel ground, island development, and channel-thread distribution near the pipeline crossing corridor.

The satellite image sequence was compiled from available archival satellite sources for the selected observation years. The imagery included historical scenes accessible through Google Earth Pro where available, as well as archival Landsat-based imagery for earlier or otherwise unavailable years. The 2001 scene was not available in Google Earth Pro and was therefore treated as an archival satellite baseline. The 2007 scene had comparatively lower visual quality than the later images; consequently, its interpretation was carried out conservatively and with particular attention to persistent planform features.

Because the available historical scenes differ in image source, acquisition conditions, spatial resolution, illumination, and water-stage conditions, the study did not rely on automatic spectral classification. Instead, a consistent manual interpretation approach was applied to all observation years within the same geomorphic AOI. This ensured that the mapped watercourse and exposed in-channel ground polygons were compared within the same spatial frame, while uncertainty related to image quality was considered during visual interpretation.

The interpretation focused on two principal spatial classes: watercourse and exposed in-channel ground. The watercourse class represents the visible river water surface within the geomorphic AOI. The exposed in-channel ground class represents alluvial islands, bars, and island-like surfaces located within or immediately adjacent to the active river corridor. These mapped classes were selected because they directly represent the main planimetric elements through which channel migration, island development, and flow redistribution can be reconstructed from multi-temporal imagery.

The use of multi-temporal satellite imagery and GIS-based vector mapping is appropriate for this type of analysis because river planform changes, bankline shifts, in-channel landforms, and sedimentary features can often be detected through repeated image interpretation.

The satellite image interpretation scheme, including the role of each observation year and the mapped GIS outputs, is summarized in Table 1.

Table 1. Satellite image interpretation scheme and mapped GIS layers[1].

Observation Year	Image source/archive	Image quality / role	Mapped classes	GIS output
2001	Archival Landsat-based satellite imagery	Baseline scene; not available in Google Earth Pro	Watercourse; exposed in-channel ground	Annual polygon layers
2007	Historical satellite imagery/ Google Earth Pro where available	Lower visual quality; interpreted conservatively	Watercourse; exposed in-channel ground	Annual polygon layers
2009	Historical satellite imagery/ Google Earth Pro where available	Clearer intermediate scene	Watercourse; exposed in-channel ground	Annual polygon layers
2010	Historical satellite imagery/ Google Earth Pro where available	Clearer intermediate scene; maximum mapped watercourse extent	Watercourse; exposed in-channel ground	Annual polygon layers
2012	Historical satellite imagery/ Google Earth Pro where available	Later-stage corridor configuration	Watercourse; exposed in-channel ground	Annual polygon layers
2013	Historical satellite imagery/ Google Earth Pro where available	Final mapped corridor configuration	Watercourse; exposed in-channel ground	Annual polygon layers

Remote sensing and aerial image analysis are widely used in fluvial geomorphology for mapping landforms and measuring temporal changes in river systems (Gilvear & Bryant, 2016). More recent studies also emphasize the role of remote sensing in monitoring river corridor conditions and interpreting fluvial processes at different spatial and temporal scales (Piégay et al., 2020).

For each analysed year, the visible boundaries of the watercourse and exposed in-channel ground were manually digitized as polygon layers. Manual digitization was preferred because the analysed corridor contains narrow channel branches, irregular island margins, shallow-water zones, and transitional wet surfaces that may be difficult to classify reliably using automatic threshold-based methods alone. The interpretation was based on visual criteria such as tone, colour contrast, texture, shape, continuity of water surfaces, and the spatial relationship between the river channel and exposed sedimentary surfaces.

All annual vector layers were prepared within the same geomorphic AOI. This ensured that watercourse area, island area, and island fraction were calculated within an identical spatial frame for all years. The use of a fixed boundary is important because it prevents changes in calculated areas from being caused by differences in map extent. Therefore, temporal differences in polygon areas can be interpreted as indicators of actual river corridor reconfiguration within the selected reach.

The vector preparation workflow included several steps. First, satellite images for each year were reviewed and visually compared. Second, watercourse and exposed ground polygons were digitized for each observation year. Third, all polygon layers were clipped to the geomorphic AOI. Fourth, topology checks were performed to reduce overlaps, gaps, and geometry errors. Fifth, area values were calculated

[1] *Note: The table summarizes the interpretation scheme used in the study. Image availability and quality varied between observation years. The 2001 scene was used as an archival baseline, while the 2007 scene was retained despite lower visual quality because it provided an intermediate temporal reference between 2001 and 2009. All mapped years were processed using the same fixed geomorphic boundary and the same visual interpretation criteria.*

for each polygon class. Finally, the annual layers were organized into a multi-temporal GIS database for overlay analysis and comparison.

A separate pipeline AOI was also prepared. Unlike the broader geomorphic AOI, which was used to analyse the general river reach, the pipeline AOI was used to assess spatial indicators near the crossing corridor. This distinction allows the study to separate reach-scale channel behaviour from local exposure-related indicators around the pipeline alignment. The pipeline layer was used only as a spatial reference for GIS-based interpretation and was not used for structural or mechanical pipeline assessment.

All spatial data were processed in WGS 84 UTM zone 38N. Area calculations were performed in projected coordinates to avoid distortions associated with geographic coordinate systems. The final GIS dataset consisted of annual watercourse polygons, annual exposed ground polygons, the geomorphic AOI, the pipeline AOI, and the pipeline alignment. These layers formed the basis for subsequent calculations of watercourse area, island area, island fraction, island fragmentation, and exposure-related spatial indicators.

Area of Interest Definition

Two spatial areas of interest were used in the study. The geomorphic AOI covers the analysed river reach and was used for calculating watercourse and island footprint dynamics. This boundary was kept unchanged for all observation years to ensure that temporal changes were compared within the same spatial frame.

The pipeline AOI represents a localized corridor around the pipeline crossing. It was used only for assessing spatial exposure indicators near the crossing zone, such as the relationship between the pipeline alignment, active watercourse, and nearby in-channel landforms.

The separation of these two areas is methodologically important. The geomorphic AOI reflects reach scale river corridor changes, whereas the pipeline AOI focuses on local interaction between channel migration and the crossing corridor. This distinction prevents mixing general fluvial trends with infrastructure related spatial indicators.

GIS Metrics and Spatial Analysis

GIS metrics were calculated to quantify the temporal reconfiguration of the river corridor and to assess the changing spatial relationship between the active channel, alluvial island surfaces, and the pipeline crossing. The analysis was based on polygon footprints of the watercourse and exposed in-channel ground prepared for 2001, 2007, 2009, 2010, 2012, and 2013. The methodological logic follows a multi-temporal planform comparison approach, in which remotely sensed river features are converted into comparable vector layers and then analyzed through overlay, area calculation, boundary extraction, and proximity measurement. Such approaches are commonly used in fluvial geomorphology for detecting channel migration, mapping river landforms, and measuring temporal changes in river corridors (Gilvear & Bryant, 2016; Piégay et al., 2020).

The analysis was carried out in several consecutive steps. First, watercourse and exposed in-channel ground polygons were prepared for each observation year and clipped to the same geomorphic AOI. Second, area metrics were calculated to describe changes in the watercourse footprint, island footprint, island fraction, and island structure. Third, temporal overlay and geometric difference operations were used to identify zones where the mapped corridor changed from water to exposed ground, or from exposed ground to water. Fourth, the localized pipeline AOI was used to compare the annual river configuration with the pipeline alignment. At this stage, the analysis included buffer measurements near the mapped bank proxy, intersections between the pipeline and the watercourse or island polygons, and the distance from the middle part of the mapped crossing segment to the nearest bank proxy. This workflow connects the interpreted satellite features with the reconstruction of river corridor evolution and with the assessment of spatial exposure indicators near the crossing.

The metrics used in this study are based on standard GIS geometric operations, including polygon area calculation, overlay analysis, buffering, boundary extraction, geometric difference, and proximity measurement. Their scientific contribution lies not in the development of new mathematical formulations, but in the integration of these spatial indicators into a multi-temporal river corridor interpretation framework for analyzing river corridor evolution near a pipeline crossing. In this framework, area metrics describe the changing composition of the active corridor, overlay metrics describe the spatial redistribution of water and exposed ground, and proximity metrics describe the changing relationship between the river corridor and the pipeline alignment. Comparable GIS-based approaches are commonly applied in river corridor analysis and geomorphic interpretation studies (Belletti et al., 2017).

For each observation year (t), two main polygon classes were used. The first class, W(t), represents the watercourse footprint, that is, the visible river water body within the geomorphic AOI. The second class, I(t), represents exposed in-channel ground, interpreted in this study as alluvial island or island-like surfaces inside the active river corridor. All area values were calculated in the projected coordinate system with metric units and then converted to hectares.

The watercourse area was defined as:

$$A_w(t) = \text{Area}[W(t)]$$

where $A_u(t)$ is the watercourse area in year t.

The island area was defined as:

$$A_i(t) = \text{Area}[I(t)]$$

where $A_i(t)$ is the exposed in-channel ground or island area in year t.

The combined mapped active footprint was calculated as:

$$A_t(t) = A_w(t) + A_i(t)$$

This combined footprint does not represent the full floodplain or the complete channel belt. It represents only the mapped watercourse and island/ground surfaces within the geomorphic AOI. It is therefore used as a local GIS indicator of river corridor configuration rather than as a hydrological measure of channel capacity.

To normalize island development relative to the mapped river corridor, the island fraction was calculated as:

$$F_i(t) = \frac{A_i(t)}{A_w(t) + A_i(t)}$$

where $F_i(t)$ expresses the proportion of exposed in-channel ground within the combined watercourse-island footprint. Higher values of $F_i(t)$ indicate a larger relative dominance of island surfaces within the crossing corridor. This metric is useful because absolute island area alone may be influenced by changes in the total mapped watercourse extent, while the fraction provides a normalized indicator of island dominance.

Temporal changes in watercourse and island areas were calculated between consecutive observation years or selected epochs. The absolute change in watercourse area was expressed as:

$$\Delta A_w(t_1, t_2) = A_w(t_2) - A_w(t_1)$$

The absolute change in island area was expressed as:

$$\Delta A_i(t_1, t_2) = A_i(t_2) - A_i(t_1)$$

Relative island growth was calculated as:

$$G_i(t_1, t_2) = \frac{A_i(t_2) - A_i(t_1)}{A_i(t_1)} \times 100$$

where $G_i(t_1, t_2)$ is the percentage change in island area between two epochs. The same logic can be applied to the watercourse footprint when relative watercourse change is required:

$$G_w(t_1, t_2) = \frac{A_w(t_2) - A_w(t_1)}{A_w(t_1)} \times 100$$

Island structure was also described using the number of island parts:

$$N_i(t) = \text{count}\big[I_{\text{parts}}(t)\big]$$

where $N_i(t)$ is the number of polygon parts after multipart decomposition. This metric was used as a descriptive indicator of island fragmentation or coalescence. In this study, changes in $N_i(t)$ are not interpreted as direct evidence of a single geomorphic process. Rather, they indicate changes in the mapped spatial structure of exposed in-channel ground. Such changes may reflect actual island fragmentation, merging of smaller bars, differences in inundation level, or image interpretation uncertainty.

For bank-related analysis, a bank proxy was derived from the boundary of the watercourse polygon:

$$B(t) = \partial W(t)$$

where B(t) is the GIS-derived watercourse boundary for year t, and ∂W(t) denotes the polygon boundary of the mapped watercourse footprint. This boundary is not a surveyed engineering bankline. It represents the planimetric water edge extracted from the annual GIS footprint. Therefore, all distance and proximity indicators based on B(t) are interpreted as GIS-based spatial indicators, not as field-surveyed bank positions or measurements of pipeline burial depth.

Pipeline-related metrics were calculated within the localized pipeline AOI. This AOI was kept separate from the broader geomorphic AOI because pipeline exposure indicators must represent the local crossing corridor rather than the entire river reach. The use of a focused crossing corridor is consistent with the broader concept that channel migration and river corridor change should be analyzed as spatial zones rather than as isolated points (Rapp & Abbe, 2003). In this study, two parallel pipeline polylines were processed and denoted as P_1 and P_2. For general notation, P_p refers to pipeline p, where $p \in \{1, 2\}$.

Near-bank exposure length was calculated using 50 m and 100 m buffers around the bank proxy. For each pipeline P_p, the length located within 50 m of the bank proxy was calculated as:

$$L_{50}^{(p)}(t) = \text{Length}\left[P_p \cap \text{Buffer}(B(t), 50)\right]$$

Similarly, the length located within 100 m of the bank proxy was calculated as:

$$L_{100}^{(p)}(t) = \text{Length}\left[P_p \cap \text{Buffer}(B(t), 100)\right]$$

For the two parallel pipelines, total near-bank exposure lengths were calculated as:

$$L_{50}^{(\Sigma)}(t) = \sum_{p=1}^{2} L_{50}^{(p)}(t)$$

$$L_{100}^{(\Sigma)}(t) = \sum_{p=1}^{2} L_{100}^{(p)}(t)$$

These indicators show how much of the pipeline alignment is located near the mapped watercourse boundary in each epoch. They do not indicate actual physical exposure of the pipeline. Instead, they identify the length of pipeline alignment located within predefined near-bank GIS zones.

Additional crossing-configuration indicators were calculated by intersecting the pipeline polylines with the watercourse and island footprints. Pipeline length intersecting the watercourse footprint was calculated as:

$$L_{w}^{(p)}(t) = \text{Length}\left[P_p \cap W(t)\right]$$

Pipeline length intersecting the island footprint was calculated as:

$$L_{i}^{(p)}(t) = \text{Length}\left[P_p \cap I(t)\right]$$

For both pipelines combined, the total watercourse-crossing and island-crossing lengths were calculated as:

$$L_{w}^{(\Sigma)}(t) = \sum_{p=1}^{2} L_{w}^{(p)}(t)$$

$$L_{i}^{(\Sigma)}(t) = \sum_{p=1}^{2} L_{i}^{(p)}(t)$$

These metrics are useful for describing whether the crossing corridor is dominated by open water or by exposed in-channel ground in plan view. A decrease in $L_u^{(\Sigma)}(t)$ together with an increase in $L_i^{(\Sigma)}(t)$ may indicate that the island footprint occupies a larger part of the crossing corridor. However, this is still a planimetric GIS interpretation and should not be interpreted as direct evidence of changes in pipeline cover, scour depth, or structural condition.

A simple minimum distance from the pipeline to the bank proxy may be misleading at a river crossing because the pipeline necessarily intersects the river corridor in plan view. Therefore, a crossing-safe midpoint distance was used. First, the pipeline segment intersecting the watercourse footprint was defined as:

$$S_w^{(p)}(t) = P_p \cap W(t)$$

The midpoint of this underwater segment was then calculated as:

$$m_w^{(p)}(t) = \text{Midpoint}\left[S_w^{(p)}(t)\right]$$

The distance from this midpoint to the bank proxy was calculated as:

$$d_{mid}^{(p)}(t) = \text{Distance}\left[m_w^{(p)}(t), B(t)\right]$$

For the two parallel pipelines, the minimum midpoint-to-bank distance was reported as:

$$d_{\text{mid,min}}(t) = \min\left[d_{mid}^{(1)}(t), d_{mid}^{(2)}(t)\right]$$

This metric describes how close the center of the mapped underwater crossing segment is to the nearest bank proxy. A decrease of $d_{mid,min}(t)$ in this distance may indicate that the active channel configuration is tightening around the pipeline crossing corridor. It should not be interpreted as a direct measurement of pipeline exposure depth or engineering risk.

Where polygon overlays between two epochs were required, watercourse expansion and contraction areas were calculated using geometric difference operations. Water expansion between two epochs was defined as:

$$E_w(t_1, t_2) = \text{Area}[W(t_2) - W(t_1)]$$

Water contraction was defined as:

$$C_w(t_1, t_2) = \text{Area}[W(t_1) - W(t_2)]$$

These overlay-based indicators can be interpreted as planform water-occupation change. They may reflect erosion, accretion, inundation differences, island emergence, vegetation stabilization, or water-stage effects. For this reason, the terms "water expansion" and "water contraction" are preferred in the metric description, while geomorphic interpretation is provided cautiously in the Results and Discussion sections.

All calculated metrics were organized into annual summary tables. The principal output indicators include watercourse area, island area, island fraction, number of island parts, total pipeline length within the 50 m and 100 m near-bank zones, pipeline length intersecting the watercourse and island footprints, and the minimum midpoint-to-bank distance.

Together, these indicators describe the evolution of the watercourse-island configuration and the changing spatial relationship between the river corridor and the pipeline crossing. The methodology is intended for GIS-based exposure screening and alluvial corridor monitoring. It does not replace hydrodynamic modeling, bathymetric survey, geotechnical investigation, or pipeline structural integrity assessment.

Results

Watercourse and Island Footprint Dynamics

The multi-temporal GIS analysis shows that the analyzed river corridor of the Kura River underwent substantial spatial reconfiguration between 2001 and 2013. Changes were observed in the geometry of the active watercourse, the extent of exposed in-channel ground, the structure of alluvial island surfaces, and the distribution of channel threads within the fixed geomorphic AOI.

The calculated metrics demonstrate that both the watercourse footprint and the island footprint changed considerably through time (Table 2). The observed variations indicate that the river corridor remained morphodynamically active during the analyzed period rather than maintaining a stable planform configuration. The watercourse area increased from 16.41 ha in 2001 to 48.17 ha in 2010, after which it decreased to 23.27 ha in 2012 and 27.05 ha in 2013. In contrast, the exposed in-channel ground increased more continuously, from 3.16 ha in 2001 to 30.76 ha in 2013. The island fraction also increased from 0.16 to 0.53 during the study period. These values show that the later corridor configuration was characterized not only by changes in water extent, but also by a much stronger presence of exposed alluvial surfaces.

Table 2. Multi-temporal watercourse and island metrics within the geomorphic AOI.

Year	Watercourse area (ha)	Island area (ha)	Island fraction	Island parts
2001	16.41	3.16	0.16	1
2007	24.43	4.37	0.15	1
2009	45.17	12.06	0.21	3
2010	48.17	8.10	0.14	6
2012	23.27	29.18	0.55	6
2013	27.05	30.76	0.53	5

The earliest analyzed epoch, 2001, represents a comparatively simple corridor configuration, with one mapped island part and a low island fraction. By 2007, the corridor already showed signs of reorganization, including an increase in both watercourse areas and exposed in-channel ground. Because the 2007 image has lower visual quality than the later scenes, this epoch should be interpreted mainly as an intermediate reference between the 2001 baseline and the clearer 2009–2013 sequence.

The period between 2007 and 2010 corresponds to the phase of maximum mapped watercourse expansion, with watercourse area increasing from 24.43 ha in 2007 to 48.17 ha in 2010. Satellite imagery and GIS overlays indicate changes in channel-thread distribution, local reorganization of island margins, and increasing complexity of the exposed in-channel ground structure. In several sections of the corridor, the active watercourse became subdivided into separate branches around the developing island system. Such multi-thread channel configurations are commonly associated with active adjustment processes in alluvial river systems (Hicks et al., 2008). This process produced a more fragmented planform pattern and altered the spatial distribution of active flow paths.

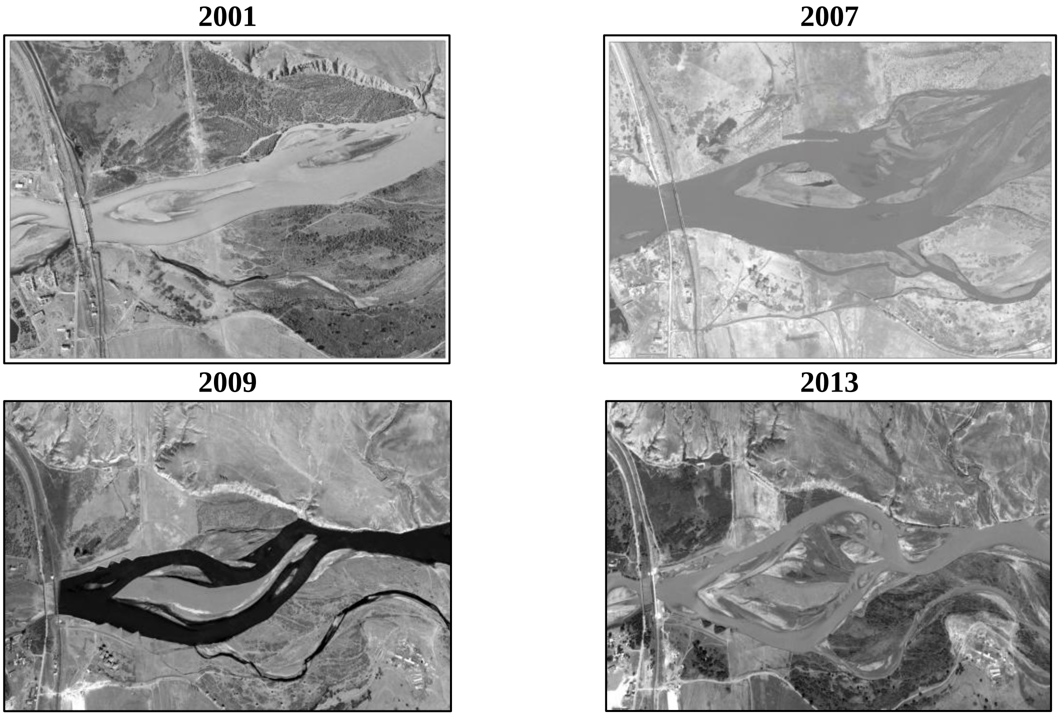

Figure 2. Selected satellite scenes illustrating temporal evolution of the Kura River crossing corridor between 2001 and 2013.

By 2012 and 2013, the role of exposed in-channel ground became dominant within the mapped corridor: island area reached 29.18 ha in 2012 and 30.76 ha in 2013, while island fraction increased to 0.55 and 0.53, respectively. The island footprint occupied a larger proportion of the geomorphic AOI, while several active water branches became narrower or more spatially constrained. The increase in island fraction values indicates that exposed alluvial surfaces became progressively more dominant within the mapped river corridor during the later observation years. At the same time, multipart island structure and local coalescence of smaller bar-like forms suggest continuing fluvial adjustment rather than stabilization of a single permanent island geometry, which is consistent with observations reported for actively evolving alluvial corridors (Ashmore, 1982; Makaske, 2001).

The temporal evolution of the river corridor is illustrated in Figure 2, which presents the multi-temporal satellite sequence for the analyzed years.

Visual interpretation of the annual satellite scenes demonstrates that changes in the study reach were not limited to simple lateral migration of a single channel thread. Instead, the river corridor experienced spatial redistribution of water flow around evolving island surfaces, localized narrowing and widening of active branches, and repeated modification of exposed sedimentary forms. These processes indicate a dynamically adjusting alluvial corridor in which the position and configuration of active water pathways changed through time.

To support comparison between epochs, annual watercourse and island polygons were overlaid within the fixed geomorphic AOI (Fig. 3). The overlay analysis highlights both persistent and transitional spatial zones within the river corridor. Some parts of the active channel remained relatively stable throughout the study period, whereas other sections experienced repeated alternation between water-covered and exposed states.

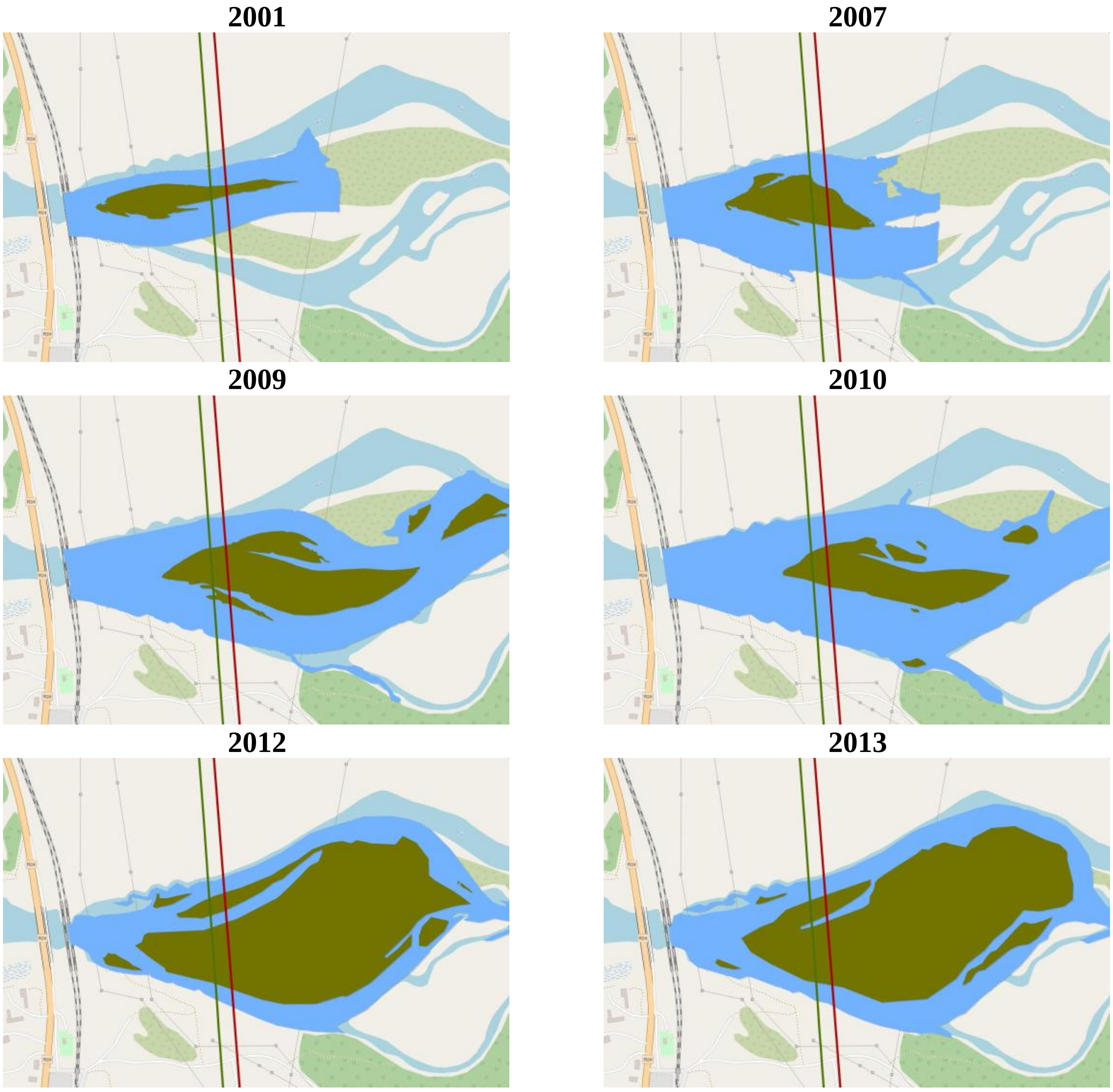

Figure 3. Multi-temporal GIS overlays of annual watercourse and island polygons illustrate spatial reconfiguration of the river corridor within the geomorphic AOI.

The overlay results suggest that the analyzed reach should be interpreted as a morphodynamically active corridor rather than as a geometrically stable river crossing. Changes in island extent, channel-thread configuration, and watercourse distribution demonstrate that the spatial structure of the river corridor evolved continuously during the observed period. These changes are important because they influence the local geomorphic context in which the pipeline crossing is located.

The observed dynamics do not directly indicate erosion hazard, bank instability, or engineering exposure of the pipeline. Instead, they represent GIS-based spatial indicators of river corridor reconfiguration. Their significance lies in demonstrating that the crossing environment changed measurably through time and that the active river corridor cannot be treated as a static spatial feature.

Multi-Temporal Channel Reconfiguration

The overlay analysis indicates that the analyzed corridor experienced progressive channel adjustment throughout the observation period. The spatial relationship between the active channel branches and the central island area changed repeatedly between epochs, producing a dynamically reconfigured river corridor rather than a stable planform geometry.

One of the most visible tendencies is the redistribution of flow around the developing island system. In the earlier epochs, the active watercourse occupied a comparatively broader corridor with less dominant exposed in-channel ground. During later epochs, the island system became more spatially pronounced and locally constrained the geometry of active channel branches. This process contributed to narrowing several water pathways and to increasing asymmetry between channel threads.

The temporal overlays also show that some sectors of the river corridor remained comparatively persistent, while other sectors underwent repeated transitions between water-covered and exposed states. Such transitions are important because they indicate spatial instability within the active corridor rather than simple lateral migration of a single riverbank.

Changes in multipart island structure suggest continuing reorganization of sedimentary surfaces within the river corridor. Such reorganization processes are typical of sediment redistribution within multi-thread alluvial systems (Church, 2006; Surian et al., 2009). In several epochs, smaller exposed areas appear to merge into larger island forms, whereas in other periods the exposed surfaces become more fragmented. These patterns are consistent with active alluvial adjustment influenced by flow redistribution and local sediment accumulation.

The results demonstrate that the river crossing corridor cannot be interpreted as geomorphically static. Instead, the spatial organization of the active watercourse evolved continuously during the study period through changing relationships between water-covered and exposed surfaces. This river adjustment behavior is particularly important in the vicinity of the pipeline crossing because it modifies the spatial context in which the crossing is located.

The identified reconfiguration patterns should be interpreted as GIS-based indicators of river corridor evolution rather than as direct measurements of erosion intensity, bank failure, or engineering exposure. Nevertheless, the observed planform adjustments demonstrate that the crossing environment remained dynamically active during the study period.

Pipeline Corridor Spatial Indicators

The calculated pipeline corridor indicators demonstrate that the spatial relationship between the active river corridor and the pipeline crossing changed substantially during the observation period. In particular, the results indicate increasing interaction between the evolving channel configuration and the localized crossing corridor during the later epochs (Table 3).

Table 3. Pipeline corridor spatial indicators for the inspected epochs[2]

Year	$\boldsymbol{d}_{\mathbf{mid,min}}$ (m)	$\boldsymbol{L}_{\mathbf{50}}^{(\boldsymbol{\Sigma})}$ (m)	$\boldsymbol{L}_{\mathbf{100}}^{(\boldsymbol{\Sigma})}$ (m)	$\boldsymbol{L}_{\mathbf{w}}^{(\boldsymbol{\Sigma})}$ (m)	$\boldsymbol{L}_{\mathbf{i}}^{(\boldsymbol{\Sigma})}$ (m)
2001	93.6	410	806	398	75
2007	169.8	417	827	743	269
2009	161.1	414	839	760	306
2010	165.3	415	837	768	218
2012	24.5	814	1200	280	488
2013	27.8	821	1201	272	500

[2] Note: $\boldsymbol{d}_{\mathbf{mid,min}}$ *is the minimum midpoint-to-bank distance for the mapped underwater crossing segment.* $\boldsymbol{L}_{50}^{(\boldsymbol{\Sigma})}$ *and* $\boldsymbol{L}_{100}^{(\boldsymbol{\Sigma})}$ *are the total lengths of the two pipeline polylines located within 50 m and 100 m of the mapped bank proxy, respectively.* $\boldsymbol{L}_{\mathbf{w}}^{(\boldsymbol{\Sigma})}$ *is the total pipeline length intersecting the mapped watercourse footprint.* $\boldsymbol{L}_{i}^{(\boldsymbol{\Sigma})}$ *is the total pipeline length intersecting the exposed in-channel ground footprint. All values are planimetric GIS indicators and do not represent pipeline burial depth, scour depth, or structural condition.*

The temporal behaviour of the principal indicators is summarized in Figure 4.

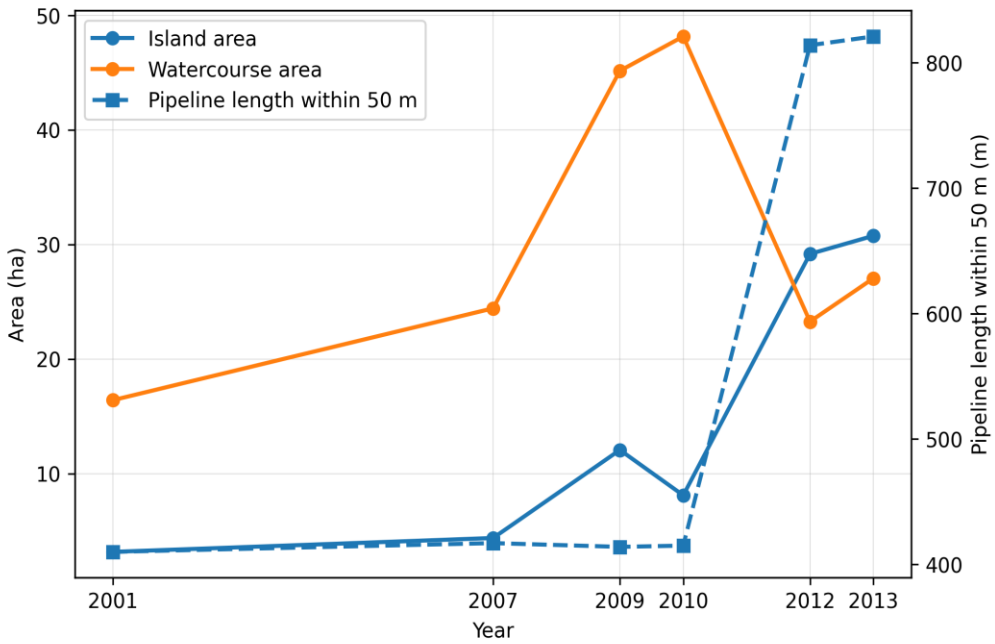

Figure 4. Temporal evolution of watercourse area, island area, and total pipeline length located within the 50 m near-bank zone.

The watercourse area increased from 2001 to 2010, reaching its maximum extent during 2010. This phase corresponds to a comparatively broader active river corridor with expanded water-covered surfaces and active channel redistribution around the island system. During the same interval, the total pipeline length located within the 50 m near-bank zone remained relatively stable, indicating that although the watercourse expanded, the immediate proximity relationship between the active bank proxy and the pipeline alignment changed only moderately.

A different tendency became visible after 2010. The watercourse footprint decreased considerably during 2012–2013, while the island area increased sharply and became one of the dominant components of the mapped corridor. This transition reflects progressive development and spatial consolidation of exposed in-channel ground within the crossing reach.

At the same time, the total pipeline length located within the 50 m near-bank zone increased abruptly from 415 m in 2010 to 814 m in 2012 and remained high at 821 m in 2013. The 100 m near-bank indicator shows the same shift, increasing from 837 m in 2010 to 1200 m in 2012 and 1201 m in 2013. Compared with the relatively stable values observed between 2001 and 2010, the later epochs indicate a substantial expansion of near-bank interaction zones along the pipeline corridor. This behavior suggests that the active channel configuration became more spatially constrained around the crossing area during the later stages of corridor evolution.

The combined interpretation of watercourse areas, island growth, and near-bank pipeline metrics indicates that the channel evolution of the corridor was not controlled only by simple widening or narrowing of the river. Instead, the corridor experienced redistribution of active flow around increasingly developed island surfaces. As the island system expanded, several active channel branches became narrower and locally shifted toward sectors of the pipeline alignment, increasing the proportion of the corridor located within predefined near-bank buffer zones.

The results therefore suggest a progressive tightening of the active river corridor around the crossing area during the later epochs. This interpretation is also consistent with the reduction of the midpoint-to-bank distance from 165.3 m in 2010 to 24.5 m in 2012 and 27.8 m in 2013. Together with the increasing dominance of exposed in-channel ground within the mapped corridor, this indicates that the crossing area became spatially more constrained in the later part of the analyzed sequence.

These indicators should be interpreted as GIS-based spatial metrics derived from planimetric relationships between annual river footprints, mapped bank proxies, and the pipeline alignment. They do not represent direct measurements of bank erosion rate, scour depth, pipeline exposure, or structural condition. Nevertheless, the temporal trends demonstrate that the spatial context of the crossing changed substantially during the study period and that the interaction between the river corridor and the pipeline alignment became progressively more localized and asymmetrical.

Morphodynamic Interpretation of the Crossing Corridor

The combined results of the multi-temporal GIS analysis indicate that the investigated reach evolved as a dynamically adjusting river corridor throughout the observation period.

The temporal relationship between the active watercourse, exposed in-channel ground, and the pipeline alignment demonstrates that the crossing environment cannot be interpreted as spatially static.

One of the principal tendencies observed during the study period is the progressive increase in the geomorphic importance of the central island system. In the earlier epochs, the active watercourse occupied a comparatively broader and more continuous corridor. During later epochs, however, the exposed in-channel ground expanded substantially and became increasingly dominant within the mapped corridor. This transition was accompanied by redistribution of flow around the island complex and by local narrowing of several active channel branches.

The observed changes suggest that the morphodynamic behaviour of the corridor was controlled not only by lateral migration of a single channel thread, but also by repeated reorganization of flow pathways around evolving sedimentary surfaces. Comparable adjustment patterns have been described in studies of active alluvial river systems and channel-thread redistribution (Ashmore, 1982; Fryirs & Brierley, 2013). As the island system expanded and locally coalesced, the active channel geometry became more asymmetric and spatially constrained. This tendency is reflected both in the increasing island fraction values and in the growth of near-bank pipeline indicators during the later observation years.

The relationship between the river corridor and the pipeline crossing also changed progressively through time. During the earlier epochs, the crossing corridor remained comparatively distant from the most spatially constrained parts of the active channel system. In contrast, the later epochs indicate increasing localization of active water pathways near segments of the pipeline alignment. The sharp increase in the total pipeline length located within the 50 m near-bank zone after 2010 suggests that the active fluvial interaction corridor became more concentrated around parts of the crossing area.

At the same time, the reduction of midpoint-to-bank distance indicators implies that the spatial configuration of the active channel evolved toward a tighter interaction with the crossing corridor. This tendency does not necessarily indicate direct engineering exposure to the pipeline. Rather, it reflects increasing spatial proximity between the active channel geometry and the pipeline alignment within the planimetric GIS framework used in this study.

The morphodynamic interpretation is further supported by the temporal overlay analysis, which shows repeated alternation between water-covered and exposed states in several sectors of the corridor. Such transitions indicate persistent instability of the local channel configuration and suggest continuing sediment redistribution within the reach. The coexistence of expanding island surfaces, narrowing active branches, and shifting near-bank zones indicates an actively reorganizing alluvial environment rather than a stable river crossing geometry.

Overall, the results support the interpretation of the crossing area as a dynamic river crossing corridor. In this context, the pipeline crossing should not be viewed solely as a fixed engineering point intersecting a stable river channel. Instead, it is located within a spatially evolving fluvial system where channel-thread redistribution, island development, and changing bank proximity continuously modify the geomorphic context of the crossing. The identified patterns therefore provide a GIS-based basis for long-term spatial monitoring of river corridor evolution near critical linear infrastructure.

Discussion

The results demonstrate that the investigated area of the Kura River functioned as a dynamically evolving river corridor throughout the study period. The temporal sequence of satellite imagery and GIS overlays indicates that the river corridor was characterized not only by lateral adjustment of the active watercourse, but also by progressive reorganization of flow pathways around expanding and restructuring island surfaces. Such behaviour is typical of active alluvial systems in which sediment accumulation, channel-thread redistribution, and alternating water-covered and exposed states continuously modify the spatial structure of the river corridor. These processes are widely recognized as characteristic features of actively adjusting fluvial systems (Church, 2006; Fryirs & Brierley, 2013).

One of the most important tendencies identified in the study is the increasing geomorphic role of exposed in-channel ground during the later observation years. The combined interpretation of island growth, increasing island fraction, narrowing active branches, and rising near-bank pipeline indicators suggests that the river corridor evolved toward a more spatially constrained configuration near the crossing zone. Similar tendencies toward localized corridor adjustment and island-controlled flow redistribution have been documented in large alluvial rivers (Gurnell et al., 2001; Surian et al., 2009). In this context, the pipeline crossing should not be interpreted only as a fixed engineering location intersecting a stable river channel. Instead, it is more appropriately viewed as part of a dynamic evolving fluvial corridor in which the geometry of active water pathways changes through time.

In this study, long-term stability of the crossing corridor is interpreted in spatial and geomorphic terms rather than in direct engineering terms. A relatively stable crossing corridor would be expected to show limited change in watercourse position, low variation in exposed in-channel ground, limited alternation between water-covered and exposed states, and relatively stable near-bank pipeline indicators. In contrast, the analysed reach shows a different pattern. The increase in island area and island fraction, the narrowing and redistribution of active channel branches, the abrupt rise in pipeline length located within the 50 m and 100 m near-bank zones, and the reduction of midpoint-to-bank distance all indicate that the crossing corridor became spatially less stable during the later observation years. Therefore, the potential risk identified here should be understood as geomorphic exposure potential: a higher need for field verification, repeated monitoring, and possible engineering review, not as direct evidence of pipeline damage or loss of cover.

The GIS-based indicators used in this study therefore provide a spatial framework for ranking or prioritizing crossing zones where river corridor evolution may alter the local exposure context of buried infrastructure. Spatial understanding of river corridor adjustment is increasingly recognized as important for long-term environmental and infrastructure management in dynamic fluvial systems (Lane, 2017). At the same time, the results must be interpreted cautiously. The calculated metrics represent planimetric GIS relationships derived from remotely sensed imagery and annual polygon overlays. They do not directly measure erosion rate, scour depth, bank stability, sediment thickness, pipeline burial depth, or structural integrity. Consequently, the presented indicators should be considered as spatial screening and monitoring tools rather than direct engineering assessment parameters.

Several sources of uncertainty should also be considered. The analysed satellite images were acquired during different years and potentially under different hydrological conditions. Variations in seasonal water level, image resolution, sediment moisture, vegetation cover, and illumination conditions may influence interpretation of water boundaries and exposed surfaces. Additional uncertainty may originate from manual digitization, simplification of polygon boundaries, and the use of watercourse boundaries as GIS-derived bank proxies. Furthermore, the study is based on planform interpretation and does not include bathymetric measurements, sediment thickness data, field-based bank surveys, or hydraulic modelling. Despite these limitations, the use of a fixed geomorphic AOI and a consistent multi-temporal GIS workflow provides a coherent basis for comparative spatial analysis of river corridor evolution.

Overall, the study demonstrates that multi-temporal GIS analysis can provide valuable insight into the spatial evolution of river crossings located within morphodynamically active environments. The proposed approach is particularly useful for long-term monitoring of riverine infrastructure corridors where repeated channel reconfiguration, island development, and flow redistribution may gradually modify the geomorphic context of the crossing area. In practical terms, the method can help identify crossing segments were additional field inspection, bathymetric survey, bankline monitoring, or pipeline-cover verification should be considered.

Conclusion

This study presented a multi-temporal GIS analysis of river channel migration near a pipeline crossing on the Kura River, Azerbaijan. Using satellite image interpretation and vector-based spatial analysis for 2001, 2007, 2009, 2010, 2012, and 2013, the study examined temporal changes in watercourse footprint, exposed in-channel ground, island structure, and the spatial relationship between the active river corridor and the pipeline crossing.

The results demonstrate that the investigated area experienced substantial channel reconfiguration during the observation period. The river corridor evolved through redistribution of active channel threads, expansion and restructuring of alluvial island surfaces, and localized narrowing of active water pathways. The increase in island fraction and near-bank pipeline indicators during the later epochs suggests that the crossing corridor became progressively more spatially constrained around the pipeline alignment.

One of the principal findings of the study is that the crossing should not be interpreted solely as a fixed engineering point intersecting a stable river channel. Instead, it should be considered part of a dynamically adjusting corridor in which changing relationships between water-covered and exposed surfaces continuously modify the spatial configuration of the crossing environment.

The proposed GIS workflow provides a reproducible framework for monitoring river corridor evolution using multi-temporal polygon overlays, area metrics, proximity indicators, and crossing-related spatial analysis. The methodology is intended primarily for GIS-based monitoring, spatial exposure screening, and prioritization of crossing segments that may require closer inspection. The derived indicators represent planimetric spatial relationships and should not be interpreted as direct measurements of pipeline exposure depth, bank failure, scour depth, or structural integrity.

Despite uncertainties associated with seasonal water conditions, image interpretation, variable image quality, and planform-based analysis, the study demonstrates that multi-temporal GIS methods can effectively identify long-term morphodynamic tendencies near river crossings. The approach may therefore support environmental monitoring and spatial assessment of riverine infrastructure corridors located within dynamically evolving alluvial systems. Future studies should integrate GIS-based analysis with field bankline surveys, water-level observations, bathymetric measurements, sediment and bank-material observations, and, where access is possible, pipeline-cover verification. Such validation would make it possible to distinguish more clearly between planimetric corridor reconfiguration and direct engineering exposure of buried infrastructure.

Competing interests

The authors declare that they have no competing interests.

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