

Article

A GIS-Based Spatiotemporal Digital Twin-Oriented Framework for a Dammed River Shoreline: Methods, Validation, and Multi-Epoch Analysis

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Abstract

Digital twins are increasingly adopted in geographic research as dynamic representations of environmental systems; however, their application to regulated river shorelines remains limited, particularly where bathymetric change, hydrological variability, and shoreline-state dynamics must be integrated within a single GIS-based framework. This study develops and validates a GIS-based spatiotemporal digital twin-oriented framework for the dam-affected shoreline downstream of the Włocławek Dam, Poland. The framework integrates four bathymetric surveys acquired in 2008–2011, water-level records, airborne laser scanning data, and three-dimensional hydrotechnical infrastructure within a unified geodatabase designed for dynamic shoreline-state reconstruction, multi-epoch analysis, and environmental monitoring. A key methodological element is the treatment of water level as a dynamic reference surface, enabling the automated delineation of inundation and exposure zones for observed and scenario-based hydrological conditions. The reconstructed bathymetric surfaces were organized as a multidimensional raster dataset with time as an explicit analytical dimension, supporting repeatable change detection, cross-sectional interpretation, and temporal trend analysis. To extend the framework beyond purely retrospective analysis, a near-real-time hydrological updating component was implemented through ingestion of operational water-level observations from the IMGW API into the geodatabase. Validation of the trend-based prediction for 2011 yielded $R^2 = 0.967$, $RMSE = 0.44$ m, $MAE = 0.28$ m, and $bias = -0.06$ m. The proposed framework provides a transferable geospatial basis for spatiotemporal modelling and monitoring of regulated river shoreline dynamics under changing hydrological conditions.

Keywords: digital twin-oriented framework; spatiotemporal GIS; bathymetric change detection; environmental monitoring; airborne laser scanning; regulated river shoreline; dynamic water-level referencing; predictive raster modelling



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1. Introduction

Recent advances in digital twin research have extended the concept from manufacturing and industrial process control toward geospatially explicit representations of environmental systems. While early formulations defined the digital twin as a dynamic linkage between physical and virtual entities across the system lifecycle [1,2], subsequent work emphasized that, in geospatial applications, digital twins should be understood not

as static three-dimensional replicas but as spatially grounded, semantically structured, and updatable analytical environments [3–7].

In geospatial research, digital twins are increasingly interpreted not only as strict real-time cyber–physical replicas, but also as updatable spatially explicit analytical environments integrating heterogeneous data, temporal states, and decision-oriented representations of environmental systems [3,6].

This development directly intersects with the long-standing evolution of temporal GIS. Foundational research established that geographic information systems must represent not only spatial entities, but also their states, transitions, and trajectories through time [8]. Later reviews confirmed that spatiotemporal modelling remains a central challenge in GIScience, particularly when repeated observations, heterogeneous update frequencies, and operational data streams must be integrated consistently within one framework [9,10]. In geospatial digital twins, this requirement extends further to the joint management of geometry, attributes, temporal states, and visualization or analysis workflows within a unified and updatable environment [11].

These issues are particularly relevant in aquatic and shoreline systems, where morphological interpretation depends simultaneously on terrain or bathymetry and on hydrological stage. In regulated river reaches, the same bed geometry may correspond to different shoreline states under different water levels, whereas similar hydrological conditions may produce different inundation and exposure patterns when morphology evolves over time [12]. This problem is especially evident downstream of large dams, where controlled flow, sediment discontinuity, and hydrotechnical infrastructure jointly shape local morphodynamics.

The downstream reach of the Włocławek Dam on the Lower Vistula River constitutes such an environment. Previous investigations documented spatially heterogeneous erosion and deposition patterns, riverbed instability, and hazard zones associated with the near-dam section and the stabilization threshold [13]. However, these studies were reported primarily as discrete campaign-based assessments rather than as components of a temporally structured geospatial system integrating bathymetry, hydrological conditions, terrain context, and infrastructure geometry within one analytical model [14]. The methodological gap therefore concerns not only data integration itself, but also the formalization of a transferable GIS-based framework capable of linking bathymetry, hydrological stage, and shoreline-state dynamics within a consistent temporal structure.

The aim of this study is therefore to develop and validate a GIS-based spatiotemporal framework for dynamic shoreline-state reconstruction in a regulated river environment, implemented as a digital twin-oriented geospatial system for the Włocławek Dam reach. The proposed framework integrates multi-epoch bathymetric measurements, water-level records, topographic context derived from airborne laser scanning, and three-dimensional representations of hydrotechnical infrastructure within a unified geospatial environment. A central component of the framework is the treatment of water level as a dynamic reference surface, allowing shoreline state to be reconstructed relative to temporally variable hydrological conditions rather than fixed elevation thresholds. In methodological terms, this study moves beyond a sequence of independent bathymetric reconstructions toward a time-aware analytical model capable of supporting multi-epoch comparison, shoreline-state interpretation, and controlled predictive extension. To strengthen the updatable character of the framework, a near-real-time hydrological ingestion component was implemented to retrieve operational water-level observations from the IMGW public API and store them in the geodatabase as the current hydrological reference state.

The contribution of this study is fourfold. First, it proposes a validated GIS-based framework for integrating bathymetric, hydrological, topographic, and infrastructure

data in a spatiotemporal shoreline analysis environment. Second, it introduces dynamic water-level referencing as the basis for shoreline-state reconstruction across multiple survey epochs. Third, it demonstrates that a multidimensional temporal raster structure can support repeatable morphodynamic analysis and short-horizon predictive extension within a unified geospatial environment. Fourth, it implements a near-real-time hydrological updating pathway from operational IMGW API observations to the geodatabase-stored water-level reference used for shoreline-state updating. Although demonstrated for the Włocławek Dam reach, the proposed framework is intended for broader application in regulated shoreline environments where multi-epoch bathymetric data, water-level observations, and topographic context are available. From this perspective, the proposed framework is intended not only to reconstruct observed shoreline states, but also to support short-horizon prediction and scenario-based decision support under changing hydrological conditions.

2. Related Work

2.1. Digital Twins in Water and Environmental Systems

Recent research shows that the implementation of digital twins in water-related and environmental systems is shifting from static digital representation toward data-assimilative, updatable modelling environments. In hydrological and water-sector applications, digital twins are increasingly used to combine process-based models, monitoring data, and operational information in support of system interpretation, scenario analysis, and decision-making [15,16]. This transition is particularly important in systems where environmental states are controlled by changing boundary conditions and anthropogenic regulation.

At the same time, the current literature indicates that water-oriented digital twins are still dominated by applications focused on distribution networks, urban water infrastructure, catchment-scale hydrology, and management-oriented digital water services [17]. Comparatively less attention has been devoted to river shorelines and near-dam fluvial environments, where the represented system must include not only hydrological forcing, but also bathymetric change, terrain context, and infrastructure-related constraints. This gap is relevant because shoreline interpretation in regulated rivers depends on the joint representation of morphology and water level rather than on geometry alone.

Recent work in the water domain further shows that digital twins are being developed across a broad spectrum of maturity, from data-assimilative hydrological or infrastructure models to more operationally connected systems. Large-scale examples, such as hydrological or basin-scale twins, highlight both the analytical potential of these systems and the practical barriers related to data access, interoperability, operational updating, and institutional implementation [15,16,18,19].

2.2. Spatiotemporal Data Structures for Multi-Epoch Surface Analysis

The analytical usefulness of a shoreline-oriented digital twin depends strongly on the way temporal information is organized. Temporal GIS research has shown that spatial observations should not be treated as isolated layers, but as components of explicitly structured spatiotemporal datasets that support comparison, querying, and evolution analysis [20]. This is particularly important for raster-based environmental modelling, where time-aware data structures enable surfaces to be analyzed not only as individual states, but also as ordered temporal sequences.

Several studies have proposed formal raster and multidimensional spatiotemporal models that are directly relevant to the construction of multi-epoch bathymetric datasets [21,22]. In such approaches, successive raster surfaces can be represented within a common temporal framework, which facilitates trend extraction, state-to-state compari-

son, and the extension of retrospective analysis toward predictive workflows. For shoreline studies, this is methodologically advantageous because it enables a transition from campaign-based interpretation to a temporally explicit model of morphological evolution.

However, the majority of existing applications focus on urban infrastructure or surface processes, with limited attention given to subsurface or bathymetric dynamics. While recent contributions highlight the applicability of digital twins to environmental management and resilience planning [23], few studies explicitly address the challenges associated with integrating multi-epoch bathymetric data and hydrological variability within a spatiotemporal GIS framework.

2.3. Bathymetric Monitoring, Data Integration, and Morphodynamic Interpretation

In fluvial and shallow-water studies, recent work has demonstrated the value of integrated bathymetric monitoring systems and hybrid survey strategies combining wet- and dry-zone observations. These approaches improve the consistency of bottom-surface reconstruction and support more complete representations of morphologically dynamic environments [24]. Their relevance is particularly high in transitional shoreline zones, where morphological interpretation depends on the continuity between submerged relief and adjacent exposed terrain.

An additional issue concerns uncertainty in change detection. Repeat-surface analysis may produce visually convincing erosion–deposition patterns even when part of the observed difference falls within the uncertainty of the underlying elevation models. Uncertainty-aware approaches to DEM (*Digital Elevation Model*) differencing have therefore emphasized the need to distinguish meaningful geomorphic change from noise introduced by survey error, interpolation, and model construction [25]. For the present study, this line of work is directly relevant because reliable interpretation of multi-epoch bathymetric change requires not only surface comparison, but also explicit consideration of methodological robustness. This perspective is consistent with established DEM-of-difference approaches that emphasize explicit treatment of uncertainty in topographic change detection, as well as more recent work showing that uncertainty-aware interpretation remains essential in high-resolution erosion monitoring workflows [25,26].

Although these studies provide important methodological foundations, they rarely frame bathymetric monitoring within an updatable geospatial digital twin integrating morphology, water-level variability, terrain context, and hydrotechnical infrastructure in one coherent analytical environment. The present study addresses this gap by positioning the digital twin not merely as a visualization scene, but as a spatiotemporal GIS framework for regulated shoreline analysis.

Taken together, the reviewed literature shows that digital twins, temporal raster structures, and bathymetric monitoring workflows are usually developed separately. Fewer studies combine these components within a single GIS-based framework for regulated shoreline systems, and fewer still include a practical hydrological updating pathway capable of linking current operational observations to shoreline-state reconstruction. In this broader perspective, geospatial digital twins are increasingly interpreted as decision-oriented infrastructures rather than as visualization environments alone.

As Metcalfe et al. [4] emphasize, geospatial science contributes to digital twins through spatial context, semantics, and analytical integration, while Xue et al. [6] show that geospatial twins must combine static and dynamic representations across multiple spatiotemporal scales. From the perspective of spatiotemporal data science, Yang et al. [27] and Alam et al. [28] frame such systems as end-to-end analytical environments linking data acquisition, harmonization, modelling, visualization, and decision support. The present study addresses this gap by combining multi-epoch bathymetric analysis, dynamic water-

level referencing, and a geodatabase-based hydrological updating component within a digital twin-oriented shoreline framework [6,16,18].

3. Materials and Methods

3.1. Study Area

The study area is located downstream of the Włocławek Dam on the Lower Vistula River, Poland, and represents a regulated river reach strongly controlled by hydrotechnical infrastructure and managed flow conditions. The Włocławek Dam, commissioned in 1970, is the largest hydropower and flow-regulation structure on the Lower Vistula and exerts a major influence on local hydraulics, sediment continuity, and channel-bed evolution. Previous investigations in the downstream zone identified intensified erosion, localized scour features, and spatially heterogeneous erosion–deposition patterns associated with the near-dam reach and the stabilization threshold [13,14].

The analyzed section includes the nearshore and near-dam zone where morphological changes are most pronounced and where repeated bathymetric surveys were available for multi-epoch analysis. The study area was defined to ensure spatial consistency across all measurement campaigns and ancillary datasets while preserving coverage of the morphodynamically active portion of the regulated shoreline. All spatial data were referenced to the Polish national coordinate system PL-2000, zone 6 (EPSG:2177) [29], appropriate for large-scale geodetic and engineering applications in the study area. The study area and its geographical context are shown in Figure 1.

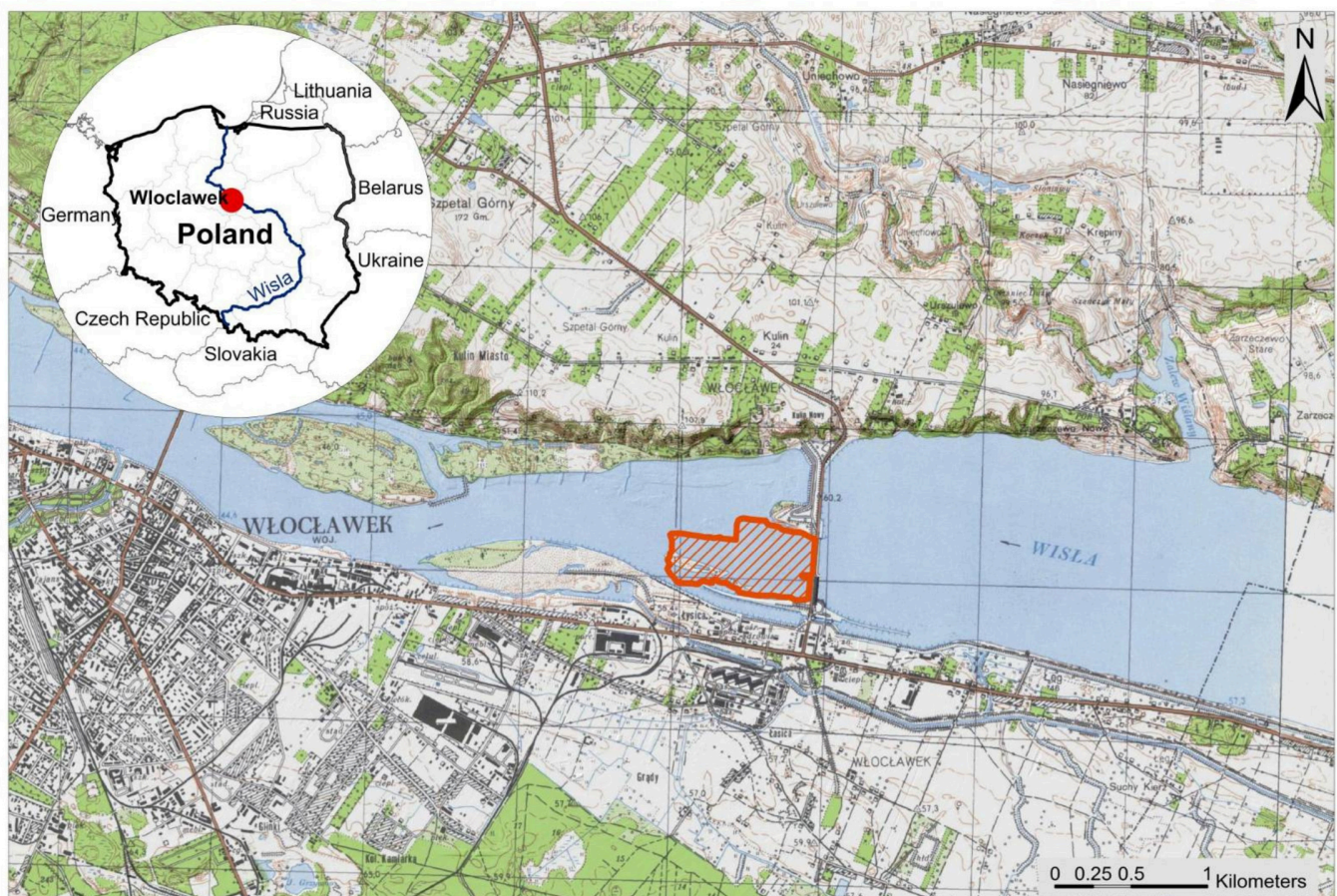


Figure 1. Location of the study area downstream of the Włocławek Dam on the Lower Vistula River, Poland. The red marker indicates its regional location, and the red outline delineates the study area.

3.2. Data Sources

The digital twin was constructed from geospatial datasets representing bathymetry, hydrology, terrain, surface context, and hydrotechnical infrastructure. Bathymetric data formed the main analytical input and were acquired during four single-beam echo sounding campaigns conducted between 2008 and 2011. Survey points were georeferenced with a GNSS and stored as temporally attributed depth observations, providing the basis for reconstructing successive riverbed states.

Hydrological data consisted of water-level records from the monitoring system of the Włocławek hydropower facility. For each bathymetric epoch, the corresponding water level was assigned as a temporal reference for shoreline interpretation. The framework also supported dynamic updating from external observations or scenario-based input.

Topographic and surface context were derived from national airborne laser scanning products, including a digital terrain model and a digital surface model. These datasets were used to represent the surrounding terrain, delineate the shoreline transition zone, and reconstruct simplified three-dimensional hydrotechnical structures within the analyzed reach. Additional 3D building and tree models were included only to improve visualization and were not used as primary analytical datasets. A summary of the integrated datasets is provided in Table 1.

Table 1. Summary of geospatial datasets integrated into the spatiotemporal digital twin.

Dataset Type	Description	Spatial Resolution/Density	Temporal Coverage	Source
Bathymetric surveys	Single-beam echo sounder measurements of riverbed depth	Variable point density	Four measurement epochs	Field surveys
Water-level records	Water-surface-level observations downstream of the dam	Point-based time series	Measurement dates	Hydropower monitoring system
Topographic data	Airborne laser scanning-derived digital terrain model (DTM)	~1 m grid	Reference epoch	National geodetic resources
Surface data	Digital surface model (DSM) for infrastructure context	~1 m grid	Reference epoch	National geodetic resources
Infrastructure geometry	3D representation of hydrotechnical structures	Object-based	Static	ALS-derived reconstruction

Before integration, all datasets were harmonized with respect to the horizontal reference system, vertical datum, spatial extent, temporal metadata, and file structure. Horizontal coordinates were referenced to PL-2000, zone 6 (EPSG:2177), while elevations were referenced to the Polish vertical reference frame PL-EVRF2007-NH [30]. The harmonization stage ensured that bathymetric, hydrological, and topographic layers could be queried and analyzed consistently within a unified GIS environment.

The 2008–2011 bathymetric sequence was used in this study primarily as a controlled methodological testbed rather than as a representation of the present-day state of the Włocławek reach. The four campaigns form an internally consistent multi-epoch dataset linked to compatible hydrological records and geodetic control, making them suitable for framework development, multi-epoch comparison, and predictive proof-of-concept analysis. Current relevance is strengthened by the implemented hydrological updating component, which connects the framework to operational water-level observations and enables shoreline-state updating under present hydrological conditions.

3.3. Digital Twin Data Model

The proposed framework was implemented as a GIS-based geodatabase designed for multi-epoch storage, analysis, and visualization of shoreline states. Its conceptual architecture is presented in Figure 2.

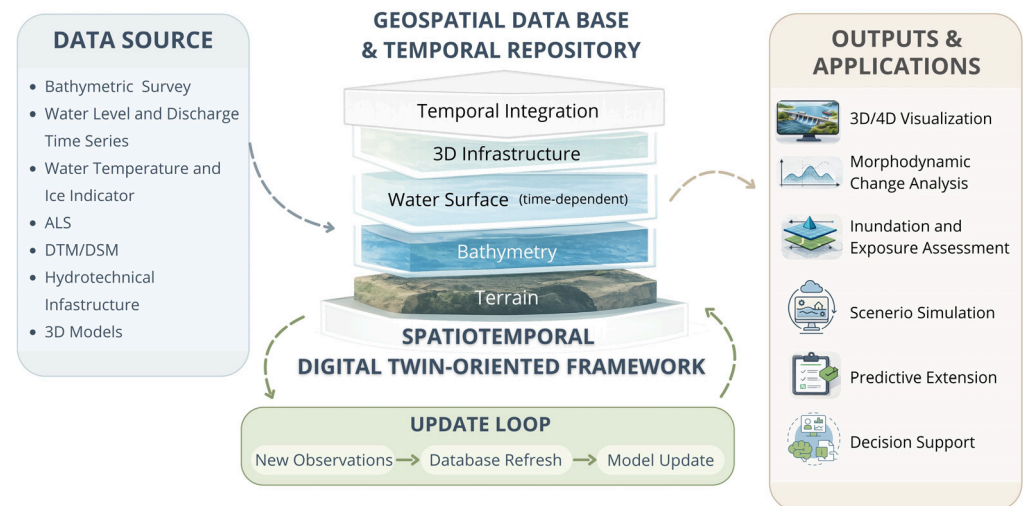


Figure 2. Conceptual architecture of the GIS-based spatiotemporal digital twin showing the integration of bathymetric, hydrological, topographic, and infrastructure data.

The data model included four information domains: bathymetric observations and derived bottom surfaces, hydrological reference conditions, topographic and surface context, and hydrotechnical infrastructure geometry.

Bathymetric datasets from individual surveys were stored as separate temporal states rather than as a single merged dataset. This preserved the chronological structure of the observations and allowed each reconstructed riverbed surface to be linked to its survey epoch and the corresponding water level. Such organization follows the logic of temporal GIS and multidimensional geospatial modelling, in which successive states are analyzed as an ordered time series rather than as isolated layers [20,21].

The framework operated at two levels. First, it provided an integrated three-dimensional scene combining riverbed morphology, terrain, water level, and infrastructure. Second, it functioned as an analytical structure in which individual epochs could be compared, converted into raster time slices, and used in change and trend analysis. This design preserved the relation between morphology, hydrology, and time.

3.4. Near-Real-Time Hydrological Updating

To extend the framework beyond a purely retrospective temporal GIS, a hydrological updating module was implemented in ArcGIS Pro 3.7 (Esri, Redlands, CA, USA) using Python 3.13.13 and ArcPy 3.7, with data stored in an Esri file geodatabase. The module retrieves operational hydrological observations from the IMGW public API for the Włocławek gauge station on the Vistula River, parses the API response, normalizes water stage values, stores the observation history in the geodatabase, and updates the current hydrological reference state used by the framework.

Within the ESRI File Geodatabase, the hydrological updating module was organized into six operational tables: 'hydro_stations', storing station metadata and source linkage; 'hydro_gauge_datum', storing the parameters required to transform gauge stage into model-referenced water-surface elevation; 'hydro_observations', storing the observation history retrieved from the API; 'hydro_current_state', storing the current hydrological reference state used by the framework; 'hydro_ingestion_log', storing ingestion metadata and processing status; and 'shoreline_update_log', storing shoreline-state recalculation history and output-area summaries.

This structure separates station configuration, datum transformation, observation history, current analytical state, and operational logging within a reproducible geodatabase design. Detailed field-level schema is beyond the scope of the present study.

The geodatabase schema separates station metadata, gauge-datum transformation parameters, observation history, current hydrological state, and process logs, allowing the ingestion and shoreline-state update workflow to remain reproducible and traceable. The resulting water-surface elevation parameter is designed to drive subsequent recalculation of shoreline-state products by comparing the current water level with the topo-bathymetric surface and assigning exposed, inundated, and transitional classes. In this form, the framework includes a functional physical-to-virtual updating pathway for the hydrological component, while the bathymetric component remains campaign-based.

The implemented hydrological updating workflow and an example shoreline-state output are shown in Figure 3.

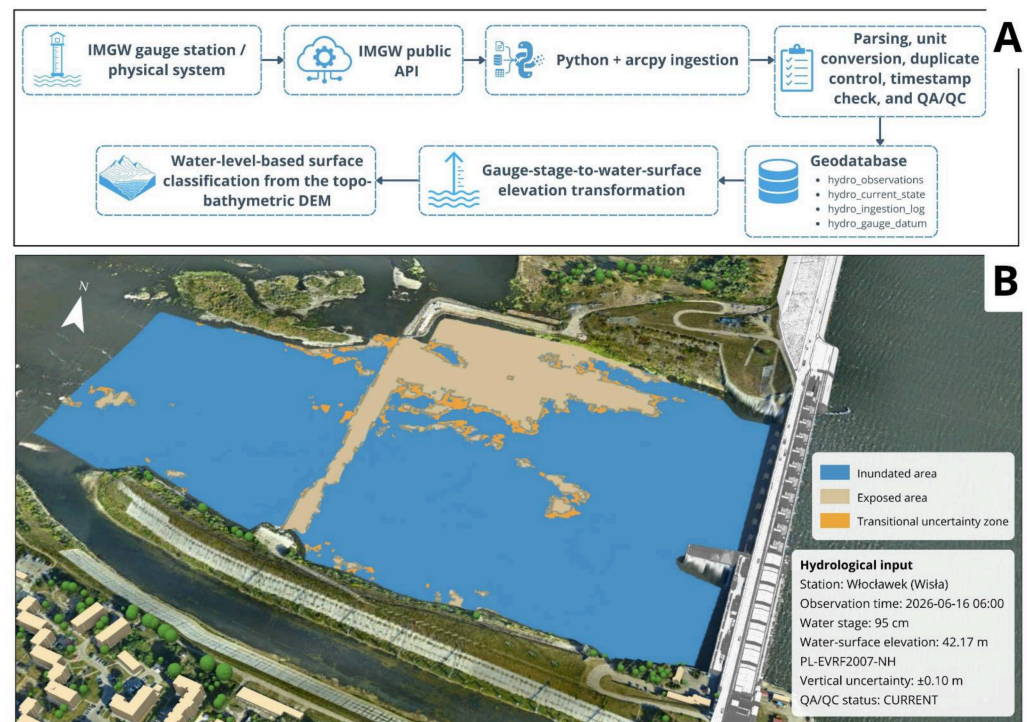


Figure 3. Near-real-time hydrological updating workflow and example shoreline-state output. (A) Conceptual workflow linking IMGW gauge observations, API-based data ingestion, geodatabase storage, water-surface elevation transformation, and shoreline-state updating. (B) Example shoreline-state classification showing inundated, exposed, and transitional zones derived from the relation between the topo-bathymetric surface and the updated water level.

3.5. Bathymetric Processing and Surface Reconstruction

Bathymetric data were processed separately for each survey epoch using a repeatable workflow including quality control, filtering, interpolation, and raster generation. Raw depth observations were checked for gross errors, isolated spikes, and locally inconsistent values, and were then filtered with the Hampel filter to reduce the influence of anomalous measurements.

Bottom surfaces were reconstructed from the filtered point datasets using thin plate spline interpolation. The interpolation method was selected through a methodological preselection stage based on benchmark comparison using a representative subset of 4000 observations drawn from the filtered bathymetric point set. To support methodological preselection of the interpolation method, a compact benchmark was performed on a representative subset of 4000 filtered bathymetric observations drawn from the full 2008–2011 dataset. The subset was constructed as a balanced sample across the four survey campaigns, with 1000 points randomly selected from each epoch, in order to preserve

inter-epoch comparability while keeping the procedure computationally tractable. Three candidate interpolators (IDW, Ordinary Kriging, and TPS (TIN)) were compared using cross-validation, and performance was assessed with RMSE and MAE. This benchmark was used only for methodological selection of the interpolation scheme and did not replace full surface reconstruction for individual epochs.

Three candidate interpolators were compared on the same subset: thin plate spline (TPS), inverse distance weighting (IDW), and Ordinary Kriging. Model performance was evaluated using root mean square error (RMSE) and mean absolute error (MAE). The benchmark results are summarized in Table 2. TPS was retained as the operational interpolation method because it yielded the lowest RMSE and produced a smooth and stable surface representation suitable for channel and nearshore analysis, while Ordinary Kriging returned a nearly identical error level.

Table 2. Benchmark comparison of candidate interpolation methods based on the representative 4000-point subset.

Method	RMSE (m)	MAE (m)
IDW	1.056	0.755
TPS (TIN)	0.529	0.361
Ordinary Kriging	0.532	0.360

TPS (TIN) yielded the lowest RMSE (0.529 m), while Ordinary Kriging produced a nearly identical result (RMSE = 0.532 m) and the lowest MAE (0.360 m, compared with 0.361 m for TPS). Because the difference in MAE was negligible and TPS provided the lowest RMSE, TPS was retained as the operational interpolation method for the present workflow.

To ensure comparability, all interpolations used a common spatial extent and a 2 m raster resolution. The resulting rasters represented temporally discrete but spatially consistent models of riverbed elevation. The same processing procedure was applied to all epochs to minimize methodological bias. Each reconstructed surface was stored both as an individual raster and as a temporally indexed layer within the multidimensional raster structure described in Section 3.6.

3.6. Dynamic Water-Level Referencing and Shoreline-State Modelling

Water level was used as a dynamic reference surface for shoreline interpretation. For each bathymetric epoch, the observed water level was assigned to the reconstructed bottom surface. Areas above this level were classified as exposed, whereas areas below it were classified as submerged. This enabled recalculation of exposure and inundation boundaries for each survey epoch and regeneration of shoreline maps from manually defined or external hydrological inputs.

This procedure improved shoreline interpretation under changing hydrological conditions, since identical bed elevations may correspond to different shoreline states. By integrating water level directly into the workflow, the digital twin preserved the relation between bathymetry and shoreline configuration and supported consistent comparison between epochs.

The predictive component was treated as a proof of concept rather than a standalone forecasting model. A cell-wise temporal trend extension was derived from the ordered 2008–2010 raster sequence and tested against the observed 2011 surface. Spatial autocorrelation was not explicitly modelled. The purpose of this step was therefore not to establish broad predictive capability, but to test whether the time-structured raster model could support short-horizon prospective shoreline assessment beyond retrospective comparison.

3.7. Multidimensional Raster Structure and Predictive Extension

The reconstructed bathymetric surfaces were organized as a multidimensional raster dataset with time as an explicit dimension. Each interpolated model represented one temporal slice of the 2008–2011 sequence and was stored on a common 2 m grid, enabling direct comparison and trend analysis [22].

This structure supported two analytical operations. First, it enabled inter-epoch differencing to identify erosion and deposition between successive campaigns. Second, it supported cell-based trend modelling of riverbed elevation change. Trend rasters were used to estimate the direction and relative magnitude of change and to generate a short-term predictive extension of the digital twin.

The predictive component was treated as a proof of concept rather than a standalone forecasting model. Its purpose was to test whether the time-structured raster model could support prospective shoreline assessment beyond retrospective comparison. In practical terms, the predictive extension was implemented as a cell-wise temporal extrapolation of bed elevation based on the ordered 2008, 2009, and 2010 bathymetric rasters. For each raster cell, the temporal tendency of bed elevation was estimated from the three preceding epochs and projected to 2011, yielding a trend-predicted bathymetric surface. The predicted cross-sections shown later in the Results were extracted from this predicted 2011 raster rather than extrapolated independently from profile lines. At the current stage, the procedure represents a data-driven trend-based extension of observed morphological change, whereas explicit incorporation of hydrodynamic forcing variables, such as discharge, flow velocity, shear stress, or sediment transport, remains a direction for further development of the framework.

3.8. Multi-Epoch Change Detection, Validation, and Uncertainty Assessment

Multi-epoch morphodynamic analysis was based on the comparison of bathymetric rasters within a common spatial framework. Elevation differences between consecutive epochs were computed to delineate erosion and deposition, and representative cross-sections were extracted in selected shoreline and near-dam sectors.

Raster differences were interpreted in light of measurement and interpolation uncertainty, which constitute essential methodological and interpretative constraint. However, the reported erosion and deposition volumes represent raw inter-epoch estimates, as no minimum-detectable-change threshold was applied to the volumetric calculations. Uncertainty was explicitly incorporated in the shoreline-state updating logic through the distinction between exposed, inundated, and transitional classes around the water-level reference surface. For the predictive extension, the 2008–2010 rasters were used for model fitting, and the 2011 surface was used for testing. Prediction accuracy was assessed using mean error, mean absolute error, root mean square error, bias, and spatial residual analysis. All analyses used a harmonized 2 m grid, common spatial extent, and heights referenced to the Polish vertical reference frame PL-EVRF2007-NH.

4. Results

4.1. Digital Twin Representation and Multi-Epoch State Organization

The developed framework integrated bathymetric surfaces, water-level records, ALS-derived terrain context, and three-dimensional hydrotechnical infrastructure within a unified GIS environment. This framework enabled joint visualization of submerged morphology, shoreline configuration, and engineering context while preserving the temporal distinction between the four bathymetric survey epochs. Figure 2 shows the conceptual architecture of the system, and Figure 4 presents the integrated three-dimensional scene used for analysis and interpretation.

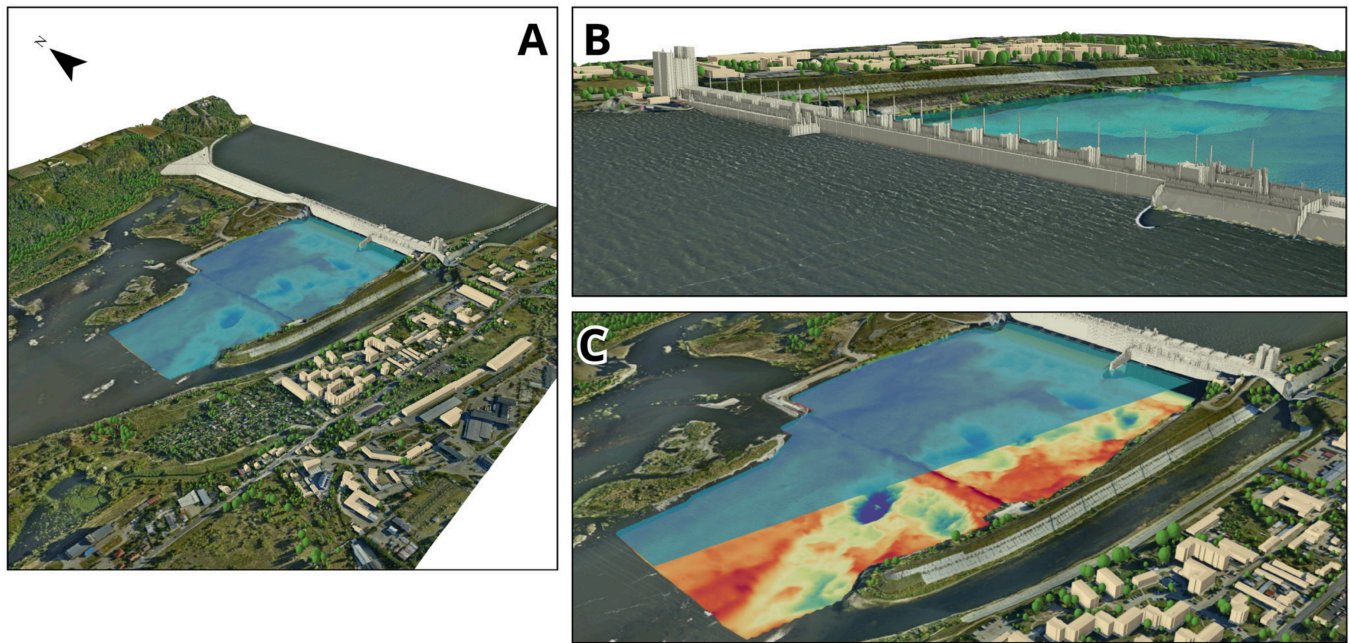


Figure 4. Three-dimensional reconstruction of the regulated bathymetric environment and hydrotechnical infrastructure of the run-of-river hydropower facility. Panels show (A) the overall local-scene view, (B) infrastructure representation, and (C) an internal sliced view exposing the relation between bathymetry and water surface.

A key outcome of the framework was the transformation of discrete bathymetric surveys into an ordered sequence of spatial states that could be explored, compared, and analyzed within a common reference environment. Unlike a set of independent bathymetric maps, the framework preserved the relation between riverbed morphology, hydrological conditions, and spatial context for each epoch. This temporal organization provided the basis for morphodynamic comparison, shoreline interpretation, and updating of derived analytical products.

The multidimensional raster structure further strengthened the temporal consistency of the model. Each survey year was treated as a separate temporal slice within a common raster framework, enabling direct comparison between epochs and supporting trend-based analysis. As a result, the framework functioned not only as a visualization environment, but also as an analytical model of riverbed change and shoreline-state variation during 2008–2011, with shoreline interpretation derived from the relation between bathymetry and temporally assigned water levels rather than from lateral shoreline mapping alone.

4.2. Support for Hydro-Morphodynamic and Operational Analysis

4.2.1. Spatial Distribution of Erosion and Deposition

Difference maps between successive bathymetric epochs revealed a heterogeneous but spatially organized pattern of bed adjustment across the analyzed reach (Figure 5). After centring the difference scale on zero, the maps show a clear alternation of erosion and deposition zones, with the strongest changes concentrated in the central part of the study area and in sectors adjacent to the hydrotechnical structures. In contrast, the marginal zones were characterized by smaller and more fragmented patches of change.

The most persistent sectors of change were concentrated along the central morphodynamically active belt and in infrastructure-adjacent zones near the dam and the stabilization threshold. In contrast, marginal sectors showed weaker and more fragmented adjustments. These recurrent patterns suggest repeated bed reworking in the same sectors rather than random redistribution across the entire reach.

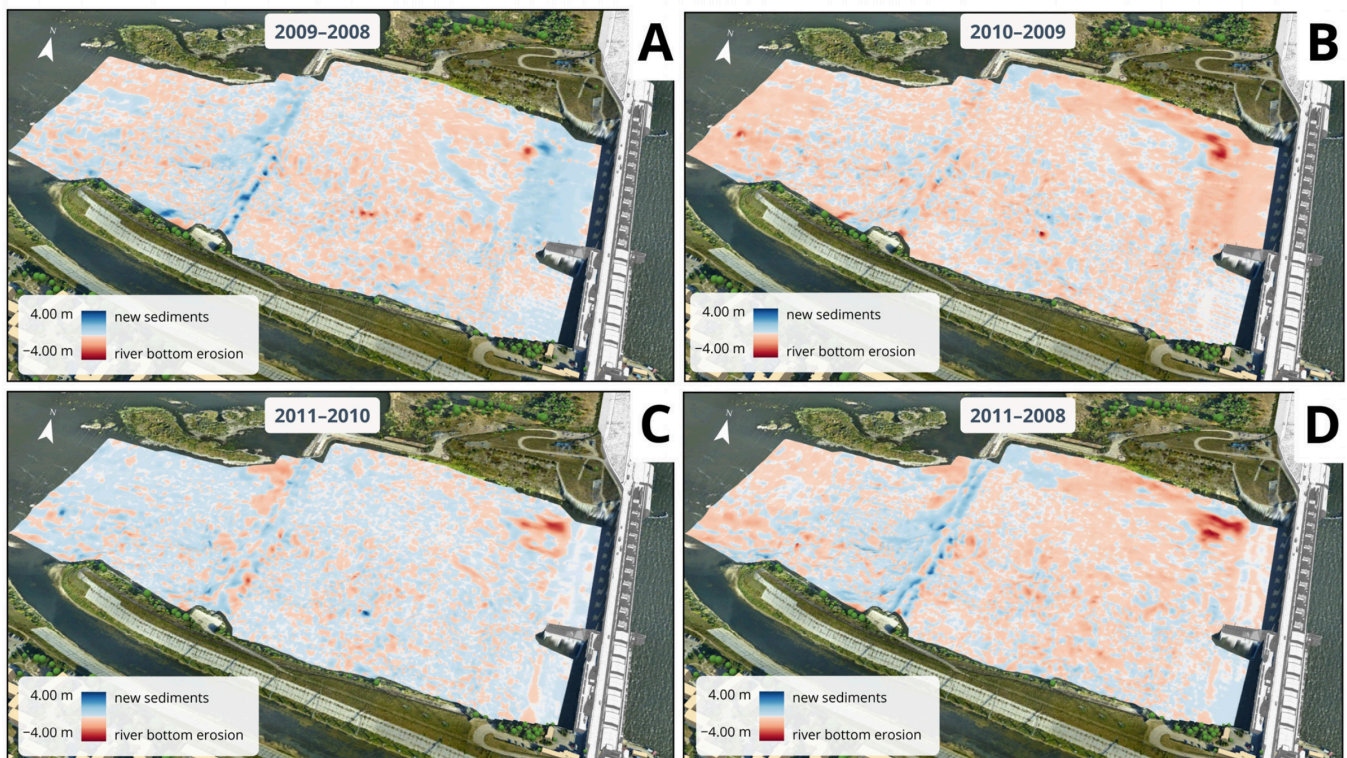


Figure 5. Elevation difference maps derived from bathymetric surfaces for successive survey intervals and the overall study period: (A) 2009–2008; (B) 2010–2009; (C) 2011–2010; and (D) 2011–2008. Blue colours indicate new sediment accumulation, whereas red colours indicate river-bottom erosion.

The spatial distribution of differences indicates that morphodynamic adjustment was not random, but controlled by persistent hydraulic conditions associated with the regulated character of the river reach. Several linear and elongated zones of change reappeared in more than one epoch pair, especially in the 2010–2009 and 2011–2008 comparisons, which suggests repeated bed reworking in the same sectors. The 2009–2008 and 2011–2010 intervals showed a broader spatial extent of change, indicating more widespread redistribution of bottom material during those periods.

These observations are supported by the quantitative results shown in Figure 6. The highest gross erosion volume was observed for the 2010–2009 interval and reached approximately 70,000 m³, while the largest deposition volume occurred during 2009–2008 and amounted to about 50,000 m³. In the 2011–2010 interval, deposition remained relatively high at about 40,000 m³, whereas erosion decreased to approximately 25,000 m³. For the cumulative 2011–2008 comparison, gross erosion and deposition reached about 55,000 m³ and 38,000 m³, respectively.

The affected areas showed a partly different pattern. The largest erosion-affected area was recorded for 2010–2009 and reached about 220,000 m², whereas the largest deposition-affected area occurred for 2011–2010 and was approximately 210,000 m². For 2009–2008, the affected areas of both processes were intermediate and relatively balanced. Overall, these results indicate that the magnitude and extent of morphodynamic change varied between epoch pairs, but remained concentrated in recurrent sectors of hydraulic activity and riverbed instability.

4.2.2. Water-Level-Referenced Shoreline State

The incorporation of water level as a dynamic reference surface substantially improved the interpretation of shoreline state across survey epochs. When reconstructed bathymetric surfaces were evaluated relative to contemporaneous water levels, the extent of exposed and

submerged zones changed markedly even where local bed geometry remained comparable. This effect is illustrated in Figure 7, which shows two water levels recorded during the 2011 measurement campaign: 43.5 m and 45.8 m (PL-EVRF2007-NH).

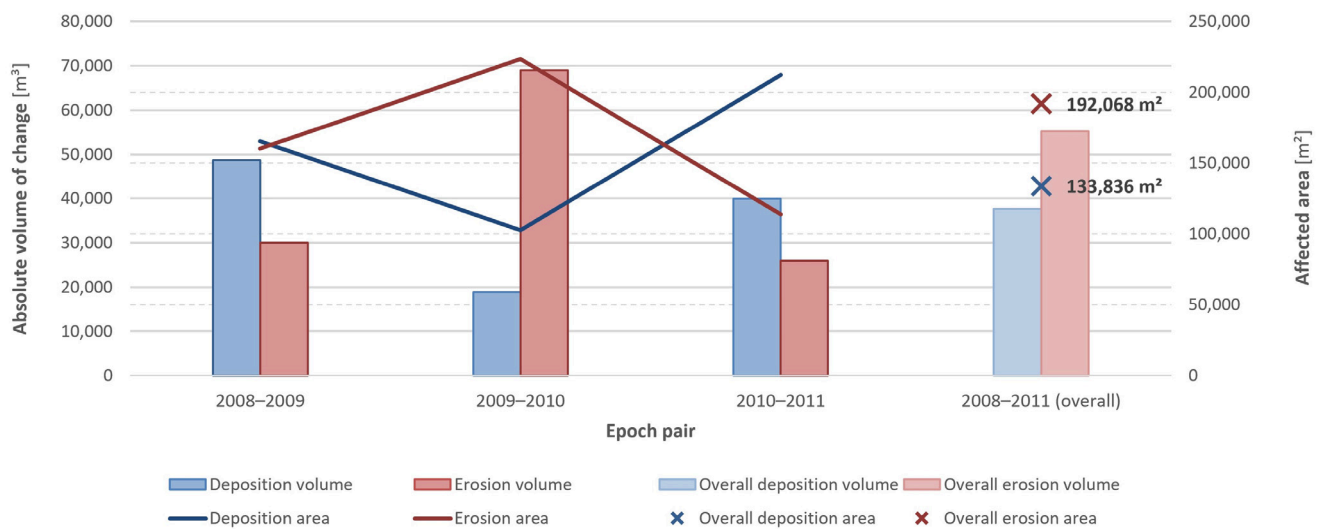


Figure 6. Gross erosion and deposition volumes and affected areas for annual epoch pairs and the cumulative 2008–2011 comparison. Solid lines show affected areas for consecutive annual intervals. The cumulative 2008–2011 result is visually separated using lighter bars and isolated cross markers.

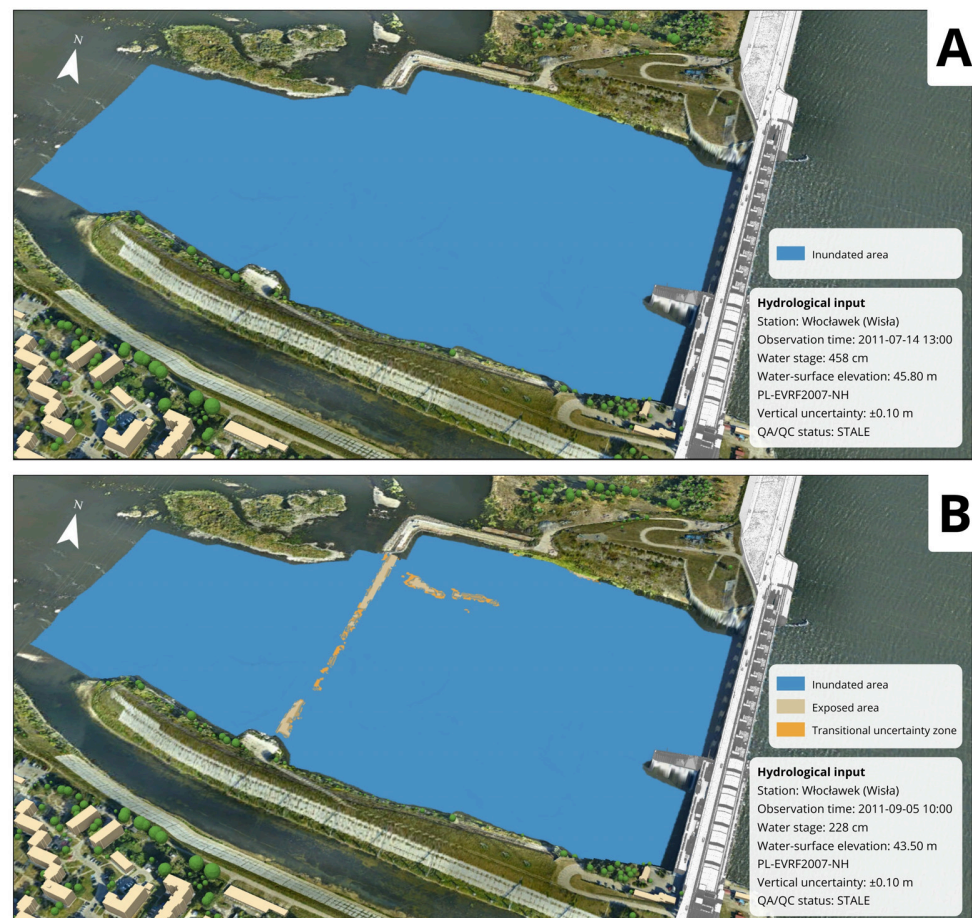


Figure 7. Water-level-referenced shoreline state during the 2011 measurement campaign for two recorded water levels: (A) 43.5 m and (B) 45.8 m (PL-EVRF2007-NH), illustrating the effect of stage variation on exposure and inundation patterns.

A water-level difference of 2.3 m produced a clear change in shoreline-state configuration. In the present study, shoreline state is understood not as a manually digitized shoreline line, but as the spatial relation between the reconstructed bed surface and the assigned water level, expressed through exposed, inundated, and transitional zones. At the lower stage, shallow marginal sectors and isolated topographic highs emerged as exposed bars or islands, whereas at the higher stage, these areas became submerged and the inundated zone became more continuous. This comparison demonstrates that shoreline interpretation in the analyzed regulated reach cannot be reduced to bed elevation alone. In low-gradient nearshore sectors, even moderate stage differences altered both the width and geometry of the exposed marginal zone.

The broader hydrological context is shown in Figure 8. The daily record indicates pronounced short-term variability in both water level and discharge during 2008–2011, with several high-flow episodes and marked stage fluctuations, particularly in 2010 and 2011. This temporal variability confirms that shoreline state in the study area was controlled not only by morphology, but also by changing hydrological conditions at the time of measurement.

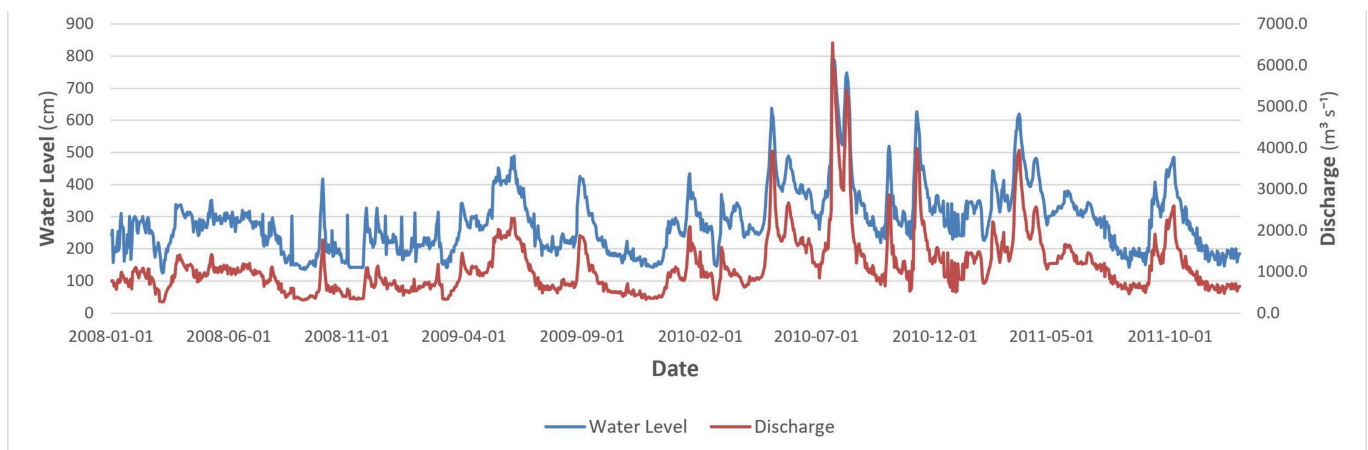


Figure 8. Daily water level and discharge recorded during 2008–2011, showing the hydrological context of the measurement campaigns and the temporal variability of shoreline-forming conditions.

Taken together, these results justify the use of dynamic water-level referencing in the digital twin. Analyses based solely on fixed elevation thresholds would have produced less consistent interpretations of shoreline evolution, whereas the adopted approach allowed shoreline state to be reconstructed under observed and scenario-based hydrological conditions.

4.2.3. Cross-Sectional Expression of Morphodynamic Change

Cross-sectional analysis complemented the plan view interpretation by resolving the vertical structure of bed adjustment along two representative transects (Figure 9). Profile 1 (A–B) was located in the near-dam sector, where hydraulic forcing is the strongest, whereas Profile 2 (C–D) crossed the central part of the study area characterized by recurrent erosion and deposition patterns. Together, these sections captured both the hydraulically constrained zone adjacent to the structure and the more laterally variable channel sector.

The predicted 2011 profiles shown in Figure 9 were extracted from the trend-predicted raster surface generated by the cell-wise temporal extrapolation of the ordered 2008–2010 bathymetric sequence. Profile 1 shows a longitudinal bed elevation range of approximately 35.2–41.3 m. The largest inter-epoch differences occurred in the upstream part of the section, especially between about 20 and 100 m, where local vertical offsets reached roughly 2–3 m.

Downstream of about 120 m, the profiles converged and remained relatively stable, with only minor local deviations except for a short, disturbed segment around 255–275 m. The trend-predicted 2011 profile closely followed the observed 2011 surface over most of the section, with the largest deviations concentrated in the initial segment and around the local disturbance near 260 m.

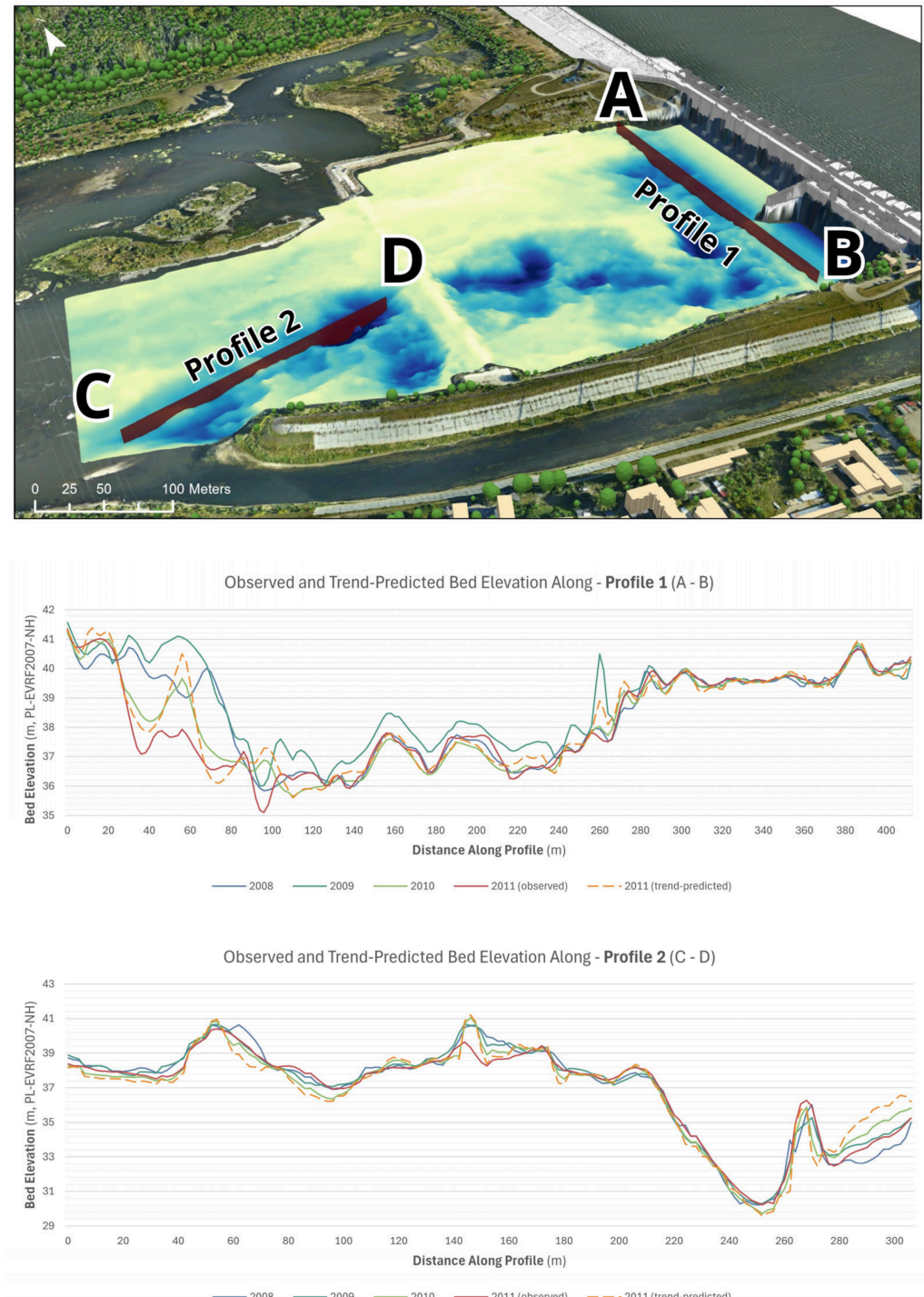


Figure 9. Cross-sectional analysis of bathymetric change and trend-based prediction. (**Top**) Spatial location of the selected profiles; colors visualize bed morphology, and dark red lines mark the profile transects. Letters A–D indicate profile endpoints. (**Middle**) Multi-epoch bed elevation curves and trend-predicted 2011 profile along Profile 1 (A–B). (**Bottom**) Multi-epoch bed elevation curves and trend-predicted 2011 profile along Profile 2 (C–D).

Profile 2 shows a wider vertical range, from about 29.5 to 41.0 m, and a more complex sequence of local highs and depressions. The strongest variability occurred between about 230 and 275 m, where a pronounced depression was followed by a sharp rise in bed elevation. Inter-epoch differences were generally moderate along most of the section, but increased locally to about 0.5–1.0 m near 55–70 m, around 145 m, and within the deep trough zone. The predicted 2011 profile reproduced the observed geometry well over most of the section, although larger deviations remained near the distal segment beyond about 280 m, where the predicted bed elevation was higher than the observed one.

These local deviations are interpreted primarily as effects of complex bed geometry, strong local gradients, and repeated bed reworking in sectors already identified as morphodynamically active in the raster differencing results. They should not be interpreted as evidence of broad predictive failure across the entire reach, but rather as localized limitations of the short-horizon trend-based extension.

Taken together, the cross-sections confirm that morphodynamic change was spatially concentrated rather than uniform. Profile 1 indicates stronger local adjustment in the near-dam zone, while Profile 2 shows more distributed bed reworking across the central channel sector. In both cases, the predicted 2011 surface reproduced the main vertical pattern of the observed morphology, although accuracy decreased locally in segments of complex bed geometry.

4.3. Automation, Repeatability, and Predictive Extension

A major outcome of the framework was the implementation of a repeatable GIS workflow integrating data acquisition, preprocessing, model generation, quality control, digital twin updating, and output generation (Figure 10). The workflow linked bathymetric surveys, ALS-based terrain data, infrastructure data, and hydrological series within a single processing chain, from import and harmonization to interpolation, water-level assignment, validation, and production of analytical outputs.

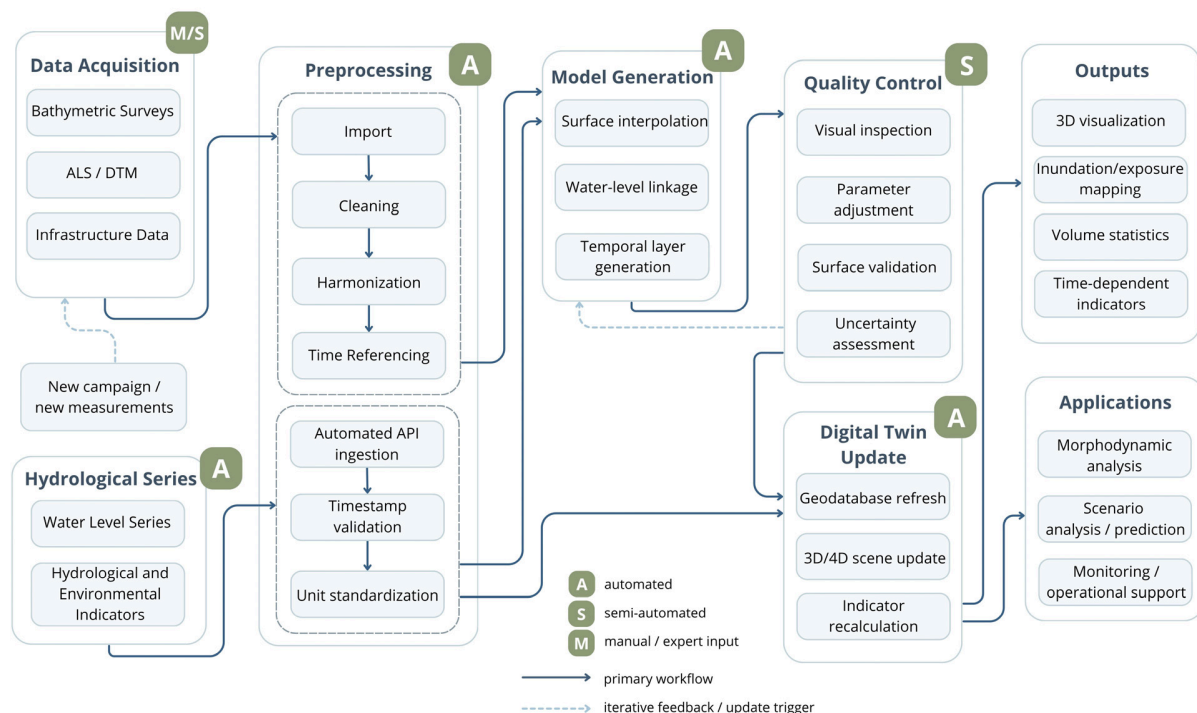


Figure 10. Workflow of the spatiotemporal digital twin, from data acquisition and preprocessing to model generation, quality control, digital twin update, and analytical outputs (M—manual; A—automated; S—semi-automated).

In the revised framework, workflow repeatability was further extended by the implementation of a near-real-time hydrological updating component. Operational water-level observations retrieved from the IMGW public API were ingested into the geodatabase, validated, transformed from gauge stage to model-referenced water-surface elevation using station-specific gauge-datum parameters, and stored as the current hydrological reference state. This step provides a practical physical-to-virtual updating pathway for the hydrological component of the framework and enables future recalculation of shoreline-state products under current conditions.

The workflow combined manual, automated, and semi-automated operations. Manual input was limited mainly to data acquisition and expert-controlled updates, whereas preprocessing, model generation, and digital twin updating were designed for automated execution. Quality control remained semi-automated, including visual inspection, parameter adjustment, surface validation, and uncertainty assessment. This structure reduced campaign-specific processing differences and improved methodological consistency between epochs.

The repeatable workflow also increased the operational value of the digital twin. Once new bathymetric measurements or updated hydrological records become available, the same procedure can be reapplied to refresh the geodatabase, update the three-dimensional scene, and recalculate derived indicators, including inundation and exposure zones, volumetric statistics, and time-dependent metrics. In this form, the framework extends beyond retrospective analysis of the 2008–2011 dataset and supports continued monitoring and scenario-based assessment.

The multidimensional raster structure further enabled a predictive extension based on temporal trend analysis. Trend rasters derived from the 2008–2010 bathymetric sequence identified persistent zones of elevation decrease and increase, corresponding to continued erosion and deposition tendencies. The predicted 2011 surface reproduced the main spatial pattern of the observed riverbed, particularly over areas of limited morphodynamic variability, whereas larger discrepancies remained concentrated in the central zone of repeated bed adjustment and near hydrotechnical structures. This result indicates that the time-structured raster model can support short-term exploratory prediction within the digital twin environment.

4.4. Predictive Validation and Residual Analysis

Validation results indicate that the trend-based prediction reproduced the general spatial structure of the 2011 riverbed surface with high overall agreement. The spatial distribution of residuals shown in Figure 11 is dominated by low differences over most of the analyzed area, whereas larger discrepancies are concentrated in a limited number of sectors.

The most distinct residual zones occur along the central belt of repeated morphodynamic activity and locally near the hydrotechnical structures, which suggests that prediction errors increased mainly where bed geometry was more variable and spatial gradients were stronger.

The residual pattern is therefore not random. Most of the study area is characterized by minor deviations between observed and predicted elevations, while the largest positive and negative residuals are confined to morphodynamically active zones already highlighted by the inter-epoch difference maps. This indicates that the predictive extension preserved the dominant spatial configuration of the riverbed, but was less accurate in sectors affected by localized erosion, deposition, or rapid bed reworking.

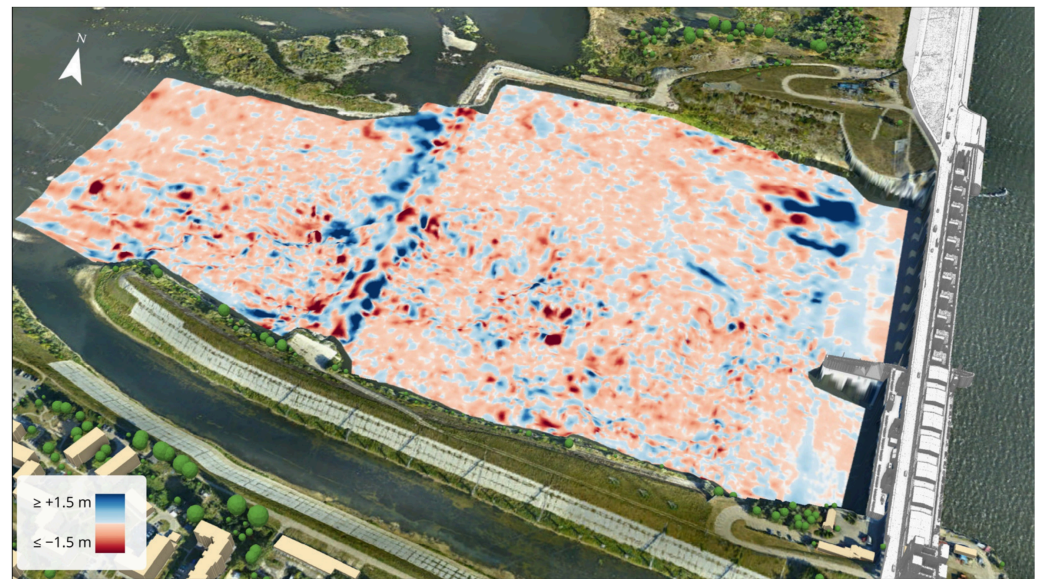


Figure 11. Residual map showing spatial differences between observed and trend-predicted bed elevation for 2011.

The quantitative assessment shown in Figure 12 confirms this interpretation. Across 81,477 valid raster cells, the agreement between observed and predicted bed elevations was very high, with $R^2 = 0.967$, RMSE = 0.44 m, MAE = 0.28 m, and a small negative bias of -0.06 m. The strong concentration of points along the 1:1 line indicates that the predicted surface closely followed the observed elevation pattern over most of the study area, while departures from the line were limited mainly to cells associated with locally complex morphology.

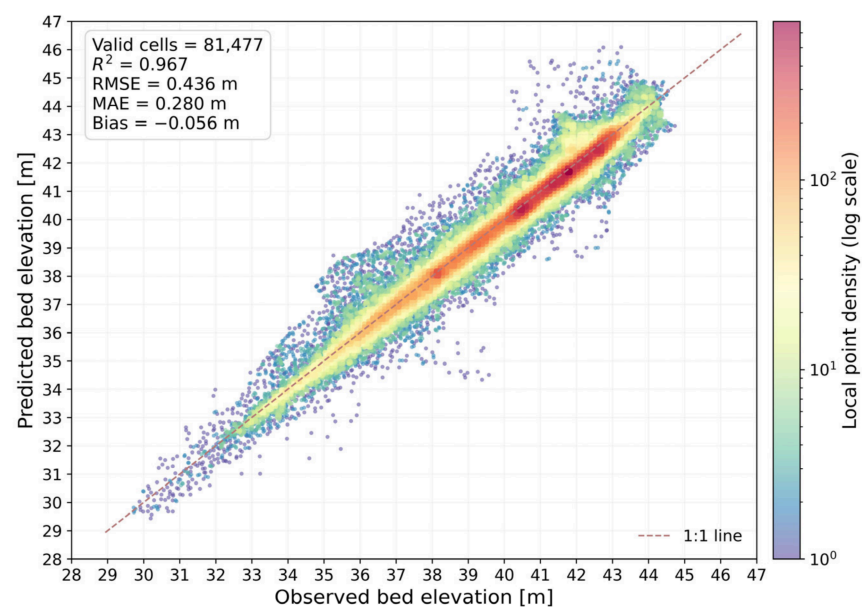


Figure 12. Validation scatter plot comparing observed and trend-predicted bed elevations for 2011 across all valid raster cells. Point colours denote local point density, while the dashed line represents perfect agreement.

Overall, these results show that the multidimensional raster structure provides a useful basis for short-term exploratory extension of bed elevation patterns. At the same time, the high agreement partly reflects spatial persistence and structural continuity of the bed surface, and should not be interpreted as evidence of broad predictive capability.

The predictive component is therefore best understood as a proof-of-concept analytical extension rather than a deterministic morphodynamic forecast.

5. Discussion

5.1. Morphodynamic Response in the Regulated Reach

The results indicate that bed adjustment downstream of the Włocławek Dam was spatially persistent but temporally variable. The highest gross erosion occurred in 2010–2009, reaching about 70,000 m³ and affecting about 220,000 m², whereas the highest gross deposition was observed in 2009–2008 and reached about 50,000 m³. In 2011–2010, deposition remained relatively high at about 40,000 m³, but its spatial extent was broader than its volumetric expression. This shows that process intensity and affected area were only partly coupled, and that bed reworking was repeated but uneven through time.

These results are consistent with earlier studies from the Włocławek reach, which identified localized scour, deposition contrasts, and zones of increased geomorphological sensitivity [13,14]. They also agree with broader observations from regulated rivers, where altered flow and sediment deficit commonly produce nonuniform downstream adjustment [31,32]. In the present case, recurrent sectors of change in the central part of the channel and near hydrotechnical structures are consistent with the influence of regulated hydraulic conditions and infrastructure-related forcing, although the present framework remains geometric rather than fully process-based.

5.2. Water Level as a Controlling Variable of Shoreline State

A key result of this study is the clear dependence of shoreline interpretation on water level. Shoreline state was derived not from bed topography alone, but from the relation between reconstructed bathymetry and the water surface assigned to each epoch. This was particularly important in low-gradient marginal zones, where relatively small stage differences produced pronounced changes in exposure and inundation extent.

This confirms that water level should be treated as a primary analytical variable rather than ancillary metadata. In practical terms, the digital twin became responsive to changing hydrological conditions because water level modified the derived shoreline products, not only the descriptive context. This shifts the framework beyond static three-dimensional visualization by making shoreline-state reconstruction directly dependent on temporally variable hydrological conditions, and thus aligns it more closely with dynamic digital twin concepts developed in water-related applications [33,34].

This interpretation is further strengthened in the revised framework by the implemented hydrological updating pathway, in which current operational observations can be ingested into the geodatabase and used to refresh the water-level reference state for shoreline-state reconstruction.

5.3. Temporal Raster Structure and Predictive Extension

The temporal raster structure constituted the analytical core of the proposed framework. By organizing the bathymetric surfaces as ordered raster states, the model supported not only pairwise comparison, but also trend analysis, profile-based interpretation, and predictive testing within a common reference structure. In this study, the multidimensional raster structure is not presented as a wholly new data model in itself, but as a functional analytical core that enables these operations to be handled within a single shoreline-oriented GIS framework [35].

The predictive test based on the 2008–2010 sequence and validated against the observed 2011 surface showed strong overall agreement, with $R^2 = 0.967$, RMSE = 0.44 m, MAE = 0.28 m, and bias = −0.06 m. At the same time, the residual map showed that the

largest discrepancies were concentrated in the central belt of repeated adjustment and near hydrotechnical structures. The predictive component should therefore be interpreted as a validated short-horizon exploratory extension of the framework rather than a deterministic morphodynamic forecast.

5.4. Repeatability and Uncertainty

The results confirm that morphodynamic interpretation must remain uncertainty-aware. Not every difference between rasters represents real environmental change; part of the variability may result from survey error, interpolation, local geometric complexity, or data acquisition strategy. In the present study, uncertainty is therefore treated as an interpretative and methodological constraint rather than as a fully implemented threshold-based volumetric classification. The reported erosion and deposition volumes should be interpreted as raw inter-epoch estimates, whereas explicit uncertainty handling is currently implemented in the shoreline-state update logic through the distinction between exposed, inundated, and transitional zones around the water-level reference surface [26,36].

The compact benchmark confirmed that TPS and Ordinary Kriging produced closely comparable errors for the representative subset, whereas IDW performed substantially worse. This supports the adopted choice of TPS as a practical interpolation scheme for the present workflow, while also indicating that interpolation sensitivity remains a relevant source of methodological uncertainty.

The repeatable workflow is equally important. By applying the same processing logic across all epochs, the framework reduces methodological inconsistency and supports more reliable interpretation of volumetric change, affected area, and residual patterns. In this form, the reliability of the digital twin depends primarily on temporal consistency, harmonized processing, and explicit uncertainty assessment rather than on a single reconstruction output.

5.5. Implications for Monitoring and Transferability

The framework has implications beyond the Włocławek case because it combines descriptive, predictive, and decision-support functions increasingly associated with digital twins as decision-oriented geospatial infrastructures. In descriptive terms, it reconstructs shoreline state by integrating bathymetry, hydrology, topographic context, and infrastructure within a temporally explicit GIS environment. In predictive terms, it supports short-horizon trend-based extension of riverbed change and prospective shoreline-state assessment. In decision-support terms, the present implementation does not provide automated optimization or closed-loop control, but it does support scenario-based interpretation and operational evaluation by enabling shoreline-state updating under observed and alternative hydrological states.

Third, the workflow is transferable to other regulated river or reservoir shorelines only under specific practical conditions, including availability of repeated bathymetric surveys, harmonized geodetic references, topographic context, and water-level observations or API-accessible hydrological records. In other words, the framework is transferable conditionally rather than universally [18,37].

5.6. Limitations and Directions for Further Development

Several limitations should be acknowledged. The bathymetric record consists of four discrete survey epochs and therefore does not capture short-term responses to individual flow events or operational changes. The framework also integrates water level as a dynamic reference surface, but does not yet include distributed hydraulic variables, sediment transport parameters, or turbine operation data. In addition, the predictive extension was evaluated on a short temporal sequence and should therefore be treated as exploratory.

These limitations are consistent with current assessments of digital twin development in water systems, which emphasize that operational synchronization, scalable data integration, and robust updating workflows remain among the main barriers to broader implementation [18,19].

Further development should focus on continued automation of hydrological data ingestion, extension of the bathymetric time series, explicit quantitative thresholding of elevation differences where justified by error modelling, and validation of predictive outputs against additional holdout epochs. Integration of hydraulic and sediment transport variables would further strengthen process-based interpretation and increase the operational value of the digital twin. These priorities are consistent with current assessments of barriers and development needs in water infrastructure digital twins and indicate a clear pathway from a multi-epoch analytical framework toward a more operational and process-aware system [19].

6. Conclusions

This study developed and validated a GIS-based spatiotemporal framework for dynamic shoreline-state reconstruction in a regulated river environment downstream of the Włocławek Dam. Implemented as a digital twin-oriented geospatial system, the framework integrates multi-epoch bathymetric surveys, water-level records, ALS-derived terrain context, and three-dimensional hydrotechnical infrastructure within a unified geospatial environment. The proposed approach moves beyond conventional campaign-based assessment toward a temporally explicit model of riverbed change and shoreline-state variation under regulated hydrological conditions.

The results show that water level should be treated as a primary analytical variable rather than ancillary descriptive information. Referencing bathymetric surfaces to contemporaneous water levels improved shoreline interpretation, especially in low-gradient nearshore zones, while the multidimensional temporal raster structure supported repeatable change detection, cross-sectional analysis, and trend-based assessment within a common reference framework.

To extend the framework beyond purely retrospective analysis, a near-real-time hydrological updating component was implemented through ingestion of operational observations from the IMGW API into the geodatabase. This provides a practical physical-to-virtual synchronization pathway for the hydrological reference state used in shoreline-state reconstruction, although the bathymetric component remains campaign-based.

The adopted workflow proved suitable for environmental-scale morphodynamic analysis. The predictive extension reproduced the main spatial pattern of the observed 2011 bed surface, although larger residuals remained concentrated in sectors of complex morphology and repeated bed adjustment near hydrotechnical structures. This predictive step should therefore be interpreted as a short-horizon exploratory proof of concept rather than as a full morphodynamic forecasting model.

Overall, the proposed framework functions not only as a visualization environment, but as a structured and partially updatable analytical model linking morphology, hydrology, terrain, and infrastructure in a temporally explicit GIS framework. Its transferability depends on the availability of harmonized bathymetric, hydrological, and topographic data. In this broader perspective, the framework brings together descriptive, predictive, and decision-support capabilities within a single spatiotemporal environment for regulated shoreline monitoring. With continued development, particularly in automated hydrological updating, longer temporal sequences, and explicit quantitative uncertainty modelling, it may evolve toward a more operational digital twin-oriented system for monitoring regulated river shorelines.

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Abbreviations

The following abbreviations are used in this manuscript:

ALS	Airborne Laser Scanning
DSM	Digital Surface Model
DEM	Digital Elevation Model
DTM	Digital Terrain Model
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
MAE	Mean Absolute Error
RMSE	Root Mean Square Error

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