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Scan-to-BIM Information Foundations and a Digital Twin Architecture for the Urban Tiber River Corridor in Rome

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Abstract

Digital Twins (DTs) are increasingly being proposed for urban river management, but their usefulness depends on the information available for specific applications. This study applies the DT methodology developed within the Agenzia del Demanio guidelines prepared by CITERA to approximately 8 km of the urban Tiber River in Rome, under an AUBAC-CITERA research agreement. The objectives concern maintenance of riverbed and bank hydraulic works, hydraulic condition monitoring and hydro-pluviometric monitoring. The application produces approximately 3.2 billion TLS/SLAM points, IFC 4.3 models of sixteen bridges, geospatial contextualisation and a target architecture for federation with the AUBAC's WebGIS. The estimated reconstructed shares of above-water model surface range from 0% to approximately 50% (unweighted mean, approximately 17%), reflecting construction and access constraints. At Ponte Risorgimento, an extracted section gives a modelled span of 100.28 m and intrados rise of 9.58 m; the latter depends on the reconstructed crown. This links an extractable geometric parameter to a specific verification need before hydraulic use. The IFC inventory and file checks identify further verification requirements. Common georeferencing, bathymetry and exchange testing are integration priorities; monitoring deployment and operational validation remain future work. The contribution supports targeted investigations within the AUBAC's wider DT programme.

Keywords: digital twin; digital model; urban river corridor; Tiber River; scan-to-BIM; BIM-GIS integration; IFC 4.3; flood risk management; hydro-pluviometric monitoring; sustainable water governance

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1. Introduction

Decarbonisation and digitalisation shape the current priorities for construction and territorial management [1,2]. The United Nations 2030 Agenda [1,3], European policy and Italy's National Recovery and Resilience Plan [4,5] frame digital technologies as means of improving efficiency, safety, sustainability and resilience [6,7]. Their value for river management depends on whether the information produced can support specific decisions.

A Digital Twin (DT) is a virtual representation synchronised with its physical counterpart at a specified frequency and fidelity [8,9]. Developed in product lifecycle

management [10] and aerospace [11], the concept combines physical and virtual entities with data exchange, potentially supported by AI, ML and IoT [8,12,13]. Its terminology remains heterogeneous [14,15]. This paper follows Kritzinger et al. [16], distinguishing among Digital Model, Digital Shadow and Digital Twin by their data flow integration, alongside reviews of enabling technologies and implementation challenges [17–20]. ISO 23247 addresses manufacturing DT architectures [21], while the Gemini Principles address shared digital infrastructure for a built environment [22].

Built environment DTs remain less mature than manufacturing and aerospace applications [8,16,23–25]. The research has addressed the links with BIM, production control and implementation taxonomies [9,26–31], and with applications in design [28,32], construction [33,34] and operation [35,36]. Trust and cybersecurity [37,38], fragmented responsibilities, data quality, interoperability and resource requirements remain barriers [8,27,39,40]. Combining data sources into usable evidence is therefore central to implementation [9,41,42].

At an urban scale, DTs can extend 3D city models and GIS [42,43]. Herrenberg combines spatial modelling, simulations and virtual reality for civic participation [44]; Zurich provides municipal geodata and planning services [45]. Reviews have identified persistent governance, integration and adoption challenges [29,46–49]. Indicator frameworks, such as ISO 37122, can inform evaluation [50,51], but application-specific definitions and baselines are still required.

In parallel, the scientific community has extended the DT paradigm to the natural environment, from a planetary scale, with initiatives such as the European Commission's Destination Earth and Digital Twins of the terrestrial hydrological cycle [52–54], down to a basin and city scale [55]. Established applications include the management of urban drainage and stormwater systems [56,57]; the prevention of hydrogeological risk through Web–GIS and UDT platforms [58,59]; the navigation of urban flood dynamics through geospatial twins [60,61]; and multi-hazard, multiscale assessment [62]. Of particular relevance is the Florence DT for the protection of the Arno and its historic urban landscape, which integrates multi-sensor geomatic solutions within a climate-risk management framework [63]; this is the closest antecedent to the present case study in combining built heritage and river hazard concerns. As for the Tiber, the literature documents the centuries-long co-evolution of the urban development of Rome and flood dynamics [64], alongside well-established hydrological and hydraulic studies on extreme floods and inundation probability [65,66], within a planning framework defined by the Floods Directive 2007/60/EC [67] and the Flood Risk Management Plan of the Central Apennine District [68].

At the technological level, the literature converges on the IoT, cloud and edge computing, 5G networks, BIM and AI/ML analytics as DT-enabling technologies. The Digital Twin Consortium's Capabilities Periodic Table (CPT) organises platform capabilities into six groupings (Data Services, Integration, Intelligence, User Experience, Management and Trustworthiness) [69]. Interoperability rests on open standards, such as the ISO 19650 series [70] for information management and the IFC format in its 4.3 version extended to infrastructure [71], and on BIM-GIS georeferencing and integration practices [72,73]. These practices are central to river corridors, where models of bridges and bank works must be federated with territorial and hydraulic datasets.

The Agenzia del Demanio guidelines [74] link management objectives to information requirements, indicators, capabilities and candidate technologies. Reviews have identified comparability and replicability across DT projects as continuing challenges [28,29,46,49,75]. This paper contributes an application study documenting the outputs and constraints encountered when using that framework in an urban river corridor. It does not claim that the selected literature constitutes an exhaustive survey of river DTs.

Table 1 compares a purposive selection of documented urban and river-related applications by scale, purpose, information assets, implementation status and reported evidence. It includes hydraulic simulation and operational service examples; operational use alone is not treated as validation.

Table 1. Comparative overview of selected Digital Twin experiences relevant to the present case study.

Case Study	Scale	Main Management Objectives	Information Assets Produced	Implementation Status	Technologies Employed	Evidence Reported
Herrenberg [44]	Urban	Participatory planning, mobility, urban comfort	3D city model, simulation outputs, VR environment	Demonstrative/pilot	3D city model, space syntax, wind flow simulation, VR	Demonstration (pilot)
Zurich [45]	Urban	Urban planning	3D city model, municipal geodata services	Operational	3D city model, GIS platform	Operational service (operational use, not a validation study)
Florence/Arno [63]	Urban riverine	Hydraulic and landscape protection of the river system	Multi-sensor geomatic datasets of the river corridor, including bathymetry and a geodetic control network	Under development	Multi-sensor geomatic solutions	Integrated surveys with geodetic control; framework under development
FlowsDT [60]	Urban	Flood dynamics navigation and emergency support	Geospatial flood scenario twin of the urban area	Operational prototype	Geospatial Digital Twin, 1D–2D coupled hydrodynamic modelling	Validated on historical flood events and social sensing; design storm scenarios, no real-time operation
Web–GIS hydrogeological risk [58]	Basin/urban	Hydrogeological risk prevention	Web–GIS risk knowledge base	Operational portal	Web–GIS platform	Operational portal (data availability, not model validation)
Tiber River (this study)	Urban riverine (river reach and exposed interfaces)	Condition-based maintenance, hydraulic condition monitoring, hydro-pluviometric monitoring	Point clouds of 16 bridges and adjoining banks; Scan-to-BIM IFC 4.3 models of the 16 bridges; geospatial contextualisation; DT architecture and monitoring configuration at design stage	Prototype: Geometric and information layers implemented; monitoring, data flows and indicator validation planned	TLS, SLAM mobile mapping, Scan-to-BIM, IFC 4.3, GIS/InfraWorks, planned IoT hydro-pluviometric sensing	Information base and target design; no operational data

1.1. Aim, Research Questions and Contributions

Within this framework, the Central Apennine River Basin District Authority (AUBAC) is the public authority responsible for river basin planning, water governance planning and flood/hydrogeological risk planning in the Central Apennine District under the Water Framework Directive 2000/60/EC [76] and the Floods Directive 2007/60/EC. The AUBAC and CITERA (Interdepartmental Research Centre Territory, Building,

Restoration and Environment of Sapienza University of Rome) signed the research agreement "Study and research activities for the development of a Digital Twin of the urban stretch of the Tiber River in Rome" [77], within which the application documented in this paper is carried out.

This study applies the previously published Agenzia del Demanio methodology [74] to the urban Tiber corridor and assesses the information assets and implementation constraints produced by that application. CITERA, with which several authors are affiliated, developed the reference framework; the study neither modifies nor independently validates it. No hydraulic calculation or operational monitoring is reported. Structural health monitoring is outside the adopted scope [78–80].

Accordingly, the study addresses three research questions:

RQ1: When a previously published Digital Twin methodology is applied to an urban river corridor that integrates the built infrastructure and natural system monitoring, which of its components can be realised with the available data, and where do the binding implementation constraints arise, in terms of information completeness, geometric reliability, interoperability and georeferencing, and governance?

RQ2: What do the survey-derived assets and IFC models reveal about the provenance of the represented geometry and the extent to which the resulting information supports the stated management objectives?

RQ3: What are the main implementation challenges, current maturity levels and remaining requirements for the evolution from a prototype digital representation towards an operational Digital Twin?

The contribution comprises a documented survey-to-model workflow, a retrospective assessment of the information foundation against management requirements, and a target monitoring architecture. Section 1.2 distinguishes the empirical findings from design outputs; Section 5 discusses their limits and transferability.

1.2. Research Gap and Novelty of the Present Study

The contribution of this study is an empirical assessment of the information produced by a survey-to-BIM application across sixteen bridges and the adjoining banks of an urban river corridor. It examines the relationship between the existence of a digital representation, the evidence supporting that representation and its suitability for the management objectives defined at the outset.

Three linked findings support this contribution. First, the bridge models combine a directly surveyed and parametrically reconstructed geometry, with the estimated reconstructed shares ranging from 0% to approximately 50% of above-water model surface. The construction and access constraints explain the acquisition gaps, while the documented Musica and Risorgimento intrados examples show why the location of reconstruction matters, alongside its overall share, when prioritising verification for subsequent hydraulic use. The quantitative section extraction at Ponte Risorgimento links the modelled intrados rise to the reconstructed crown, identifying a specific geometric verification target (Section 4.3). Second, the sixteen-model IFC inventory and the checks on Ponte della Musica and Ponte Risorgimento document the entity mappings, spatial organisation and file-check outcomes, providing a basis for defining semantic and exchange verification. Third, the assessment relates these findings to the intended uses, identifying the information already available for geometric documentation and targeted investigations and the additional observations, common reference systems and exchange tests required for integration.

The novelty claimed is therefore the case-specific evidence and its joint interpretation across geometry provenance, information structure and intended use. The study does not introduce a new acquisition technique or Digital Twin methodology. The architecture,

monitoring configuration and indicators are design outputs informed by this assessment; their operational effectiveness remains to be tested.

Section 2 describes the framework and procedures; Section 3 defines the case and its requirements; Section 4 reports the assets, architecture and maturity; and Sections 5 and 6 discuss the findings and subsequent work.

2. Materials and Methods

The methods comprise adoption of the reference framework, the case study protocol, geometric acquisition, information modelling, geospatial contextualisation and monitoring design. Generative AI tools were used as follows: ChatGPT (OpenAI, GPT-5.6; August–October 2026) for language editing, improving manuscript organisation and clarity, figure layout, and assistance in preparing the scripts for IFC validation, geometric section extraction and consistency checks; and Claude (Anthropic, Claude Opus 5.5; October 2026) for revision editing, consistency checks across the text, tables and supplementary files, and figure editing. The authors reviewed and verified all outputs and take full responsibility for the content; AI tools were not used for data acquisition, and AI assistance is not a source of measured results.

2.1. Reference Methodology

The study adopts the Digital Twin methodology published in the Agenzia del Demanio guidelines [74], prepared by CITERA. Its origin in the authors' research environment is disclosed; it is not treated as an independent external standard.

For the purposes of this paper, only those elements of the reference methodology that are necessary to follow the case study are recalled here; the reader is referred to the published guidelines for the complete framework, its taxonomies and its supporting tool. In summary, the methodology requires a Digital Twin project to be characterised, before any technological choice, by three descriptors: the intervention category (new construction, regeneration of the existing, or transformation), the process phase (design, execution, or operation) and the management objectives pursued. The objectives are organised into families that include—alongside energy efficiency, environmental and economic sustainability, use and enhancement, and safety and security—the management of the natural and built environment, which covers soil defence, resilience of the built environment, hazard condition monitoring, environmental quality monitoring and hydro-pluviometric monitoring. Once a project is characterised in these terms, the methodology associates the resulting configuration with the corresponding information requirements—that is, the input data the platform must acquire, in continuous or discontinuous flow, from the heterogeneous sources—and with the performance indicators that make the effectiveness of the architecture measurable. It also associates the configuration with the capabilities the platform must possess, expressed with reference to the Digital Twin Capabilities Periodic Table of the Digital Twin Consortium [69], and articulated into the six groupings Data Services, Integration, Intelligence, User Experience, Management and Trustworthiness, each associated with candidate enabling technologies and technological solutions. The methodology further adopts the Plan–Do–Check–Act continuous-improvement cycle [81] as the frame within which indicators are defined, populated, analysed and translated into corrective actions.

In this application, the management objectives guide the information requirements and technology selection. The instrument choices additionally reflect accessibility, traffic, geometry and safety constraints, as described below.

2.2. Case Study Materials and Application Protocol

The case study concerns the urban stretch of the Tiber River in Rome and was carried out within the AUBAC–CITERA research agreement described in Section 1.1. The materials for the application comprised: the territorial, hydrological and planning documentation made available by the AUBAC, including the hazard delineations of the Flood Risk Management Plan of the Central Apennine District [68] and the thematic layers published through the authority's WebGIS environment [82,83]; the geometric survey data acquired *ex novo* for this study on the sixteen bridges and the adjoining banks of the stretch; and the information models derived from them.

The application protocol followed four operational stages, described in Sections 2.3–2.6: acquisition of geometric and geospatial data; Scan-to-BIM information modelling; BIM-GIS integration and geospatial contextualisation; and definition of the Digital Twin architecture together with the conceptual configuration of the hydro-pluviometric monitoring component. Ponte della Musica "Armando Trovajoli" was adopted as the reference element on which the full sequence was first carried out. The survey-to-model sequence was extended to the remaining fifteen bridges; the banks were surveyed but remained point cloud assets.

The internal checks concerned geometric consistency, element identification and the exchange format [70,72]. "Verified" denotes those checks, not metrological certification. The registration and alignment statistics and the reference IFC check are reported below; no independent geometric accuracy assessment or controlled TLS–SLAM benchmark was performed.

RQ1 was assessed retrospectively, after the application, against five criteria: information completeness (share of surveyed and reconstructed bridge geometry, and acquisition of the riverbed); geometric reliability (registration and alignment statistics, and availability of independent checks); interoperability and data mapping (outcome of the IFC schema check, share of generic proxy entities, and exchange tests); georeferencing (completion of the registration to the target reference system); and governance constraints (documented preconditions for deploying the monitoring network). For each criterion, the evidence available in this study is reported together with its documented gaps in coverage or verification, and a component is identified as a binding constraint when it could not be achieved with the available data or within the study period and prevented a downstream component. Because the criteria were defined after the application, the assessment (Section 5) is descriptive rather than a test of a prior hypothesis.

2.3. Geometric and Geospatial Data Acquisition

The geometric acquisition was carried out through two complementary techniques, both included among the technologies associated with the data-acquisition-and-ingestion capability in the reference methodology: multi-station terrestrial laser scanning (TLS) and SLAM mobile mapping performed with an Emesent Hovermap ST-X system, which was either backpack-mounted or hand-carried. A DJI Matrice 350 RTK unmanned aerial platform was employed for the acquisition of aerial imagery and orthophotos of the banks and of the portions not reachable from the ground, complementing the ground-based acquisition in line with UAV-supported bridge inspection [84].

The selection of TLS or SLAM was made, element by element, according to the documented context constraints: accessibility of the element and of its surroundings, presence of pedestrian and vehicular traffic during the acquisition window, geometric complexity of the structure, and safety conditions. The multi-station TLS was selected where traffic conditions allowed for static occupation of multiple stations and where the maximum surface coverage and point density were required; SLAM mobile mapping was selected for elements characterised by continuous pedestrian and vehicular traffic and by

extended, articulated areas, where the acquisition time and robustness to anthropic disturbance prevailed as criteria. In this application, TLS was used on the reference bridge and SLAM on the other fifteen bridges and on the bank tracts (Figure 1).

Acquisition was planned so as to cover the riverbed interfaces, the bank hydraulic works (embankment and retaining walls) and the crossing structures. Portions that could not be reached because of the presence of water, of physical barriers or of unsuitable safety conditions were recorded as such and handled at the modelling stage, as described in Section 2.4. Because acquisition was limited to surfaces above the waterline, the submerged riverbed was not surveyed; the riverbed component of the condition-based maintenance objective (Objective 1) is therefore not supported by the present information base and requires the bathymetric acquisition identified in the roadmap (Section 4.7).

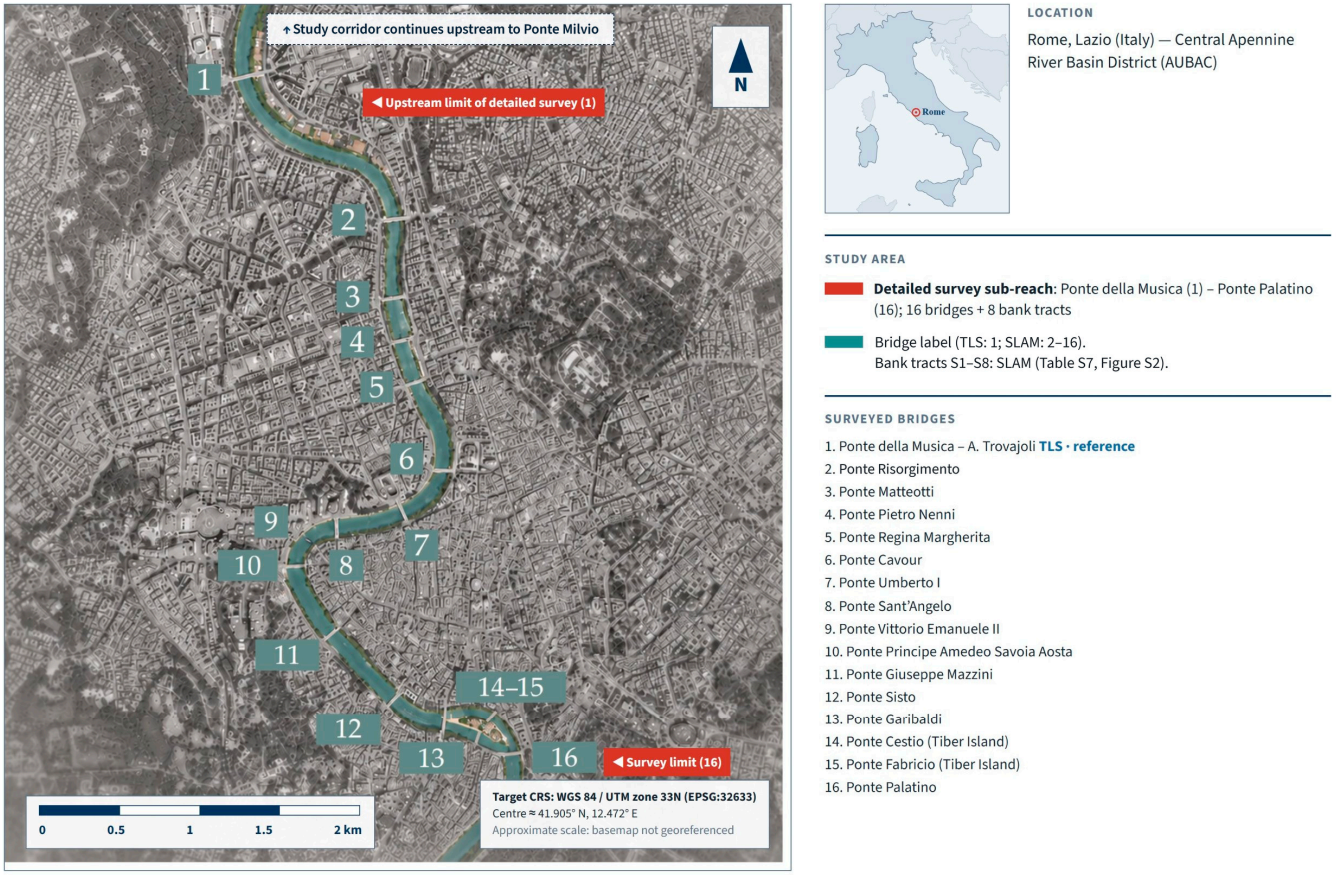


Figure 1. Study area: The approximately 8 km urban stretch of the Tiber River between Ponte Milvio and Tiber Island and the detailed-survey sub-reach between Ponte della Musica (1) and Ponte Palatino (16), with the sixteen surveyed bridges and the acquisition technique (TLS for the reference bridge, SLAM for the others). The target coordinate reference system is WGS 84/UTM zone 33N (EPSG:32633). The basemap is schematic and is not georeferenced. The displayed scale is indicative only and must not be used for metric interpretation. The eight surveyed bank tracts are identified separately in Table S7; they are not necessarily bounded by consecutive bridges. A metric location map of the bridges and bank tracts is provided in Supplementary Figure S2. (Image layout created with the assistance of ChatGPT (GPT-5.6))

2.4. Scan-to-BIM and Information Modelling

The registered point clouds were transposed into information models through a Scan-to-BIM workflow. The elements directly detectable in the point clouds were modelled on the basis of the acquired geometry; the portions that the survey could not reach

were reconstructed parametrically according to an evidence-constrained criterion and estimated separately from the survey-derived geometry (Section 4.3); this treatment is consistent with established practice in the information modelling of historic masonry crossings [85,86].

The resulting models were semantically structured through Property Sets (Psets) and classification, and shared among the project partners following the principles of the ISO 19650 series [70]. Export was performed in the open IFC 4.3 format [71], adopted as the target schema for infrastructure assets and as the basis for subsequent integration with GIS systems and territorial management platforms. We intend for the entities to receive stable identifiers and linking keys to the hydrological–hydraulic observations of the relevant section or corridor portion, which will be introduced gradually as the monitoring component becomes operational.

Fourteen models were exported with Autodesk Revit 2024 (Autodesk, Inc., San Francisco, CA, USA) IFC exporter 24.3.30.11 (schema identifier IFC4X3); the reference bridge and Ponte Risorgimento used Revit 2027 exporter 27.2.0.39 (IFC4X3_ADD2). All sixteen used the default IfcSite–IfcBuilding–IfcBuildingStorey structure, not IfcBridge/IfcBridgePart. The Ponte della Musica reference model was checked with IfcOpenShell 0.9.0 [87] against the IFC4X3_ADD2 schema with EXPRESS-rule checking enabled: no rule violations were reported, whereas twelve schema errors concerned the inverse attribute IfcCompositeCurveSegment.UsingCurves (Table S1). The check was repeated during revision and reproduced the same twelve issues. An inverse-reference traversal found no incoming references to the segments and only their respective segment references to the twelve polylines; neither set was reachable from an element representation. This confirmed the localised reference defect, without testing the geometric accuracy or cross-platform behaviour. Because the errors remain in the file, no unqualified claim of schema conformity is made. The entity counts for all sixteen models are provided in Table S2. The reference model contains 63 IfcBuildingElementProxy objects among 1127 physical elements (5.6%); the per-model share ranges from 0% to approximately 6%. Ponte Risorgimento was re-exported after 234 cornice dentils were assigned to IfcMember, with the predefined type USERDEFINED and object type DENTIL. A lower proxy share describes the mapping specificity, not semantic correctness; the appropriateness of these assignments requires element-level review. Bridge-specific spatial structure and exchange tests remain outstanding. The project repository must also be distinguished from the operational CDE proposed in Figure 2. An additional check of the final Ponte Risorgimento export with IfcOpenShell 0.9.0, including EXPRESS rules, reported no issues (validation summary and separate logs in the Supplementary Materials). Its 298 physical elements, excluding two IfcOpeningElement instances, include one proxy (0.34%) and the 234 dentils described above. The two file checks do not establish geometric accuracy, semantic correctness or cross-platform interoperability. The accompanying IFC_file_manifest.csv identifies all sixteen exports by filename, reported size, SHA-256, schema and exporter, alongside the physical element and proxy counts.

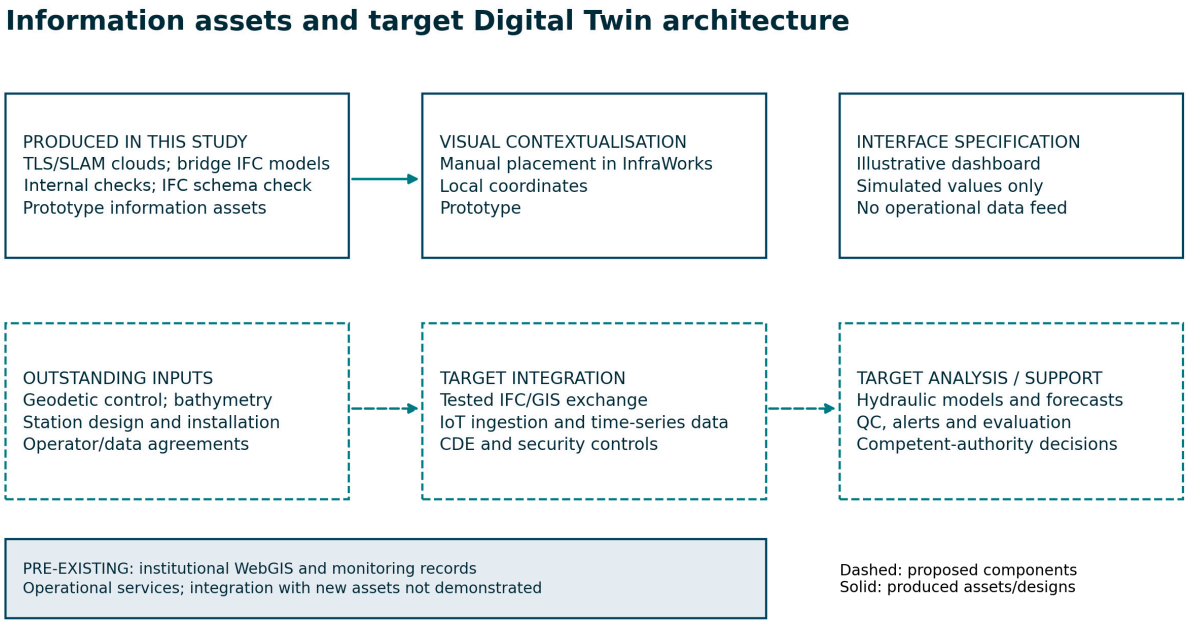


Figure 2. Information assets and target Digital Twin architecture. Solid boxes denote produced assets or interface specifications; dashed boxes denote outstanding components. Institutional systems are pre-existing. No live feed to the illustrative dashboard is implied. Institutional actions remain subject to the responsibilities of the competent authorities (Section 4.7).

A longitudinal vertical section was extracted from the Ponte Risorgimento IFC to relate a geometric parameter to its observational basis. The arch was identified by its model name and geometry, although it was exported as IfcRoof. The IfcOpenShell 0.9.0.post1 applied element placements and generated a mesh with a 1 mm mesher deflection setting. The section plane followed the long axis through the centre of the arch's oriented horizontal bounding rectangle. The lower section boundary defined the modelled intrados; the horizontal span and maximum rise above the chord joining its springings were calculated. The modelling team confirmed the springings and qualitatively identified the surveyed ends and reconstructed crown. Figure S4, Table S8 and the accompanying script document the procedure; the mesher setting is not a survey-accuracy estimate.

2.5. BIM-GIS Integration and Geospatial Contextualisation

Geospatial contextualisation was performed by importing the IFC 4.3 models, together with the bank survey, into Autodesk InfraWorks 2026 (Autodesk, Inc., San Francisco, CA, USA), used at this application stage as a geospatial contextualisation and integrated visualisation environment for the corridor geometry and its territorial context. The model thus prepared constitutes the reference geometric input for future hydraulic simulations, which remain the responsibility of dedicated hydraulic modelling tools not implemented in the case study; the data flow therefore covers the geometric and contextual preparation up to, but not including, the execution of simulations.

The future hydraulic modelling component will require a defined set of additional inputs beyond the geometry produced here. The first is a continuous hydraulic terrain model combining the terrestrial point clouds with a bathymetric survey of the submerged channel, referring to a vertical datum common to the survey geometry, the bathymetry and the gauge zero. The model will also require roughness (Manning) coefficients for the bed, banks and floodplain; upstream and downstream boundary conditions together with the corresponding initial conditions; discharge or stage hydrographs for the design and

validation events, drawn where possible from the historical gauge record and the PGRA scenarios; and independent water-level or high-water-mark data for calibration and validation. Depending on the decision purpose, the corridor may be represented with a one-dimensional model for long-reach steady and unsteady profiles; a two-dimensional model where the floodplain and quay inundation patterns are of interest; or, locally, a three-dimensional model around individual piers. Established codes include HEC-RAS [88] for one- and two-dimensional simulations; TELEMAC-2D [89] or MIKE 21 [90] for two-dimensional simulations; and computational fluid dynamics codes, such as OpenFOAM [91], for local three-dimensional analyses. The Scan-to-BIM geometry is intended to feed into these tools rather than to replace them, and the bridge models will contribute pier, abutment, deck-soffit and opening geometry as flow obstructions rather than full structural detail.

The submerged riverbed was not surveyed in this study (Section 2.3) and is therefore the first data requirement of the hydraulic component planned for future work. It could be acquired with a boat-mounted single- or multibeam echosounder, supplemented where appropriate by moving-boat ADCP surveys, which can also support discharge measurement; airborne bathymetric LiDAR, an alternative whose penetration depends on water clarity and decreases in turbid water; and existing surveyed cross-sections, where available, could provide an initial and coarser description. The bathymetric data could then be merged with the terrestrial point clouds in a common horizontal and vertical reference, using the overlap at the waterline and at the bank toes, to produce the continuous hydraulic terrain model. The available dataset does not include the surveyed bathymetry, a vertical reference shared by the bridge geometry, bathymetry and gauge zero, or documented hydraulic boundary conditions for a case-specific comparison. Local coordinates alone would not prevent an illustrative calculation, but a calculation based on assumed missing inputs would not establish the hydraulic benefit of the acquired geometry for this reach. A comparison between the simplified and survey-derived bridge geometry is therefore deferred until these inputs are available (Section 6).

Definitive georeferencing in the UTM 33N system (EPSG:32633) and federation with AUBAC's Territorial Information System and WebGIS environment were defined as requirements of the architecture and were prepared, but not completed, within the period covered by this study; their status is reported in Sections 4.4 and 4.7.

2.6. Digital Twin Architecture and Monitoring Configuration

On the basis of the objectives adopted for the corridor and of the information requirements identified through the reference methodology, an architecture for the Digital Twin of the river stretch was defined; organised into an input stage, an integration stage and a visualisation–analysis stage; and a conceptual configuration of the hydro-pluviometric monitoring network for the reference stretch was prepared. The architecture and the monitoring configuration are the design outputs of the case study: with the exception of the components explicitly reported as implemented in Section 4.7, they describe a target state still to be implemented. The architecture is presented in Section 4.1 and the monitoring configuration in Section 4.5.

3. Case Study: The Urban Stretch of the Tiber River in Rome

3.1. Case Study Context and Rationale

The case study concerns the urban stretch of the Tiber for a length of approximately 8 km between Ponte Milvio and the Tiber Island; within this stretch, the detailed survey covered the sixteen bridges and the banks between Ponte della Musica "Armando

Trovajoli" and Ponte Palatino, corresponding to the sub-stretch subject to detailed digital documentation within the present study (Figure 1).

The stretch crosses the historic heart of Rome, where the co-evolution of the city and the river is documented by over two millennia of socio-hydrological history [64], and where hydraulic risk, although mitigated by the nineteenth-century embankment walls, remains the subject of planning and study [65,66,68]. Several features make this stretch a relevant case for an application study. The corridor is a continuous linear system in which the engineered elements and natural processes are inseparable: the bridges and banks are simultaneously heritage and infrastructural assets and boundary elements of the flow section, so that their geometry conditions hydraulic behaviour and their conservation depends on it. The stretch concentrates, within a few kilometres, a high density of crossings of different ages, materials and structural typologies; a densely used public space along the quays; and a floodplain that includes the historic centre of a capital city. Its management responsibilities are distributed among several authorities, and hydraulic risk planning for the stretch is framed by the Floods Directive [67] and by the Flood Risk Management Plan of the Central Apennine District [68], which fall within AUBAC's institutional mission.

The information base available at the outset was correspondingly fragmented. Territorial, hydrological and hazard information is available through the authority's planning instruments and WebGIS environment, including PGRA hazard delineations, hydrological themes and hydraulic works inventories [68,82,83]; hydrological and hydraulic knowledge of the stretch is supported by a well-established tradition of studies on extreme floods and inundation probability in Rome [65,66]. What is missing is an accurate, homogeneous and open-format geometric description of the corridor's physical boundary, that is, of the crossings and of the bank hydraulic works, together with an information structure capable of associating that geometry with hydrological–hydraulic observations. Filling this gap is the primary purpose of the application described here.

3.2. Case Study Objectives and Digital Twin Scope

Following the reference methodology [74], the case study is characterised as an intervention of regeneration of the existing built environment, since the project intervenes on existing assets, optimising their management without changing their use, and as within the operation phase, being aimed at improving the management and monitoring of the river stretch, including the sixteen bridges and the adjoining banks.

Three management objectives are adopted for the corridor, in agreement with the competent authority and consistent with its statutory remit: condition-based maintenance of riverbed and bank hydraulic works, understood here as predictive maintenance based on repeated geometric and hydromorphological observations; hydraulic condition monitoring in support of the resilience of critical infrastructure and of the territory; and hydro-pluviometric monitoring in support of flood risk and water governance decision processes. Table 2 summarises this characterisation and its operational meaning for the case study.

Within the family management of the natural and built environment defined by the reference methodology, the first objective corresponds specifically to the resilience-of-the-built-environment sub-category, as it concerns the conservation and condition-based upkeep of the riverbed and bank hydraulic works that bound the flow section, while the second and third objectives correspond to hazard condition monitoring and to hydro-pluviometric monitoring in support of water governance, respectively. At the present stage, Objective 1 is therefore supported for the bank hydraulic works and the crossings, which were surveyed, but not for the riverbed itself, whose characterisation requires the bathymetric acquisition to be added to the roadmap (Section 4.7).

Table 2. Characterisation of the case study and operational meaning of each descriptor.

Descriptor	Case Study Selection	Operational Meaning Within the Case Study
Intervention category	Regeneration of the existing built environment	Frames the case study within the existing urban river corridor, including its interfaces with bridges and riverbanks.
Process phase	Operation	Refers to the management phase, supporting observation, monitoring and decision-making during the operational stage.
Objective 1	Management of the natural and built environment: condition-based maintenance of riverbed and bank hydraulic works	Intended to support the planning of interventions on the riverbed and hydraulic structures through the periodic comparison of surveys, models and historical data.
Objective 2	Management of the natural and built environment: hydraulic condition monitoring	Intended to support the monitoring of hydrological and hydraulic conditions, as well as of the interferences affecting flow dynamics and the resilience of the river corridor.
Objective 3	Management of the natural and built environment: hydro-pluviometric monitoring	Intended to support the observation chains and modelling components used for flood risk and water governance decision processes.

The scope of the Digital Twin follows directly from this characterisation. The critical infrastructure elements are represented as being exposed to, or interfering with, river dynamics, and as beneficiaries of the system's forecasting capability; the quantities monitored are hydrological, hydraulic and environmental; and the structural response of the bridges lies outside this scope. Structural health monitoring and traffic load control constitute adjacent Digital Twin application domains, widely addressed in the literature [51,78–80,92,93], which do not fall within the application scope documented here. This scoping has a cost, discussed in Section 5: the geometric details collected for the bridges (intrados and extrados) are not exploited for structural diagnostic purposes within this study.

Although some information requirements are shared among the three objectives, their operational differentiation emerges along three dimensions, namely the time horizon, decision purpose and prevailing data type, as summarised in Table 3.

Table 3. Relationship between the objectives adopted for the case study, their decision-making function and the prevailing data types.

Objective	Temporal Horizon	Decision-Making Purpose	Predominant Data Type
Condition-based maintenance of riverbed and bank hydraulic works	Periodic (cyclic comparison of surveys)	Planning of routine management interventions for river components, including the riverbed and bank hydraulic structures.	Survey-derived geometric data, point clouds and Scan-to-BIM models
Hydraulic condition monitoring	Continuous/real time	Identification of conditions affecting flow dynamics and the exposure of the river corridor, without structural assessment of hydraulic crossings.	Hydrological–hydraulic, geospatial and geometric data related to cross-sections and physical interferences
Hydro-pluviometric monitoring in support of water governance	Continuous/real time	Support for flood risk and water governance decision processes in accordance with the Water Framework Directive, the Floods Directive and district planning instruments.	Hydro-pluviometric data from monitoring networks

3.3. Information Requirements Adopted for the Case Study

Based on the objectives identified for the case study and following the reference methodology, the information requirements of the platform are specified for each objective. The complete specifications, with one variable per row, physical units distinguished from data formats, and the availability of each data item in this study, are given in the Supplementary Materials (Tables S3–S5). Across the three objectives, the requirements fall into three availability classes. The geometry of the crossings and the point clouds of the banks and crossings above the waterline are produced or acquired in this study. The terrain and geospatial datasets, PGRA hazard data, historical meteorological records and maintenance archives exist in the competent authority's systems or in existing networks. Bathymetric and hydromorphological data and scour and sediment measurements are not acquired in this study. Existing hydrometric records are not analysed here; station-specific water level, discharge and flow velocity observations for the proposed monitoring configuration remain future inputs (Section 4.7). These specifications, like the indicators and capabilities listed in Tables 4–7, are requirements derived from the reference framework, specialised for the river corridor; the Status column in Tables 4–6 indicates whether each indicator is proposed for this case or reinterpreted from the framework, and Table 7 reports the maturity level of each capability area.

Table 4. Performance indicators adopted for the condition-based maintenance objective.

KPI	Unit of Measurement	Status
Share of condition-triggered interventions	%	Proposed
Maintenance warning lead time	days	Proposed
Downtime reduction (unavailability of the monitoring and alert chain)	%	From framework, reinterpreted
Digital vs. physical inspection time	person-h/km	Proposed
Maintenance ROI (net benefit/cost)	%	From framework, reinterpreted

Table 5. Performance indicators adopted for the hydraulic-condition-monitoring and corridor-resilience objective.

KPI	Unit of Measurement	Status
Hydraulic advance-warning lead time	h	Proposed
Response time to water events	min	Proposed
Availability of the monitoring and alert chain	%	Proposed
Alert precision and recall (%)	%	Proposed
Scenario-update latency	s, min	Proposed
Time to activate competent authority's protocols	min	Proposed

Table 6. Performance indicators adopted for the hydro-pluviometric-monitoring objective.

KPI	Unit of Measurement	Status
Flood advance-warning lead time	h	Proposed
Accuracy of water-level forecasts (RMSE; NSE)	cm (RMSE); dimensionless (NSE)	Proposed
Alert precision and recall (%)	%	Proposed
Model–observation scenario-update latency	s, min	Proposed
Coverage of the monitoring network along the stretch	%; stations/km	Proposed
Reduction in competent authority's protocol activation time	%	Proposed

Table 7. Capabilities required for the case study, technologies adopted or planned for the Tiber application, and maturity level.

Capability Area	Capabilities Required for the Case Study	Technologies Adopted	Maturity Level
Data Services	Data acquisition and ingestion; data transmission; real-time processing; data aggregation; historical time-series storage; storage and archiving	TLS multi-station acquisition; SLAM mobile mapping (Emesent Hovermap ST-X; Emesent Pty Ltd., Brisbane, Australia); UAV imagery (DJI Matrice 350 RTK; SZ DJI Technology Co., Ltd., Shenzhen, China); IoT hydro-pluviometric sensing (radar and ultrasonic stage gauges, rain gauges, ADCP current meters, scour sensors, piezometers); IoT transmission protocols; cloud/edge services; time-series storage; CDE for information deliverables	Geometric acquisition: prototype with internal checks; sensing, transmission and time-series storage: conceptual
Integration	Engineering systems integration (BIM-GIS); OT/IoT systems integration; API services	IFC 4.3 exchange; Autodesk InfraWorks contextualisation; Esri ArcGIS Enterprise (version 11.5.0) WebGIS environment of the authority; UTM 33N georeferencing and federation with the Territorial Information System; IoT gateway and API services	BIM-GIS contextualisation: prototype; georeferencing, federation, OT/IoT integration and API services: conceptual
Intelligence	Alerts and notifications; data analysis; forecasting; machine learning; simulation	Hydrological–hydraulic modelling for flood scenario generation; anomaly detection and forecasting on hydrological time series; dynamic threshold updating; alerting chain	Conceptual: no analytical or machine learning component operational at the time of writing
User Experience	Basic visualisation; real-time monitoring; dashboards	Model and point cloud viewers; WebGIS consultation of hazard and thematic layers; illustrative dashboard specification for hydrological–hydraulic indicators	WebGIS consultation: operational (pre-existing); model visualisation: prototype; dashboard: specification (simulated values)
Management	Device management; system monitoring and alerts; event logging	Device management and platform-monitoring services; event logging for auditability and service continuity	Conceptual
Trustworthiness	Data encryption; device security; authentication; confidentiality and privacy by design; reliability	Encryption and access control; authentication protocols; privacy-by-design provisions for camera-based monitoring; redundancy of water level measurement	Conceptual: design requirements defined, subject to the governance provisions discussed in Section 4.5

For condition-based maintenance of riverbed and bank hydraulic works (Table S3), the requirements refer to the river component of the corridor, that is, the riverbed and the bank hydraulic works (embankments, retaining walls), leaving aside the structure of the bridges. The objective is to move from cyclical maintenance to programming based on the periodic comparison of geometric surveys and hydromorphological data: the Digital Twin is intended to support the early identification of bank erosion and, once bathymetric surveys are available, of riverbed sedimentation and scour, orienting interventions also as a function of low-flow hydrological windows, consistent with the literature on data-driven predictive maintenance [78,94,95].

Geometric and information models form the base of this information set; the periodic comparison between successive surveys is intended to turn inspection into a repeatable, quantifiable process for the bank hydraulic works and, once bathymetric surveys are available, for the riverbed (Section 5.3). Historical maintenance data, once processed with

machine learning algorithms not yet implemented (Section 4.7), will support the updating of intervention priorities.

For hydraulic condition monitoring (Table S4), the information set is enriched with environmental and territorial context data, consistent with the multi-hazard approach proposed in the literature [58,62,68]. Monitoring pursues the timely recognition of anomalous hydrological–hydraulic conditions, the assessment of flood scenarios and support for the activation of the competent authority's protocols.

For hydro-pluviometric monitoring in support of flood risk and water governance decisions (Table S5), the information set centres on the observation chain of the river reach, intended to assist the near-real-time model–observation comparison supporting early warning, planning and technical assessment under the Floods Directive and the district planning instruments [60,61,67,68].

3.4. Performance Indicators Adopted for the Case Study

For each objective, a set of performance indicators is proposed, using the reference framework [74] and adapting it to the river corridor requirements, with the indicator standards providing broader context [50]. The indicators are reported in Tables 4–6. They are proposed for this application and have not yet been validated against real operational data, which will become available only once the monitoring network is installed (Section 4.7).

Table S6 defines the formulas, units and computation rules. The forecast errors, alert precision/recall, lead time, availability and latency concern distinct aspects of performance. The baselines are specified separately: pre-installation practice where comparable records exist, and an explicitly declared operational reference period otherwise. The responsible data providers, validating bodies, reporting frequencies and acceptable thresholds must be agreed upon by the station operators and competent authorities before deployment; responsibility is not assigned generically to the AUBAC. Downtime refers to the observation/alert chain, and maintenance ROI requires a declared counterfactual. Remaining useful life is not adopted for the riverbed and bank works. Measurement and model uncertainty must be included in future evaluation.

For condition-based maintenance of riverbed and bank hydraulic works (Table 4), the indicators relating to intervention scheduling and to the updating of the knowledge base prevail.

For hydraulic condition monitoring (Table 5), the temporal dimension prevails, with the lead time and response speed, together with the availability of the observation chain and the reliability of alerting, also measured by alert precision and recall [61].

For hydro-pluviometric monitoring in support of water governance (Table 6), indicators of the effectiveness of the forecasting system prevail, consistent with the objectives of the Floods Directive and with the literature on early warning in urban river systems [60,61,67].

Within the PDCA cycle adopted by the reference methodology, these indicators will be fed by data collected during operation (Do), analysed against the expected targets (Check), and translated into corrective actions and improvement strategies (Act), enabling the progressive validation of the operational thresholds [81].

3.5. Capabilities and Technologies Adopted in the Application

The objectives, information requirements and indicators set out above were translated into the platform capabilities required for the case study, expressed according to the six groupings of the Capabilities Periodic Table [69], and, for each capability area, into the technologies actually adopted or planned for the Tiber application. Table 7 reports this configuration, together with the maturity level of each area, on the scale defined in Section 4.7, so that the technologies effectively deployed in the case study are distinguished from those that belong to the target architecture. The candidate technologies and solutions listed in the reference methodology but not retained for this application are not reproduced here.

The selection recorded in Table 7 was made as an application decision within the reference framework. It was based on the technical criteria described in Section 2.3 for acquisition (accessibility, traffic conditions, geometric complexity, safety, and acquisition time), on interoperability requirements for modelling and integration (open schema, alignment with the principles of the ISO 19650 series, and compatibility with the authority's existing geospatial environment), and on the institutional context for the platform and monitoring layers (continuity with the existing hydrometric network of the stretch and with the authority's information system).

4. Results

This section reports the results of the application: the Digital Twin architecture defined for the river stretch (Section 4.1), the survey products (Section 4.2), the information models (Section 4.3), the geospatial contextualisation (Section 4.4), the monitoring configuration and user-facing outputs (Section 4.5), the extension of the workflow to the whole stretch and the information assets produced (Section 4.6), and the maturity reached by each component together with the implementation roadmap (Section 4.7).

4.1. Digital Twin Architecture of the River Stretch

Within the architecture defined for the case study, bridges and banks appear as geometric components and as interfaces between the watercourse and the urban fabric. The architecture, illustrated in Figure 2, is organised into three main stages—input, integration and visualisation–analysis—which structure the data handling from physical reality to information useful for decision-making [13,15]. Figure 2 distinguishes the assets produced in this study (solid boxes: surveys, point clouds, Scan-to-BIM/IFC models, visual contextualisation in InfraWorks and the dashboard specification) from the target components still to be implemented (dashed boxes), including the planned monitoring stations (Table 8), and from the pre-existing institutional systems (shaded box); the maturity level of each component is reported in Section 4.7.

Input stage (physical-entity data): This stage comprises building the geometric informational replica, made of TLS/SLAM point clouds and of the survey-based information model exported in IFC 4.3, and, in the target configuration, acquiring dynamic flows from the planned hydro-pluviometric network of the section (stage gauges, rain gauges, ADCP current meters, scour sensors and piezometers), together with meteorological and territorial data and with acquisition, streaming, transformation (ETL) and OT/IoT security services [7,9]. Scan-to-BIM modelling, reported in Section 4.3, falls within this stage and constitutes the twin's foundational level.

Integration stage (data connection): In the target configuration, the data would flow into the DT's cloud platform, where the information model, georeferenced in the UTM 33N system, would be federated with the AUBAC's Territorial Information System through BIM-GIS integration [71,72]; the REST APIs, the MQTT/LoRaWAN protocols and

a CDE organised according to the principles of the ISO 19650 series would support interoperability and traceability; time-series databases would ensure historicisation; and encryption and event logging would support the system's trustworthiness [37,70].

Visualisation–analysis stage (virtual-entity data): In the target configuration, the Digital Shadow would evolve into a predictive DT through ML algorithms for anomaly detection on hydrological time series, forecasting of levels and discharges, and updating of operational thresholds [16,31]; these machine learning components are proposed as part of the target architecture and remain subject to future implementation and validation, none being operational within this study. Flood early warnings, continuous model–observation comparisons, indicator dashboards and what-if simulations are intended to support risk management and civil protection decisions, closing the PDCA continuous-improvement cycle [81,96].

Table 8. Planned monitoring stations for the reference stretch (station types and rationale as in the configuration described above; quantities and target sections to be finalised in the operational phase).

Station Type	Target Location	Purpose/Rationale	Relation to Existing Network
Radar water-level gauge	Beneath bridge decks	Primary water-level (stage) measurement	Continues the existing historical hydrometric network
Ultrasonic water-level sensor	On embankment walls	Redundant water-level measurement	Redundancy of the primary gauge
ADCP current profiler	Riverbed at control sections	Index velocity; discharge through a calibrated index-velocity rating	New; feasibility subject to debris, sediment and flood conditions
Scour sensor	Around piers and foundations	Local scour evolution	New
Piezometer	Within embankment walls	Pore water pressure (seepage inferred)	New
Rainfall/meteorological station	Elevated locations	Catchment rainfall and weather	Continues the existing meteorological network
Camera + computer vision	Along the quays	Water level, floating debris, vessel traffic	Subject to privacy-by-design and a data-protection impact assessment

4.2. Geometric Survey and Point Clouds

On the reference element, Ponte della Musica "Armando Trovajoli", the geometric complexity of the structure and the favourable condition of the absence of vehicular traffic, with very limited pedestrian traffic, guided the choice towards the terrestrial laser scanner with multi-station acquisitions, so as to ensure complete coverage of the accessible surfaces and maximum data density [97]. For the other fifteen bridges, characterised by pedestrian and vehicular traffic and by large, complex areas, SLAM mobile mapping with the Emesent Hovermap ST-X system, used backpack-mounted or hand-carried, was selected: during the trial days it appeared less affected by anthropic disturbance and required shorter acquisition times. The same selection logic was extended to the banks of the stretch, which were likewise surveyed using SLAM mobile mapping.

These observations were field experiences rather than comparative scientific evidence: the time, density, RMSE, occlusions and repeatability were not recorded in a comparable way during the trial days, and a controlled quantitative comparison on an overlapping test area is left to future work (Section 6).

The survey campaign produced point clouds totalling approximately 3.2 billion points (3218 million) across the sixteen bridges and the adjoining banks (Section 4.6). On the reference element, the multi-station TLS from 22 scan positions returned about 500 million points, with a mean density of 80,000 points/m² on the surveyed surfaces and an overall acquisition time of approximately 2 h. On the remaining fifteen crossings and on the banks, the SLAM mobile mapping returned on the order of 7–30 million points per bridge and 80–660 million points per bank tract, with mean densities of about 2000–4000 points/m² on the bridges and 6000–10,000 points/m² on the banks, corresponding to a mean Euclidean distance between neighbouring points of 10–20 mm. The acquisition times were about 15–35 min per bridge and 30–90 min per bank tract (about 0.7–1.6 km long, mostly 1.3–1.6 km), with each tract being walked back and forth at an effective rate of about 2–2.5 km/h to ensure point overlap and loop closure; these slower trajectories, rather than a difference in instrument performance, explain the higher densities recorded on the banks. Overall, the choice of technique traded density against acquisition time: the TLS on the reference bridge produced densities about 20–40 times higher than SLAM did on the other bridges, but required a roughly 3–8 times longer acquisition, whereas SLAM made it practicable to cover all the crossings and the bank tracts of the sub-reach. The processing requirements and the quality indicators available also differed between the two techniques, as described below.

The terrestrial laser scanner used on the reference bridge was a Leica BLK360 G2 (Leica Geosystems AG, Heerbrugg, Switzerland), with a nominal 3D point accuracy of about 4 mm at 10 m (7 mm at 20 m). The 22 scan positions were registered by cloud-to-cloud alignment, with a reported cloud-to-cloud bundle error of 8 mm and an overall registration strength of 78%, a software index of the geometric constraint of the registration network rather than an accuracy percentage. The SLAM cloud of the adjoining bank at Ponte della Musica was then co-registered to the TLS cloud by point-pair alignment in CloudCompare version 2.13.2 [98], with an RMS residual of about 32 mm on the selected pairs. These values describe the internal registration and alignment agreement of the points used for the fitting: no check points or surfaces excluded from the alignment were available, so they do not establish independent accuracy, nor accuracy across all surveyed assets, and an independent check on the representative elements remains future work. The point densities are reported as points per unit of effectively surveyed surface (not bounding area), computed on the filtered point cloud before subsampling. Because a single mean density does not reveal local gaps, coverage completeness is addressed only qualitatively: the critical areas (bridge soffits, piers and retaining walls) were specifically targeted during acquisition, and the model portions reconstructed where measurements were missing are quantified in Section 4.3. Those model-surface shares are not a point cloud completeness metric; no per-element coverage metric is available. The manufacturer specifications report a relative SLAM drift of ±0.03% for the Hovermap ST [99], whereas no corresponding value is published for the ST-X used here; as an order of magnitude, 0.03% of a 1.6 km tract would correspond to about 0.5 m if uncorrected, and twice as much over the back-and-forth trajectory, so a nominal value cannot replace a drift measured in the campaign. The drift was mitigated by acquiring each tract along closed or overlapping trajectories and by aligning every tract to the surveys of the bridges at its endpoints, which provide rigid structures common to both datasets; georeferencing with ground control points could not be applied for instrument availability reasons. After this alignment, the mean discrepancy at the tract endpoints was approximately 15 mm. Because it was computed on the structures used for the alignment, it is treated as an internal fit indicator, not a validated drift estimate; the deviations along the intermediate parts were not checked.

RGB colourisation of the SLAM point clouds was derived from GoPro MAX video (GoPro, Inc., San Mateo, CA, USA) acquired simultaneously with the scan, while the TLS

cloud was coloured using its integrated camera. Full processing, including colourisation in Emesent Aura 1.10.2 (Emesent Pty Ltd., Brisbane, Australia), required 3–4 h per bridge and about 6 h per bank tract on a workstation with 32 GB RAM, an Intel Core i9 CPU at 2.00 GHz and an NVIDIA GeForce RTX 4080 16 GB GPU, for a cumulative field time of approximately 17.5 h and a cumulative processing time of approximately 104 h (96–112 h). The resulting files range from 0.5 to 1 GB per bridge and from 10 to 13 GB per bank tract in .las format; the latter was reduced to 2–3 GB in the subsampled version prepared to contain the file size for downstream use.

Figure 3 shows the point cloud of the Ponte della Musica "Armando Trovajoli" and the adjoining banks prior to its transposition into the Scan-to-BIM workflow, distinguishing the TLS, SLAM and overlapping coverage; the occluded areas and the unsurveyed submerged riverbed; together with the dataset quality indicators reported in this section.

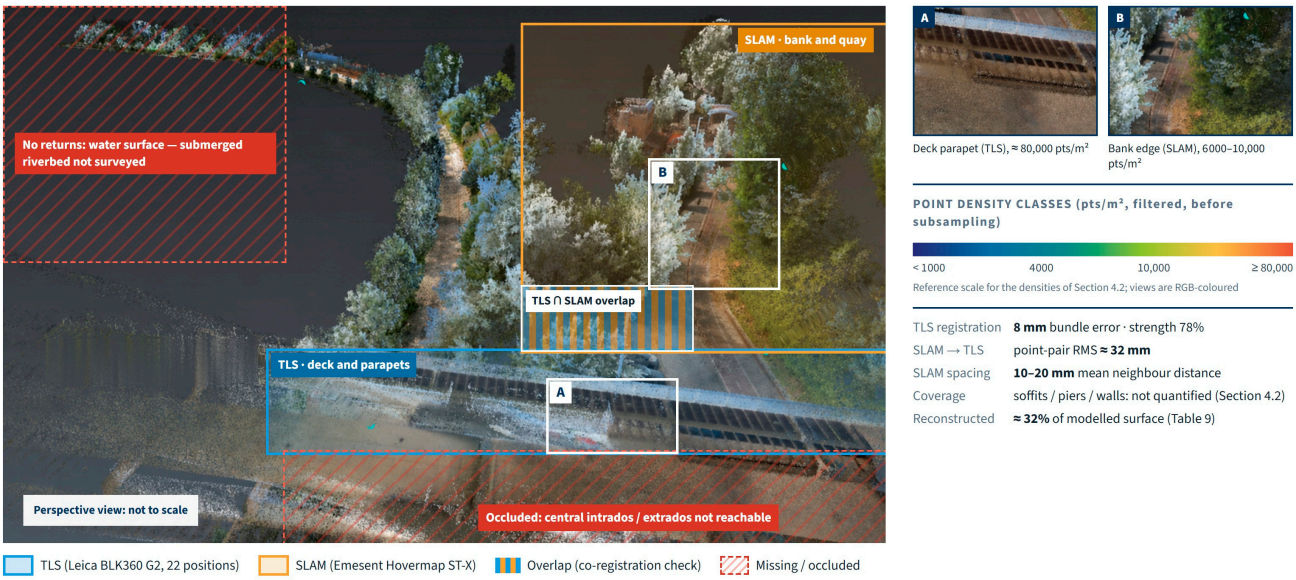


Figure 3. Point cloud of the Ponte della Musica "Armando Trovajoli" and the adjoining banks from multi-station terrestrial laser scanning and SLAM mobile mapping: coverage by technique and overlap, occluded and submerged (not surveyed) areas, point density scale and dataset quality indicators. (**A**) Enlarged view of the deck parapet (TLS), ≈80,000 pts/m²; (**B**) enlarged view of the bank edge (SLAM), 6000–10,000 pts/m².

4.3. Information Models in IFC 4.3

The point clouds were transposed into information models following the Scan-to-BIM workflow and the semantic structuring described in Section 2.4.

The Scan-to-BIM models were specified at a target Level of Development of LOD 300, taken as broadly corresponding to LOD C of UNI 11337-4 [100], and at a Level of Information Need, in accordance with ISO 7817-1 [101] (adopted as UNI EN ISO 7817-1 [102], which supersedes UNI EN 17412-1 [103]). The Level of Information Need was defined for this project as: G2 "defined" for the geometric component, that is, the geometry defined in the dimension, position and functional envelope without constructional micro-detail; A1 for the alphanumeric component (identification code, prevailing material, state of conservation, year of construction, date of last inspection, and link to documentation); and D0–D1 for the documentary component. These levels express the information requirements of the models, not their verified fidelity to the as-built condition: Section 4.2 reports the internal registration statistics, which do not establish independent accuracy for individual surveyed or reconstructed model surfaces. In the exported files, the elements were

mapped mainly to IfcWall, IfcSlab, IfcBeam, IfcColumn, IfcMember, IfcPlate, IfcRailing, IfcRoof and IfcLightFixture, with IfcGeographicElement, IfcFurniture and IfcCurtainWall in a few models, and to IfcBuildingElementProxy where no dedicated class was assigned. In the reference model, the 1127 physical elements comprised IfcBeam (884), IfcSlab (81), IfcBuildingElementProxy (63), IfcColumn (48), IfcRailing (16), IfcMember (eight), IfcWall (eight), IfcLightFixture (eight), IfcStair and IfcStairFlight (four each), IfcFurniture (two) and IfcPlate (one) (Table S2). The models were authored in Revit, with the exporter versions reported in Section 2.4, organised by discipline and, at the present stage, held in internal coordinates pending georeferencing to UTM 33N (EPSG:32633).

The sixteen bridges were modelled individually, whereas the adjoining banks remained point cloud assets. The reconstructed shares in Table 9 are approximate modeller estimates obtained by overlaying the point cloud on the BIM model, in which the missing portions were reconstructed parametrically with the support of the photographic survey. For each bridge, the proportion of each main component's above-water surface not covered by survey observations was estimated from the point cloud–model overlay. These component-level estimates were combined using approximate weights reflecting each component's share of the modelled above-water surface, and the resulting bridge-level percentage was rounded. They describe the estimated share of modelled above-water surface reconstructed where survey observations were missing; the submerged bases and foundations were excluded. No per-bridge record of total and reconstructed surface areas was available, so these values are not independently reproducible area measurements. Their unweighted mean is approximately 17%; the complementary 83% describes the estimated survey-derived share under the same classification and is not point cloud completeness. The Boolean property "Geometria/Spessore Ipotizzato" (assumed geometry/thickness) denotes the assumed shape or thickness in selected project families; it is not a complete provenance classification. It was not applied to system families, such as basic walls, floors and roofs, and was introduced after the Musica reference model. Its absence therefore does not indicate survey-derived geometry. The checked exports reflect these modelling conventions rather than an export loss. The property cannot reproduce the surface-based estimates in Table 9, since an element may also be only partly reconstructed. The estimated reconstructed shares range from 0% to approximately 50%; the reference bridge has an estimated share of 32%, including the inaccessible parts of the deck extrados and central intrados. These estimates describe model provenance, not geometric accuracy.

The differences in estimated reconstructed shares reflect acquisition constraints encountered at the individual bridges. At Ponte Pietro Nenni, where the estimated reconstructed share reaches approximately 50% (Table 9), construction works obstructed survey acquisition. At the other bridges with higher reconstructed shares, the survey gaps involved the intrados and were associated with restricted access to the quays or lower parts of the structures. These conditions help explain the variation in the bridge-level estimates, although Table 9 does not quantify the contribution of individual components to the reconstructed share.

Table 9. Survey-derived assets for 16 bridges and 8 bank tracts: acquisition, dataset size, processing, LOD and estimated reconstructed above-water surface share (submerged bases/foundations excluded). Shares are approximate modeller estimates (Section 4.3). Available local quality indicators are reported in Section 4.2. In this table, "n/a" indicates a value that is not applicable.

Element	Technique	Scan Pos./Trajectory	Points (Millions)	Mean Density (pts/m²)	Acquisition/Processing Time	LOD	Reconstructed (%)
Ponte della Musica "A. Trovajoli" (reference)	TLS	22	500	80,000	2 h/3–4 h	LOD 200/300	≈32
Ponte Risorgimento	SLAM	closed loop	9	2500	~20 min/3–4 h	LOD 300	≈15
Ponte Matteotti	SLAM	closed loop	14	3000	~20 min/3–4 h	LOD 200/300	≈35
Ponte Pietro Nenni	SLAM	closed loop	7	2000	~15 min/3–4 h	LOD 200/300	≈50
Ponte Regina Margherita	SLAM	closed loop	15	2500	~20 min/3–4 h	LOD 300	≈3
Ponte Cavour	SLAM	closed loop	13	2500	~25 min/3–4 h	LOD 300	≈15
Ponte Umberto I	SLAM	closed loop	14	3000	~20 min/3–4 h	LOD 300	≈5
Ponte Sant'Angelo	SLAM	closed loop	15	2500	~35 min/3–4 h	LOD 300	≈30
Ponte Vittorio Emanuele II	SLAM	closed loop	12	2000	~25 min/3–4 h	LOD 300	≈10
Ponte Principe Amedeo Savoia Aosta	SLAM	closed loop	12	2000	~25 min/3–4 h	LOD 300	≈10
Ponte Giuseppe Mazzini	SLAM	closed loop	20	4000	~20 min/3–4 h	LOD 300	≈3
Ponte Sisto	SLAM	closed loop	11	2500	~20 min/3–4 h	LOD 300	≈3
Ponte Garibaldi	SLAM	closed loop	30	4000	~25 min/3–4 h	LOD 300	0
Ponte Cestio (Isola Tiberina)	SLAM	closed loop	11	3500	~20 min/3–4 h	LOD 300	0
Ponte Fabricio (Isola Tiberina)	SLAM	closed loop	10	2500	~35 min/3–4 h	LOD 300	≈20
Ponte Palatino	SLAM	closed loop	15	2500	~30 min/3–4 h	LOD 200/300	≈40
S1—Banks—P. della Musica–P. Risorgimento (left)	SLAM	back and forth (~1.3 km)	660	8000	~60 min/~6 h	n/a (not modelled)	n/a
S2—Banks—P. Risorgimento–P. Cavour (left)	SLAM	back and forth (~1.6 km)	390	10,000	~80 min/~6 h	n/a (not modelled)	n/a
S3—Banks—P. Cavour–P. G. Mazzini (left)	SLAM	back and forth (~1.6 km)	80	7000	~90 min/~6 h	n/a (not modelled)	n/a
S4—Banks—P. G. Mazzini–P. Palatino (left)	SLAM	back and forth (~1.4 km)	330	10,000	~70 min/~6 h	n/a (not modelled)	n/a
S5—Banks—P. Risorgimento–P. Cavour (right)	SLAM	back and forth (~1.6 km)	350	10,000	~80 min/~6 h	n/a (not modelled)	n/a

S6—Banks—P. Cavour–P. G. Mazzini (right)	SLAM	back and forth (~1.6 km)	100	6000	~80 min/~6 h	n/a (not modelled)	n/a
S7—Banks—P. G. Mazzini–P. Palatino (right)	SLAM	back and forth (~1.4 km)	400	10,000	~80 min/~6 h	n/a (not modelled)	n/a
S8—Banks—Isola Tiberina	SLAM	back and forth (~0.7 km, island)	200	10,000	~30 min/~6 h	n/a (not modelled)	n/a
Subtotal—16 bridges	**TLS + SLAM**	**—**	**≈708**	**≈2730 (SLAM, mean of 15); 80,000 (TLS)**	**≈8 h field/≈56 h proc.**	**LOD 300 (LOD 200/300 for 4 bridges)**	**≈17 (mean)**
Subtotal—8 bank tracts	**SLAM**	**—**	**≈2510**	**≈8875 (mean)**	**≈9.5 h field/≈48 h proc.**	**n/a (not modelled)**	**n/a**
Total/mean over the stretch (16 bridges + 8 bank tracts)	**TLS + SLAM**	**—**	**≈3218 total**	**SLAM ≈ 4870 (mean of 23 elements); TLS 80,000 (ref)**	**≈17.5 h field/≈104 h proc.**	**LOD 300 (LOD 200/300 for 4 bridges)**	**≈17 (mean, 16 bridges)**

LOD 300 is taken as broadly corresponding to LOD C of UNI 11337-4. LOD and the Level of Information Need (LOIN, ISO 7817-1)—G2 (geometric), A1 (alphanumeric), and D0–D1 (documentary)—denote information requirements, not verified accuracy, and refer to survey-derived geometry. LOD 200/300 denotes bridges whose reconstructed share exceeds 30%, this being a project reporting convention rather than independently verified accuracy (Section 4.3). The bank densities exceed the bridge densities, although the same SLAM instrument was used, because each bank tract was walked back and forth at about 2–2.5 km/h (Section 4.2).

Here, "evidence-constrained" reconstruction means that, where survey data were missing, the geometry was reconstructed to the simplest envelope consistent with the available evidence, without adding detail not supported by it, using the photographic survey, geometric assumptions and, where available, design documentation made available by the competent authorities. At Ponte Risorgimento, the modelling team reconstructed the uncovered above-water portions of the arch intrados by parametrically continuing the arch profile observed in the point cloud at its ends into the central gap. The source for this inference was the same survey cloud, rather than an independent measurement of the missing surface. Supplementary Figure S3 shows the point cloud/model overlay from the river and from below, with a legend identifying the surveyed point cloud and the reconstructed model surfaces. This example documents the source, gap and inferred geometry but does not establish the as-built accuracy of the reconstructed portions. For the document-derived portions, the as-designed condition may differ from the present asset because of subsequent repairs or modifications; the photograph- and assumption-based portions also remain unverified against independent measurements. Such a reconstruction is not necessarily conservative in a hydraulic sense, since a simplified envelope may enlarge or reduce a flow opening; the sensitivity of hydraulically relevant quantities to the reconstructed portions remains to be assessed. The stated LOD 300 and the G2/A1/D0–D1 Level of Information Need specify the intended representation of survey-derived geometry; the reconstructed portions represent an inferred overall dimension, position and functional envelope, without independent verification against survey measurements, and bridges with a reconstructed share above 30% are labelled LOD 200/300 as a project reporting convention, not a standard-defined 30% threshold or an accuracy class (Section 4.6). The same target level was adopted for all crossings, from the ancient masonry bridges to the contemporary steel arch of Ponte della Musica, because the models describe the crossings as hydraulic interfaces and managed assets rather than as structural or heritage records (Section 3.2): constructional and decorative micro-details lie outside the G2 requirement whatever the period of construction, and what varies between crossings is the share of reconstructed geometry, declared per bridge. The dates and approval status of the design documents used for other reconstructed portions are not reported.

The extracted Risorgimento section has a modelled horizontal span of 100.28 m between the confirmed springings and a maximum intrados rise of 9.58 m above the chord joining them (Figure S4; Table S8). The arch is represented as a roof object with a constant nominal thickness of 0.30 m. Its lower face follows the point cloud near the springings, whereas the central crown is reconstructed by continuing the observed profile. The maximum rise occurs within this reconstructed region. The value is therefore reproducibly extractable from the IFC, but its observational support is incomplete. The exact transition locations between surveyed and reconstructed portions were not recorded. This example identifies the crown geometry as a specific verification target before hydraulic use; it does not quantify the reconstruction error or hydraulic effects.

4.4. Geospatial Contextualisation and Preparation for BIM-GIS Federation

The resulting models, together with the bank survey, were imported into Autodesk InfraWorks (Figure 4), which allowed for their geospatial contextualisation and their preparation for hydraulic and monitoring analyses. The models, held in internal coordinates, were positioned in the InfraWorks scene by manual placement for visual contextualisation. No planimetric registration to UTM 33N (EPSG:32633) was performed, and no common vertical datum was established for the geometry, future bathymetry and gauge zero; the positions and elevations in Figure 4 are therefore indicative. The context layers loaded in InfraWorks (March 2026) were an orthophoto from Bing Maps (Microsoft Corporation) accessed through a WMS connection, a 1 m × 1 m raster digital terrain model in

TIFF format obtained from the Lazio Region Geoportal, and building-volume and surface-water vector layers from the Geotopographic Database of Roma Capitale (ETRS89/UTM 33N); they provide visual background only and are not results of this study.

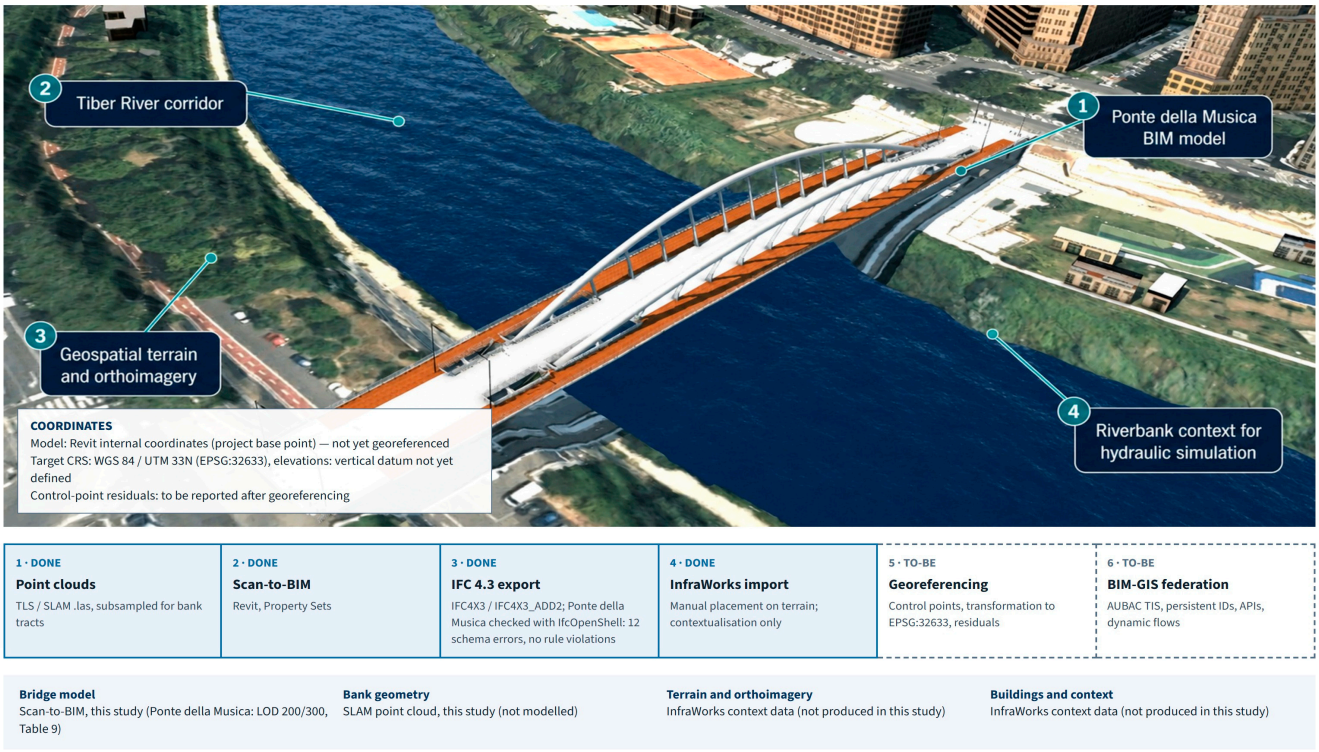


Figure 4. Geospatial contextualisation of the Scan-to-BIM models and bank point clouds in Autodesk InfraWorks, with coordinate status, layer data sources and workflow (steps 1–4 implemented; georeferencing and BIM-GIS federation not yet implemented, see Section 4.7). Manual placement establishes visual context, not geodetic registration. The Ponte della Musica check reports twelve schema errors and no EXPRESS-rule violations (Section 2.4; Table S1); this is not an unqualified schema-conformity result or a test of geometry or interoperability.

The geospatial side of the integration is already institutionally supported by AUBAC's district-scale WebGIS and diagnostic Digital Twin environment, implemented on the Esri ArcGIS Enterprise platform with Experience Builder and is publicly accessible [82,83]. As documented in the related AUBAC case study [83], this environment operates at district scale as a public knowledge, planning and decision-support infrastructure, exposing the knowledge and hazard themes of the basin through activatable layer groups (including hydrology, hydrogeological risk with the PAI and PGRA layers, and hydraulic works) together with query, comparison and 3D-view functions (Figure S1, Supplementary Materials). Activating the PGRA layer on the urban stretch of the Tiber shows how the stretch can already be consulted against the currently effective hydraulic hazard delineations.

This relationship also clarifies the distinction between the present paper and the previously published AUBAC district-scale Digital Twin case study [83]. While [83] documents the institutional development of AUBAC's WebGIS/Digital Twin environment at river basin district scale, the present study focuses on a specific urban river corridor and on the Scan-to-BIM, IFC 4.3 and BIM-GIS workflows, through which the bridge and bank

geometries are organised into an information base intended for future federation and hydro-pluviometric monitoring.

The IFC 4.3 information models of the bridges, together with the surveyed point clouds of the adjoining banks, are intended to be federated within this environment once georeferencing in the UTM 33N system is completed, so that the district's thematic layers, the BIM models and, eventually, the IoT sensor flows will converge into a single access point for technical assessment, planning support and management of the urban stretch, following the BIM-GIS integration paradigm discussed in the literature [58,63,72]. At present, the verified evidence concerns only the consultation of the thematic layers and PGRA delineations in the existing portal; the federation of the IFC models, API services and the ingestion of IoT flows remain future components.

4.5. Configuration of the Hydro-Pluviometric Monitoring Component

On the basis of the information requirements reported in Section 3.3, a preliminary configuration of the hydro-pluviometric network for the reference stretch was defined. This configuration is a design output: no sensor was installed within the period covered by this study. The data involved in the monitoring component are therefore of five kinds, kept distinct throughout: the existing data (the historical hydrometric and meteorological records, the PGRA hazard layers and the datasets of the AUBAC WebGIS); the data acquired in this study (point clouds and information models); the proposed sensors (Table 8), not yet installed; the simulated values, used only in the illustrative dashboard specification described below; and the future operational data, on which the indicators in Section 3.4 will be validated. The exact station quantities, locations and measurement ranges remain to be specified.

To address the hydro-pluviometric-monitoring objective, the sensing infrastructure would extend beyond the bridge itself to encompass the surrounding river reach (Figure 5; stations listed in Table 8). Radar water-level gauges installed beneath the bridge deck and ultrasonic sensors mounted on the embankment walls would provide redundant water-level measurements. Acoustic Doppler Current Profilers (ADCPs) at control sections would continuously measure an index velocity, from which the discharge could be derived through an index-velocity rating relating the measured velocity to the mean cross-sectional velocity, with the wetted area obtained from a stage–area relation; the rating would require calibration and periodic verification with independent discharge measurements [104], while scour sensors installed around piers and foundations would monitor the evolution of local scour. Piezometers embedded within the embankment walls would measure the pore water pressure, from which seepage conditions could be inferred through a seepage analysis rather than measured directly. The proposed network would also include meteorological and rainfall stations installed at elevated locations; cameras positioned along the quays equipped with computer-vision algorithms for the detection of water levels, vessel traffic and floating debris; and visual or acoustic early-warning devices where decided upon by the competent authorities. Coordination would be required with the operators of the existing historical hydrometric network of the monitored stretch.

The engineering feasibility of each station must be assessed against the hydraulic and operational conditions of the reach. In particular, permanent deployment of ADCP equipment on the bed of the Tiber has to account for debris and floating material's impact; sediment transport and burial; accessibility for maintenance, power supply and data transmission; and survivability during flood peaks; bed-mounted, side-looking and bridge-mounted configurations, together with suitable redundancy, should be compared before installation. Sensor siting, measurement ranges, flood survivability, power and communications, and maintenance requirements are therefore treated here as design requirements to be verified in the operational phase, not as established performance.

Since the quays are a heavily used public space, the proposed computer-vision processing would target river and infrastructure conditions and not the identification of individuals, in line with privacy-by-design and data-ownership requirements; a formal data-protection impact assessment specific to camera placement and image retention policy requires agreement on the controller and competent responsibilities prior to deployment and is not addressed further in this study. The alert water levels (attention, pre-alarm, and alarm) defined by civil protection planning would constitute the system's operational thresholds [68]. At this stage, attention, pre-alarm and alarm are logical classes of the architecture, to which numerical values still have to be assigned: the thresholds will need to be associated with the specific station and hydrometric section, with the current version of the official plan, and with local hydraulic calibration; their automatic transfer between different sections of the river is not assumed. Risk in the strict sense, which also involves exposure, vulnerability and consequences, is not computed dynamically in the present architecture; what the proposed system would couple is hydraulic condition observations (level, discharge, velocity, and rainfall) with the static PGRA hazard layers, so that real-time threshold exceedances could be read against the mapped hazard classes to inform the competent authorities. This is why the monitoring objective is termed hydraulic condition monitoring rather than risk monitoring.

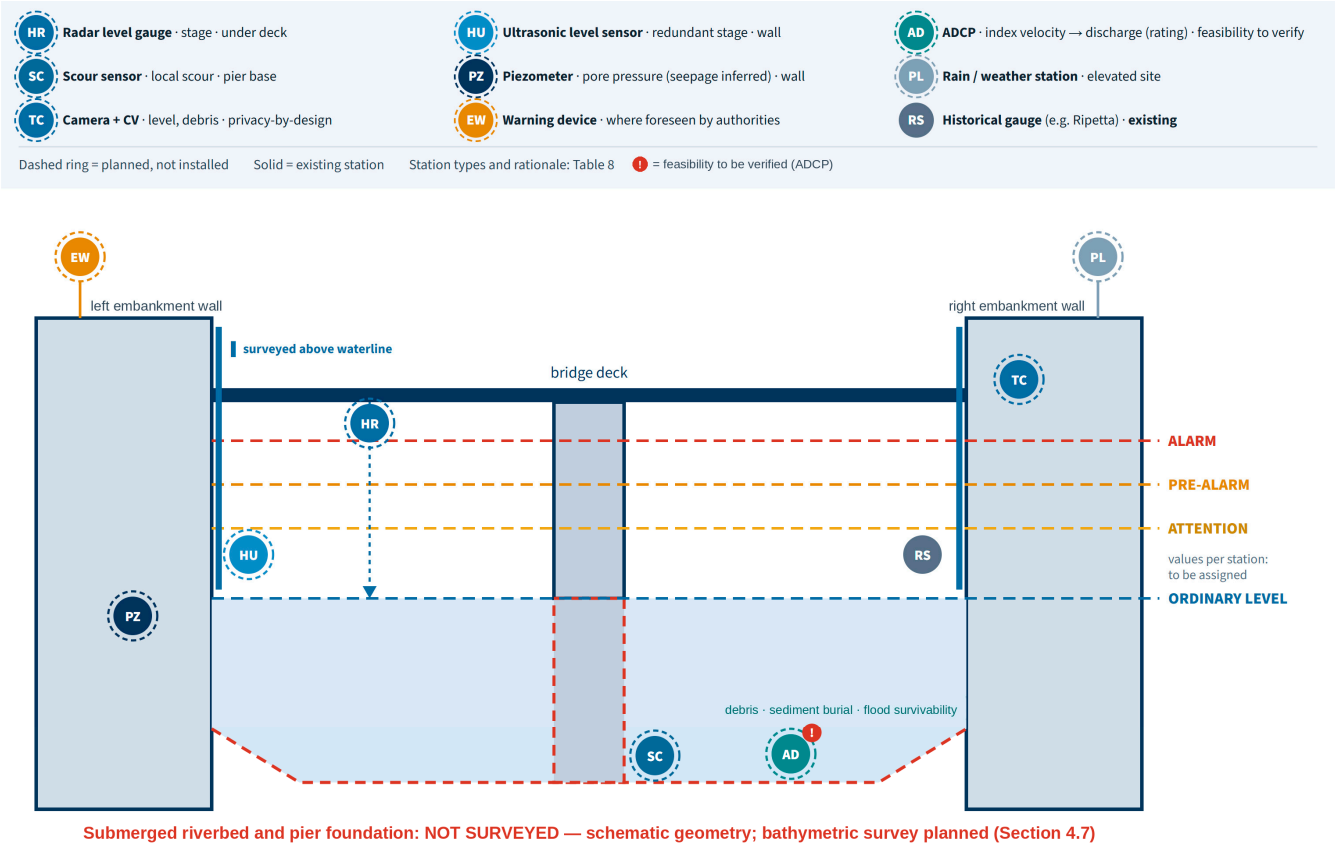


Figure 5. Conceptual layout of the planned hydro-pluviometric sensing configuration on a typical cross-section of the urban stretch, distinguishing surveyed surfaces from the unsurveyed riverbed and showing the alert classes, whose station-specific values remain to be assigned (stations listed in Table 8).

The intended functioning of the monitoring system is described by the conceptual flow chart in Figure 6. The hydro-pluviometric data, acquired at the edge and transmitted to the cloud platform, would first pass a data quality control step, with fault-handling

branches for communication failure (store-and-forward buffering, redundant link) and for sensor malfunction or missing data (flagging, switch to the redundant sensor, gap-filling with an uncertainty flag). The validated data would then be synchronised with the BIM-GIS model and analysed, together with forecasts carrying propagated uncertainty, against the attention and alarm levels set for the hydrometric quantities. A threshold exceedance would generate an alarm candidate which, once confirmed, would be issued as an alert supporting notification, coordination or protocol activation by the competent authorities according to the applicable institutional procedures, while unconfirmed candidates would be logged without being issued; a rapidly rising trend would generate a proactive alert and intensify monitoring, and the return of values to normal would close an event [60,61]. Issued alerts and observed exceedances would then be matched a posteriori, using a predefined one-to-one matching rule at the same station and class, each issued alert being classified as a true or false positive and each observed exceedance without a preceding alert as a false negative (Supplementary Table S6), feeding the indicators in Section 3.4, while ML algorithms are foreseen as updating forecasts and dynamic thresholds based on the model–observation comparison, with the outcomes of checks and actions feeding back into the twin through historicisation and model recalibration [94,95]. Updating model parameters or thresholds would require separate evaluation on held-out events; retrospective matching does not itself validate the forecasting model.

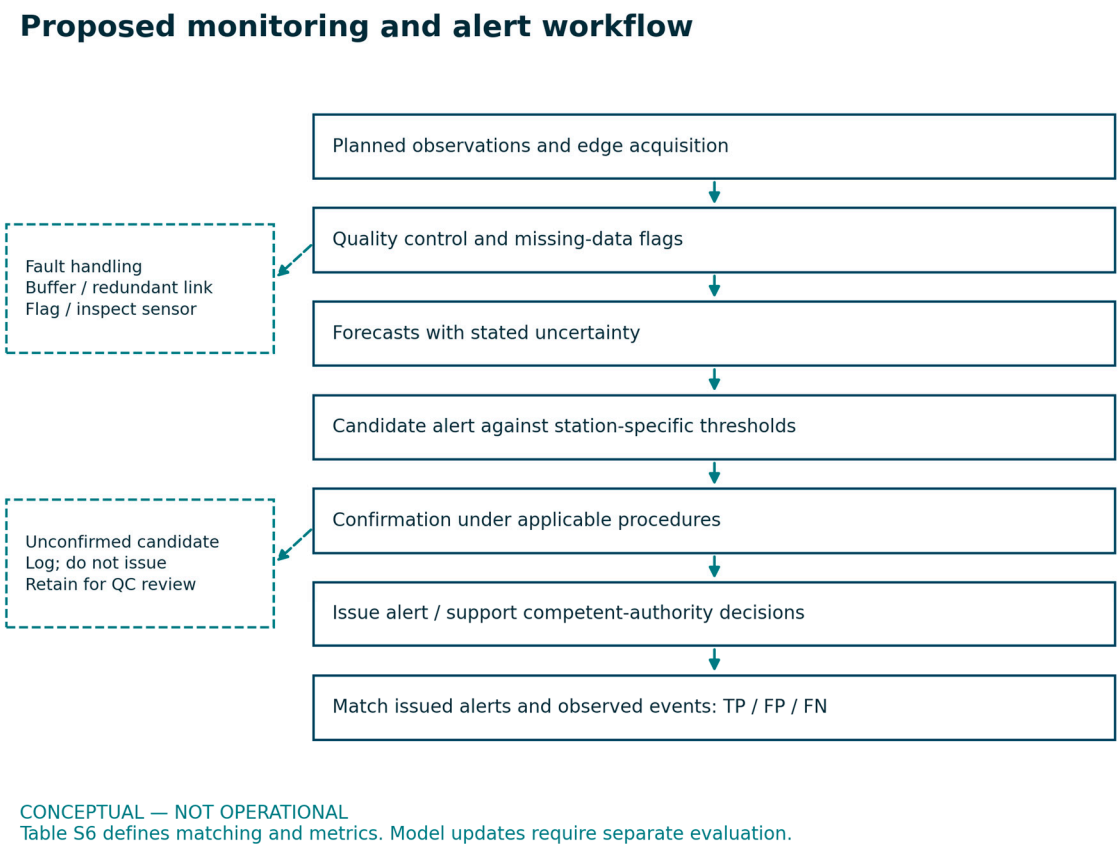


Figure 6. Proposed monitoring and alert workflow, including data quality checks, fault handling, confirmation and retrospective evaluation. No operational implementation is claimed. Indicator definitions are in Table S6; institutional actions remain with the competent authorities.

The user-facing output is illustrated by a dashboard specification with simulated values (Figure 7), aligned with the User Experience capabilities identified for the case. The

illustration shows an example forecast error, alert precision and recall, lead time, availability and scenario latency, together with station status and an event log [36,96]. The intended interface would also display the water-level, discharge and rainfall series and station-specific thresholds once observations are available. It is intended to support the AUBAC technical assessment and coordination with the competent authorities. No live connection to the information model or measured operational performance is demonstrated.

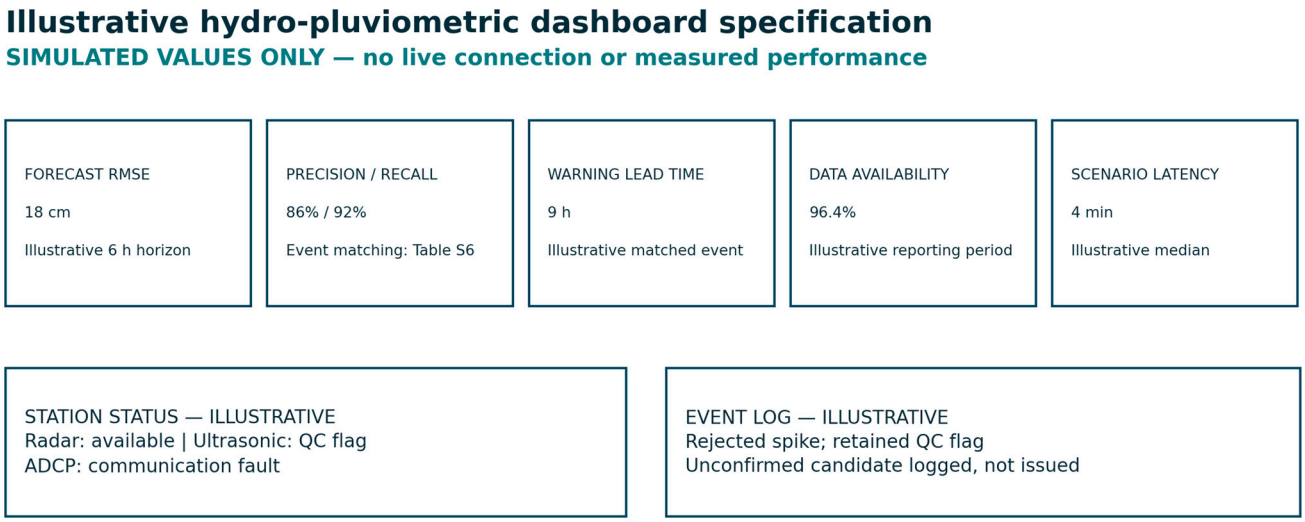


Figure 7. Illustrative dashboard specification with simulated values only. No operational data feed or measured performance is represented. Formulas and proposed evaluation rules are in Table S6.

4.6. Extension to the Whole Stretch and Information Assets Produced

Extending the workflow to the other fifteen bridges and to the banks of the stretch replicated the same sequence, with the acquisition solution selected according to the context constraints of each element, as described in Section 2.3. The campaign produced a high-resolution point cloud for each element of the stretch and a corresponding IFC 4.3 information model for each of the sixteen bridges (Table 9), whereas the adjoining bank tracts, although surveyed as point clouds, were not modelled at this stage. In some cases, the acquisition of certain portions was partial or not feasible because the areas concerned were inaccessible owing to the river, physical barriers or unsuitable safety conditions; these portions were handled with the evidence-constrained parametric reconstruction described for the reference element.

The assets produced, semantically structured and prepared for georeferencing in the UTM 33N system (EPSG:32633), are intended to enable four practical advantages for the AUBAC: geospatial consistency, with overlay of the geometries onto official cadastral maps and orthophotos; institutional integration with the Territorial Information System; scalability for environmental and hydraulic simulations, flood risk and hydrogeological instability; and traceability of survey campaigns and hydraulic–environmental management interventions [63,72].

4.7. Implementation Status, Maturity and Roadmap

Table 10 separates component status from evidence of operational readiness. The descriptive scale is conceptual (specified only), prototype (produced but incompletely evaluated), tested (checked against stated criteria), integrated (connected within a specified workflow) and operational (routine institutional use). Integration is explicitly scoped; it does not by itself establish accuracy or cross-platform conformity. Survey acquisition is described as implemented with internal checks, rather than assigned an overall validated quality level.

Table 10. Maturity level of the Digital Twin components developed for the Tiber River case study.

Component	Status	Note	Maturity Level
TLS/SLAM geometric survey of the 16 bridges and adjacent banks	Implemented	Acquired assets used in modelling and visual contextualisation; internal checks only; no independent accuracy assessment or geodetic registration	Prototype
Scan-to-BIM information models (IFC 4.3)	Implemented	Semantic structuring (Psets, classification) completed; management parameters to be added; default IFC spatial structure	Prototype
Geospatial contextualisation in Autodesk InfraWorks	Implemented	Supports visualisation and future hydraulic simulations	Prototype
Consultation of hazard layers on the AUBAC WebGIS portal	Implemented (pre-existing institutional system)	PGRA layer verified on the study stretch	Operational
UTM 33N georeferencing and BIM-GIS federation	Planned	Prerequisite for operational integration with AUBAC's Territorial Information System	Conceptual
Hydro-pluviometric sensor network	Planned	Preliminary configuration defined; installation not yet started	Conceptual
Continuous data flow and cloud DT platform	Planned	Architecture defined in Section 4.1; not yet operational	Conceptual
ML-based anomaly detection and forecasting	Planned	Requires historical/real-time data not yet available	Conceptual
Indicator validation against real data	Planned	Scheduled within the 24-month roadmap	Conceptual

Figure 8 presents a proposed 24-month implementation horizon, not a statistically validated duration [96]. Georeferencing, IFC exchange testing and bathymetry precede operational reuse; station design, installation and commissioning precede continuous observation. A representative hydraulic model and forecasting tests would then be developed using the modelling approaches discussed in Section 2.5. Before the evaluation data are collected, the responsible operators and competent authorities would agree to the event definitions, matching windows, severity classes, baselines, thresholds and a minimum event sample. The candidate independence rules would use recession periods estimated from historical hydrographs. The calibration and test events should be separated chronologically; any leave-one-event-out analysis would be reported as exploratory and not substituted for an untouched test set. The confidence intervals should be estimated at event level. The required sample size would follow a predeclared precision target for recall in the alarm class. M12 and M24 are review gates: if adequate events are unavailable, collection would continue or results would remain descriptive. The proposed improvement criterion combines increased warning lead time with a predeclared non-inferiority margin for the proportion of false issued alerts, FP/(TP + FP), evaluated against comparable baseline events. The margin, confidence level and sample-size calculation remain to

be agreed upon. This is a protocol proposal, not an already approved or executed validation.

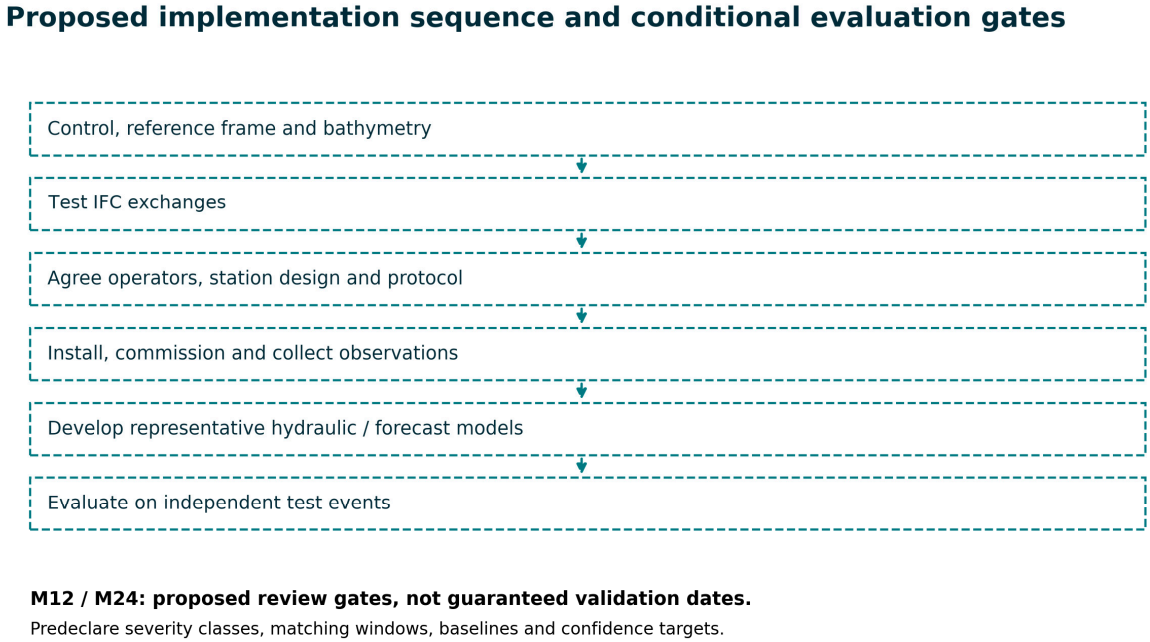


Figure 8. Proposed implementation sequence and conditional M12/M24 evaluation gates. Durations, responsibilities, thresholds and sample requirements require agreement before operational deployment; the schedule is not evidence of achieved validation.

The benefits expected from the completion of this roadmap, namely a more complete and timely observational picture, reduced acquisition and update latency, longer advance-warning lead time, reduced forecast error and false alarms, and faster activation of the competent authority's protocols, are evaluation endpoints still to be measured against this protocol, and are reported here as expected results.

5. Discussion

Read against RQ1, the application shows that the descriptors of the reference methodology (intervention category, process phase and management objectives) can be carried, without structural adaptation, down to the information requirements, indicators and technology choices for bridges and bank hydraulic works, elements that the framework addresses as built assets, but that here act as boundary conditions of a natural process. Assessed retrospectively against the criteria defined in Section 2.2 (Table 11), the geometric and information components are produced with the available data, with internal registration statistics but no independent accuracy assessment, whereas the georeferencing, interoperability testing, riverbed data and the governance preconditions of monitoring prove to be the binding constraints (Section 5.2). The exercise is informative precisely because the case sits at the boundary of the framework's original domain.

In relation to RQ2, the sixteen bridge models document the observed and inferred geometry, with the estimated reconstructed shares ranging from 0% to approximately 50% of the modelled above-water surface. These estimates describe provenance rather than accuracy. Acquisition constraints and the documented intrados examples identify a practical reason to consider both the amount and the location of reconstructed geometry when planning further investigations. The IFC inventories and file checks likewise identify issues to address through semantic review and exchange testing. The resulting assets

support geometric documentation and the identification of information gaps; common georeferencing, bathymetry and application-specific verification are required for hydraulic and monitoring use. In relation to RQ3, the application remains a Digital Model with a target Digital Twin architecture.

The application also makes explicit a sequence that is often left implicit in single-case DT reports: from the management objective to the information requirement, and from there to the acquisition technique, the information model, the integration environment and the monitoring configuration. The selection criteria at each step are documented here alongside the final technological stack, so that another authority facing a comparable corridor can follow the reasoning.

The empirical results concern the inventory, model provenance and checks performed; the architecture and indicators specify subsequent work. In particular, the IFC check reveals a default building-based spatial structure, while manual placement in InfraWorks exposes the gap between visual contextualisation and geodetic integration. These are documented findings from one application, with the transfer limits discussed in Section 5.5.

Table 11. Retrospective assessment against the RQ1 criteria (Section 2.2), evidence in the present application and implications for the intended uses (RQ2).

RQ1 Criterion	Evidence in the Present Application	Implications for the Intended Uses (RQ2)
Information completeness	Estimated 83% survey-derived and 17% reconstructed above-water model surface (unweighted mean of 16 bridge estimates); submerged bases/foundations excluded; area totals unavailable for independent recomputation. Riverbed was not acquired (bathymetry pending). The Risorgimento section links modelled intrados rise to the reconstructed crown (Section 4.3; Table S8).	Supports above-water geometric documentation and identification of survey gaps. Subsequent analysis requires explicit reconstruction provenance and targeted verification; assessment of submerged riverbed change requires bathymetry.
Geometric reliability	Internal statistics: TLS bundle error, 8 mm; SLAM–TLS alignment, RMS approximately 32 mm. Mean endpoint discrepancy approximately 15 mm, computed at the alignment structures. No independent check points or measured intermediate drift.	Documents local fitting consistency for the reported alignments. Surface accuracy and change-detection thresholds require independent checks and repeated-survey uncertainty assessment.
Interoperability/data mapping	Reference IFC check: no EXPRESS-rule violations; 12 UsingCurves inverse-attribute errors, confirmed by reference traversal to be outside element representations; additional Risorgimento check: no issues. Entity counts available for all 16 models: proxy share 0–6%; reference model 63/1127 (5.6%). Default building-based spatial structure; no complete exchange, MVD/IDS or geometry-retention test.	Provides an IFC inventory and documented file checks to scope further verification. Semantic correctness and information preservation require element-level review and defined exchange tests.

Georeferencing	Binding constraint: definitive UTM 33N (EPSG:32633) georeferencing not completed.	Provides visual contextualisation for examining the corridor. Combining bridge geometry, bathymetry and gauge observations requires a common horizontal and vertical reference.
Governance constraints	Binding constraint for deployment: camera DPIA, reconciliation with existing networks, and assignment of station-specific thresholds.	Provides a proposed monitoring configuration for institutional coordination. Deployment requires agreed-upon responsibilities, reconciliation with existing networks, a camera DPIA and station-specific thresholds.

5.1. Applying a Built Environment Methodology to an Urban River System

Extending a DT methodology conceived for built assets to an urban river system required a specific interpretative effort. The literature has predominantly addressed this domain through separate components—urban drainage [56,57], hydrogeological risk [58,59], flood dynamics [60,61] and structural monitoring of bridges [78,94,105]—but rarely in an integrated way. The three objectives adopted for the corridor, condition-based maintenance of riverbed and bank hydraulic works, hydraulic condition monitoring and hydropluviometric monitoring in support of water governance decisions, reflect the need for a unified reading of the urban stretch of the Tiber, in keeping with the AUBAC's institutional mission and in analogy with the Florentine experience on the Arno [63].

The most consequential interpretative decision concerns the role of the bridges. Within the scope adopted here, bridges and banks are represented as geometric interfaces exposed to, or interfering with, the flow; structural diagnosis lies outside this representation. This scoping aligns the application with the statutory remit of the competent authority, but it has an evident cost: the geometric detail collected on the crossings, including intrados and extrados, is not exploited for structural diagnostic purposes. The same information base could support a structural health monitoring reading of the same corridor under a different objective configuration and a different institutional owner, which is one of the more transferable observations to emerge from this case.

The articulation of the architecture according to the input–integration–visualisation/analysis structure, already used by the same research group in the hospital domain [96], proves usable in a river context as well, although further application contexts are needed to establish whether this indicates cross-sector transferability.

5.2. Implementation Challenges

Four classes of difficulty emerged during the application, and they are reported here because they are likely to recur in comparable settings.

Acquisition in a live public space: The quays and bridges of central Rome are in continuous use. Traffic, pedestrian flows and safety constraints determined, element by element, which acquisition technique was feasible, and made a uniform survey protocol across the sixteen crossings impossible. Construction works obstructed acquisition at Ponte Pietro Nenni, while restricted access to the quays and lower structural areas limited intrados coverage at other bridges with higher reconstructed shares (Section 4.3). Missing above-water portions were reconstructed parametrically, with their estimated surface share declared per bridge (Table 9); submerged bases, foundations and the riverbed remained outside the surveyed and modelled geometry.

Georeferencing: The survey was carried out in local coordinates, and definitive georeferencing in UTM 33N was not completed within the period covered by this study. This is the single most binding constraint on the evolution of the information base:

without geodetic realignment, federation with the authority's Territorial Information System, overlay onto official cartography, and any coupling with hydraulic models remain unavailable. In applications of this kind, the geodetic frame should be fixed at the outset, before the integration stage. A Global Navigation Satellite System (GNSS) receiver was unavailable during the survey campaign, so the point clouds could not be tied to an external coordinate reference system and were processed within a local frame; this limitation concerns the absolute position and orientation of the surveyed geometry, and does not establish independently checked geometric accuracy within the local survey. The RTK-capable UAV (Section 2.3) was used as a photographic instrument, for aerial imagery and orthophotos of the banks and of the portions not reachable from the ground; an approximate georeferencing based only on its onboard GNSS module was not considered reliable, and future campaigns will use a ground-based RTK GNSS antenna for georeferencing. Definitive georeferencing will therefore require control points surveyed with this antenna; a transformation from the local frame to UTM 33N estimated on those points; and a vertical datum common to the survey geometry, the bathymetry and the gauge zero of the hydrometric stations. Its positional accuracy will be reported through control-point residuals and independent check points rather than assumed in advance. The layout of the control points, the transformation parameters and the vertical reference to be adopted will be defined in that campaign and cannot be specified at this stage; georeferencing therefore remains both a current limitation and future work.

Because the SLAM bank cloud at Ponte della Musica was co-registered to the TLS reference, its geometric agreement could be checked locally within the shared frame (Section 4.2). This local alignment provided a limited geometric consistency check, not a controlled comparison of the two surveying techniques, and it does not extend to the other bridges and bank tracts. Discrepancies in such a check reflect the combined effects of SLAM reconstruction errors, TLS measurement and registration uncertainty and the alignment procedure itself, and the check does not establish absolute positional accuracy in a national or global reference system, which would require independently surveyed geodetic control and check points. The reported RMS is calculated on fitting pairs; an independent local accuracy assessment would also require measurements excluded from that fitting. Independent GNSS or total-station observations on surfaces excluded from fitting were not collected during the campaign, and a ground GNSS receiver was unavailable. An independent assessment therefore requires additional field measurements; internal registration statistics cannot substitute for them.

The IFC export alone does not establish interoperability. The reference check identified twelve schema errors, reported as confined to unreferenced geometric entities, with no identified effect on elements or properties (Section 2.4), whereas the entity mappings still require element-level review. Bridge-specific spatial structure, persistent identifiers, exchange requirements and cross-platform tests remain necessary before claiming semantic preservation.

Institutional and governance constraints: The monitoring configuration involves a public river corridor and a heavily frequented public space, with responsibilities distributed among several authorities. Reconciliation of the proposed hydro-pluviometric network with pre-existing monitoring infrastructure operated by other authorities along the same reach, the association of alert thresholds with specific stations and with the current version of the official planning instruments, and the data-protection assessment required for camera-based monitoring are governance preconditions of deployment, and they condition the timeline more than the technology does.

5.3. Implications for Asset and Hydraulic Risk Management and for BIM-GIS Integration

For the management of bank hydraulic works and crossings, the current survey provides a baseline for the future comparison of accessible above-water surfaces; riverbed sedimentation and submerged scour cannot be assessed from the present terrestrial dataset and require repeated bathymetric surveys. Moving from cyclical to condition-based scheduling of interventions would require survey campaigns repeated on a defined cycle and referenced to a stable geodetic frame, which returns to the constraint identified above.

The information assets produced in this study form part of the broader AUBAC programme for developing a district-scale Digital Twin in support of river basin planning and water governance [83]. Within that programme, the bridge models and bank point clouds provide a detailed geometric information layer that complements the territorial and planning information available through the institutional WebGIS [82,83]. Their present contribution is a documented three-dimensional record of the surveyed above-water assets, with the provenance and reconstruction limitations described in Section 4.3. This record provides a basis for examining the asset geometry, identifying information gaps and planning targeted investigations, although improvements in institutional workflows have not been measured.

The intended next step is to connect this geometric information with the authority's geospatial environment and relevant hydrometric observations. Once a common spatial reference and the necessary data checks are established, selected applications could include comparison with subsequent surveys, interpretation of water levels in relation to the local asset geometry, and preparation of inputs for hydraulic modelling. These applications define the practical development pathway of the present work; their implementation and evaluation are reserved for subsequent studies.

The comparison between successive campaigns is envisaged with the Multiscale Model-to-Model Cloud Comparison (M3C2) algorithm [106], which estimates local surface change along the surface normal together with a per-point confidence interval accounting for local roughness, sampling and registration error. The detectable change magnitude cannot be inferred from point spacing alone: it will be estimated on the first repeated survey from the registration uncertainty, the local surface roughness and the confidence level adopted, so the capacity to detect changes of a given size, such as bank toe erosion, localised settlement or accretion, remains a hypothesis to be verified. The present TLS bundle and SLAM–TLS fitting statistics (8 and 32 mm, Section 4.2) are not inter-epoch uncertainties and cannot establish a numerical detection threshold. That threshold requires repeated surveys and an appropriate uncertainty assessment. The repeat interval would be set in the monitoring plan according to the process observed, for example, annual for slow bank evolution or event-driven after significant floods. The approach proposed here relies on repeated field surveys of the same surfaces. A hydro-morphodynamic model simulating sediment transport and morphological change would be a further extension of the framework, additionally requiring bathymetry; sediment grain-size distributions; bed material characteristics, including cohesion; and sediment boundary conditions.

For hydraulic risk management, the models document above-water geometry relevant to future hydraulic calculations, including bridge piers, abutments, deck-soffits, openings and bank works. The Musica and Risorgimento examples show that reconstructed portions can include intrados geometry forming the upper boundary of bridge openings. In the Risorgimento section, the 9.58 m rise is determined by the reconstructed crown: a quantity can be extracted precisely from the model while still requiring observational verification. The bridge-level reconstructed percentage should therefore be considered together with the location of the reconstructed portions when identifying priorities for geometric verification and additional survey. This is particularly relevant to future

analyses involving water levels near the deck-soffit. The opening geometry also depends on the piers, abutments and riverbed, with hydraulic behaviour dependent on the flow conditions (Section 2.5). Within the AUBAC's wider Digital Twin programme, this interpretation provides a basis for planning targeted data acquisition before hydraulic application; the effects of reconstructed geometry on calculated water levels or velocities remain to be quantified.

In a future one- or two-dimensional model, these elements would enter as cross-section geometry and obstruction parameters, but the transfer would not be direct, because no direct IFC-to-solver transfer was tested in this workflow. Only the hydraulically relevant geometry would be extracted from the bridge models, namely, pier positions, widths and nose shapes, abutments, deck-soffit and deck-top elevations and opening widths. This geometry would be converted into the bridge structures of the hydraulic code, such as bridge cross-sections with pier and deck data in a one-dimensional model, or obstruction polygons and soffit levels in a two-dimensional mesh. The semantic structure of the models, such as the IFC entity class and element type, would serve to select these elements, while the remaining structural detail would not be used; elements exported as generic proxies would have to be identified manually. Because the models are held in local coordinates, deck and soffit elevations would become usable in a hydraulic model only once the common vertical datum is fixed (Section 2.5). Compared with conventional surveyed cross-sections at a limited number of stations, the survey-derived models describe the full three-dimensional geometry of each crossing, from which bridge sections could be extracted at any position and updated after interventions; compared with terrain-based representations derived from digital elevation models, they resolve the deck and opening geometry that a terrain surface cannot represent. The information base produced here would therefore make such a hydraulic assessment possible once the bathymetry and boundary conditions are added, but whether this additional detail changes water levels, backwater or velocities appreciably has not been tested (Section 5.4), and the portions reconstructed from design documentation carry lower reliability (Section 4.3).

The contribution should be read alongside existing river corridor geomatic and BIM-GIS research. The Florence–Arno study [63] addresses integrated acquisition of the river and historic urban environment, including geodetic control and bathymetry. The present case focuses on the provenance and information structure of a sixteen bridge Scan-to-BIM portfolio and on the requirements that remain unmet for its intended uses. Its additional evidence consists of bridge-level reconstruction estimates, a sixteen file IFC inventory, two documented file checks, a scripted Risorgimento section extraction linked to its qualitative provenance, and an explicit association between these findings and application requirements. These observations do not establish superior performance or generalise the behaviour of IFC software; they document how known integration requirements constrain this particular institutional application.

5.4. Limitations

The study presents several limitations, which follow from the prototype status of the system and from the single-case design.

The main limitation is that the information model currently operates in local coordinates: definitive georeferencing is future work (Section 5.2). The integration of management parameters and the validation of the reconstructed parts are scheduled for the next phase. The hydro-pluviometric network has not yet been implemented, so the indicators and operational thresholds adopted are proposed and not yet validated with real data (Section 4.7); the numeric alert thresholds are placeholders for a calibrated hydraulic model still to be developed, together with the incorporation of climate-adjusted rainfall scenarios. Acquisition of some portions was partial because of accessibility constraints,

with information gaps that evidence-constrained parametric reconstruction mitigates but does not eliminate [105,107]. The local TLS–SLAM alignment is exploratory and the accuracy indicators are internal registration and alignment statistics without independent check points; the submerged riverbed was not acquired, so the riverbed component of Objective 1 is not yet supported by the data. No hydraulic calculation is reported, so the effect of the survey-derived geometry on hydraulic results has not been quantified and the contribution is limited to the preparation of the geometric information base. The machine learning components for anomaly detection and forecasting are not operational, and BIM-GIS federation has not been tested on a complete exchange. The reference IFC file also retains twelve schema errors confined to entities outside element representations, as documented by the reference graph inspection (Section 2.4).

The methodological interpretation is limited to this single application. Project resources and institutional and physical constraints jointly influenced the outcomes, and the study design does not isolate the effect of the adopted framework. Assessing its general validity or comparing it with alternative frameworks would require further applications and a comparative study design.

5.5. Transferability

The transferability of what is reported here is best stated in graded terms. The survey-to-IFC workflow, including the context-based criteria for choosing between static and mobile acquisition under traffic and accessibility constraints and the evidence-constrained treatment of non-detectable portions, is the most directly transferable element, as a decision procedure rather than as a validated performance comparison of the two techniques, and may inform comparable masonry or mixed-typology crossing portfolios along an embanked urban river. The scoping decision, which treats crossings as hydraulic interfaces and not as structural assets, is transferable wherever the information owner is a water or basin authority; for an infrastructure operator it would need to be revisited. The architecture and the monitoring configuration are transferable as a scheme, but their parameters, particularly alert thresholds, station placement and the articulation with existing hydrometric networks, are strictly local. Any wider claim would require application to at least one further corridor and one further institutional context, which is identified in Section 6 as a priority for future work.

6. Conclusions and Future Developments

This study documented the application of a previously published Digital Twin methodology [74] to the urban stretch of the Tiber River in Rome, an embanked historic reach in which sixteen crossings, the bank hydraulic works and a densely used public space coexist with a floodplain of very high exposure, and in which management responsibilities are institutionally distributed.

The application produced an information foundation: high-resolution TLS/SLAM point clouds of the sixteen bridges and the adjoining banks; IFC 4.3 Scan-to-BIM models of the sixteen bridges, with the share of parametrically reconstructed above-water surface estimated per bridge and a reproduced Musica schema check reporting twelve inverse-attribute errors and an additional Risorgimento check with no reported issues; geospatial contextualisation in an infrastructure-modelling environment; and a target Digital Twin architecture with a conceptual configuration of the hydro-pluviometric monitoring network and an illustrative dashboard specification with simulated values.

The assessment identifies substantial variation in geometry provenance: the estimated reconstructed share ranges from 0% to approximately 50% of above-water model surface, with an unweighted mean of approximately 17%. The construction works at Ponte Pietro Nenni and restricted access to intrados and lower structural areas at other

bridges explain the acquisition gaps. The Musica and Risorgimento examples demonstrate that reconstructed portions can include intrados geometry relevant to the representation of bridge openings. The Risorgimento section makes this relationship explicit: its modelled span is 100.28 m, while the 9.58 m rise depends on the reconstructed crown. This identifies a specific target for geometric verification before hydraulic use. The IFC inventory and file checks identify additional semantic and exchange verification needs, while common georeferencing and bathymetry remain requirements for integration with hydraulic data. The contribution is this case-specific assessment of the available information and the investigations required for its intended reuse; the hydraulic effects and operational benefits remain to be evaluated.

For the AUBAC, the immediate value of the work lies in establishing a documented geometric information base for the surveyed corridor, which could inform further investigations and provide a foundation for subsequent integration and application studies within the authority's wider Digital Twin programme.

Within these limits, the case provides a documented reference for authorities intending to undertake comparable applications in other urban river contexts, contributing to the resilience, sustainability and data-driven territorial management objectives promoted by the 2030 Agenda: most directly SDG 9 (resilient infrastructure and innovation); SDG 11 (sustainable cities and communities) and SDG 13 (climate action); and, through the hydro-pluviometric and water governance objective, SDG 6 (clean water and sanitation). The expected sustainability mechanism, still to be demonstrated, is not limited to digitalisation as such: it lies in the possibility of making the maintenance of bank works and, with bathymetric data, of riverbeds more condition-based, reducing unnecessary survey repetition and poorly targeted interventions, improving the availability of risk-relevant information, and preparing the observation chain required for more timely flood risk assessment.

Future work follows directly from the open points identified above. The first steps are definitive UTM 33N georeferencing using a ground-based RTK GNSS antenna, and BIM-GIS federation, including IFC import/export testing against an agreed exchange specification, the bathymetric acquisition of the riverbed and the installation of the hydro-pluviometric monitoring network within the proposed implementation horizon, subject to adequate observations, so that the indicators adopted in Section 3.4 can be validated against real operational data. A hydraulic model will then be set up for a representative bridge section, first to compare the simplified and survey-derived geometry under identical boundary conditions, and then for the stretch, enabling coupled simulation of the river, bridges and banks under flood scenarios that incorporate climate-adjusted rainfall and discharge projections alongside historical design values; a hydro-morphodynamic extension for sediment transport and morphological change will follow once bathymetric and sediment data are available. Further work includes a controlled, quantitative TLS–SLAM comparison on an overlapping test area, to assess the density, RMSE, acquisition time and repeatability, together with an independent accuracy check of representative elements, using check points excluded from the alignment; machine learning algorithms tested for anomaly detection and forecasting on real hydrological time series; and trustworthiness mechanisms, including an assessment of the security risks specific to Digital Twins and a data-protection impact assessment for camera-based monitoring. Application of the same reference methodology to at least one further river corridor and institutional context, including the extra-urban reaches of the river basin, would be needed to test the transferability of the observations reported here.

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Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182111262/s1, Figure S1: The "AUBAC Digital Twin" WebGIS portal: study stretch between Ponte della Musica and Ponte Palatino, including the Tiber Island, with the banks of the Tiber highlighted and the location of the Central Apennine hydrographic district (basemap source: webgis.abdac.it); Figure S2: Location map of the detailed-survey sub-reach in WGS 84 / UTM zone 33N (EPSG:32633): positions of the sixteen surveyed bridges, numbered as in Table 9, and indicative extent of the eight bank tracts S1–S8 of Table S7, drawn between the bridge axes along the corresponding bank. Bridge positions, river centreline and water area are taken from OpenStreetMap (© OpenStreetMap contributors, ODbL; data retrieved on 7 October 2026) and projected to UTM 33N. The map locates the surveyed assets; it does not georeference the survey, whose point clouds and models remain in local coordinates (main text, Section 5.2); Figure S3: Ponte Risorgimento: SLAM point cloud overlaid on the Scan-to-BIM model. (a) Elevation from the river; (b) arch intrados viewed from below. The point cloud represents surveyed geometry. The uncovered model surfaces identified by the modelling team as reconstructed are shown in pink in (a) and in uniform grey in the central intrados in (b). The missing above-water intrados was inferred by parametrically continuing the arch profile surveyed at its ends across the central gap. The figure illustrates the source and extent of geometric inference; it does not establish independent accuracy or a reproducible reconstructed surface-area percentage; Figure S4: Longitudinal vertical section of the Ponte Risorgimento arch model. The horizontal span is 100.28 m; the maximum intrados rise above the springing chord is 9.58 m. The maximum occurs in the reconstructed crown identified by the modelling team. The arrow indicates its qualitative location, not the limits of the reconstructed region. Elevations are local model coordinates; no water level or bathymetry is represented. Only the selected arch object is shown. The figure documents model geometry and its provenance limitation, not independent survey validation; Table S1: IfcOpenShell validation log of Ponte della Musica (CSV and raw JSONL files); Table S2: IFC entity counts per class for the sixteen bridge models (CSV file); Table S3: Input data adopted for the condition-based maintenance objective; Table S4: Input data adopted for the hydraulic-condition-monitoring objective; Table S5: Input data adopted for the hydro-pluviometric-monitoring objective; Table S6: Proposed operational definitions of the indicators in Tables 4–6. Operators, validating bodies, baselines, frequencies and acceptance criteria require agreement before deployment. The protocol in Section 4.7 has not been executed; Table S7: Surveyed bank tracts corresponding to Table 9 and the schematic inventory in Figure 1; their indicative extent is mapped in Figure S2; Table S8: Quantities extracted from the Risorgimento model section. Values are model-derived and rounded to two decimal places; additional validation summary, Musica and Risorgimento validation logs, and Musica reference-graph inspection; IFC file manifest with filenames, reported sizes and SHA-256 hashes; IFC export configuration file; README file describing the IFC evidence and checks; section-extraction script (risorgimento_section_analysis.py), derived profile and segment CSV files, results JSON, Figure S4 image files and geometry README.

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Data Availability Statement: The publicly available planning and geospatial datasets analysed in this study can be accessed through the AUBAC WebGIS portal at: https://webgis.abdac.it/portal (accessed on 25 August 2026). Survey-derived point clouds, Scan-to-BIM models and dashboard materials are not publicly available at this stage because they are deliverables of an ongoing institutional research agreement and are subject to technical validation and authorisation by the data-owning institutions. The IFC validation logs, entity counts per model and the IFC file manifest are provided in the Supplementary Materials. The section-extraction script, derived profiles and Table S8 are provided in the Supplementary Materials. Access to the source IFC model required to reproduce the extraction may be requested through the corresponding author and is subject to authorisation by the data-owning institutions.

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Abbreviations

The following abbreviations are used in this manuscript:

AECO	Architecture, Engineering, Construction and Operation
ADCP	Acoustic Doppler Current Profiler
AI/ML	Artificial Intelligence/Machine Learning
API	Application Programming Interface
AUBAC	Central Apennine River Basin District Authority

AECO	Architecture, Engineering, Construction and Operation
BIM	Building Information Modelling
CDE	Common Data Environment
CPT	Digital Twin Capabilities Periodic Table
DPIA	Data Protection Impact Assessment
DT/UDT	Digital Twin/Urban Digital Twin
ETL	Extract, Transform, Load
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
IFC	Industry Foundation Classes
IoT	Internet of Things
KPI	Key Performance Indicator
LOD	Level of Development
LOIN	Level of Information Need
M3C2	Multiscale Model-to-Model Cloud Comparison
MAE	Mean Absolute Error
MVD/IDS	Model View Definition/Information Delivery Specification
NSE	Nash–Sutcliffe Efficiency
OT	Operational Technology
PAI	Piano stralcio per l'Assetto Idrogeologico (river basin hydrogeological plan)
PDCA	Plan–Do–Check–Act
PGRA	Flood Risk Management Plan (Piano di Gestione del Rischio di Alluvioni)
RMS	Root Mean Square
RMSE	Root-Mean-Square Error
ROI	Return on Investment
SDG	Sustainable Development Goal
SLAM	Simultaneous Localisation and Mapping
TLS	Terrestrial Laser Scanning
TP/FP/FN	True Positive/False Positive/False Negative
UAV	Unmanned Aerial Vehicle
UTM	Universal Transverse Mercator

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