

Towards a National Geospatial Digital Twin in Slovenia: Multi-Source Integration and a Flood Pilot for Hazard Management

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Abstract

National geospatial infrastructures are evolving from classic spatial data infrastructures into connected geospatial ecosystems in which authoritative reference data, Earth observation (EO), sensor observations and analytical services are combined in operational workflows. This paper proposes a framework for a Slovenian national geospatial digital twin grounded in the emerging Geo Slovenija ecosystem and demonstrates one validated flood-related component through a pilot application in the Lake Cerknica karst polje. The framework links authoritative cadastral and topographic data, terrain and 3D data, EO products and hydrometeorological observations in a web-based 2D/3D environment. The flood pilot reconstructs daily inundation states from a digital terrain model and a long-term gauge record (1954–2025), while independent EO-based benchmarking is performed against 26 PlanetScope scenes acquired between 2023 and 2025. The results show a distinct non-linear water-level-area relation and moderate to good agreement with EO-derived water masks (mean IoU = 0.62 +/- 0.26; mean F1 = 0.75 +/- 0.22), with clearly stronger and more stable performance during stable lake phases. The paper contributes a national-scale architectural perspective and a computationally lightweight, validated flood-state reconstruction workflow that can serve as a transferable building block for hazard monitoring and decision support in Slovenia.

1. Introduction

National geospatial infrastructures are no longer confined to the discovery, access and exchange of static spatial datasets. Alongside the wider shift from spatial data infrastructures (SDIs) to geospatial information ecosystems, national platforms are increasingly required to facilitate ongoing data integration, analysis, simulation and decision-making support. The United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) explicitly describes this shift as moving towards a future geospatial information ecosystem, where data, standards, institutions, analytics and users function as an interconnected digital public resource (Coetzee et al., 2021; UN-GGIM, 2025). For national agencies, this means authoritative geospatial data must be reusable for not only mapping and administration, but also the operational monitoring of hazards, infrastructure, ecosystems and land use change.

At the same time, the concept of the digital twin has expanded from the field of manufacturing to the urban and geospatial domains. In this context, a digital twin is more than just a visually rich 3D model. Instead, it is a temporally explicit and connected digital representation of a real system, linking static reference data layers, dynamic observations and analytical models to support state estimation, interpretation and scenario analysis (Grieves & Vickers, 2017; Jones et al., 2020; Metcalfe et al., 2024). City-scale digital twins have received particular attention in smart city research and practice (Hamalainen, 2020; Ketzler et al., 2020). However, national-scale geospatial twins are more challenging to implement as they require integration across multiple institutions, scales, and update cycles while ensuring consistent authoritative data.

These challenges are particularly pertinent to hazard management. Floods, droughts, landslides and wildfires require terrain data, observation systems, authoritative national layers

and event-oriented analytics to be used together. Traditional portals are inadequate for this task because value lies not only in viewing data, but also in integrating observation, modelling and decision support products within a single operational environment. Flood applications are an instructive case study because they depend on accurate elevation data, consistent temporal data and the rapid integration of observations.

Slovenia offers favourable preconditions for such development. The country has well-established geospatial datasets, a national topographic and cadastral backbone, regular orthophoto and laser scanning programmes, and a developing cross-sector ecosystem organised through Geo Slovenija. In this context, the national digital twin can be understood as a realistic digital replica of the built and natural environment, where geolocation acts as the key that connects models, observations and services. The practical progression leads from reality capture and 2D/3D representation to linking with static datasets and integrating dynamic feeds. This eventually leads to more automated operations and two-way information exchange.

The contribution of this paper is twofold. First, it formulates a scientific and operational framework for a Slovenian national geospatial digital twin grounded in Geo Slovenija, authoritative national datasets, EO and web-based analytical services. Second, it demonstrates one validated flood-related component of this framework through a pilot study in the Lake Cerknica system. The pilot combines a terrain-based inundation workflow, long-term gauge observations and independent EO-based validation. The paper, therefore, addresses both the architectural question of how a national geospatial twin can be organised and the methodological question of how one concrete hazard workflow can be embedded in it.

To make the scientific framing explicit, the paper addresses three research questions: **RQ1:** How can a Slovenian national geospatial digital twin be structured to integrate authoritative

reference data, EO, hydrological observations and 2D/3D representations through Geo Slovenija? **RQ2:** To what extent can a terrain-constrained, gauge-driven flood-state reconstruction reproduce EO-observed water extent in the Lake Cerknica pilot? **RQ3:** What do the Lake Cerknica pilot results imply about transferability, scalability and operational readiness for national deployment of the DT?

2. Related work

The concept of a digital twin is rooted in the idea of a connected physical and digital system in which data flows support monitoring, prediction and management. Grieves and Vickers (2017) offered one of the foundational interpretations of a digital twin as a coupled physical–virtual system. Meanwhile, Jones et al. (2020) demonstrated through a systematic review that the literature contains heterogeneous definitions and implementation patterns. In the geospatial domain, this ambiguity is further exacerbated because the object of interest is seldom a single machine or asset, but rather a landscape, city or entire national territory comprising multiple scales, actors and processes.

Therefore, urban and geospatial digital twins have been discussed in terms of both technical systems and institutional arrangements. Batty (2018) emphasised the importance of understanding digital twins as analytical urban models rather than merely as digital replicas. Ketzler et al. (2020) reviewed digital twins in cities as a rapidly developing field in urban planning and management. In contrast, Jeddoub et al. (2023) emphasised the ongoing discrepancy between conceptual definitions and practical implementations, particularly with regard to data integration. More recently, Metcalfe et al. (2024) have argued that geospatial science is central to national and international digital twins, as issues such as scale, reference systems, semantics, uncertainty and interoperability form the basis of their operation.

Recent flood-related DT studies illustrate two complementary approaches. Urban twins, such as FlowsDT-Galveston, use a combination of high-resolution LiDAR, infrastructure models, and 1D/2D hydrodynamics to enable street-scale scenario analysis and 4D visualisation (Mandal et al., 2026). In contrast, stormwater DTs with online data assimilation focus on sensor quality control, uncertainty management, and short-term operational forecasting within drainage networks (Kim et al., 2025). While these studies demonstrate methodological richness, they are typically city- or catchment-specific and do not, in themselves, resolve national issues such as authoritative reference-data governance, cross-domain interoperability, and reuse across hazards.

Flood-related digital twins and digital hydrology systems offer useful applications. In flood analysis, the performance of models depends strongly on the relationship between topography, observations, and update frequency. Classical flood inundation modelling ranges from physically based hydraulic schemes to simplified raster-based reconstructions and empirical remote sensing approaches. Bates and De Roo (2000) demonstrated the value of raster-based inundation methods that exploit detailed terrain data. Teng et al. (2017), meanwhile, reviewed the wide spectrum of flood inundation models, emphasising the trade-offs between complexity, data requirements, uncertainty, and run time. In operational settings, approaches that are computationally efficient yet capable of rapid updating remain particularly relevant when the goal is

state reconstruction and decision support rather than the detailed modelling of all hydraulic processes.

Against this background, the Slovenian contribution is novel in three linked ways. Firstly, it incorporates the twin in Geo Slovenija as a national governance and interoperability layer rather than as a standalone city platform. Secondly, it explicitly treats temporal heterogeneity by distinguishing between static reference layers, periodic structural refreshes, near-real-time observations, and event-derived analytical outputs. Thirdly, it validates one flood-state component against independent EO reference data, providing reproducible evidence for a transferable DT building block, despite the paper not claiming to present a new, high-fidelity hydrodynamic solver.

3. Framework for the Slovenian National Geospatial DT

3.1 From SDI to geospatial ecosystem: Geo Slovenija as the national foundation

The proposed Slovenian geospatial digital twin is not intended to be an isolated application. Rather, it is built on top of the evolving national spatial data infrastructure and the so called Geo Slovenija ecosystem, which connects several state domains concerned with real estate, spatial planning, the environment, nature, and water. Geo Slovenija provides practical solutions such as cross-domain catalogues, metadata, registries, reusable service building blocks and sandbox-style environments, making spatial datasets and services discoverable and interoperable across institutional boundaries. This is a crucial role because a national geospatial digital twin requires stable governance and interoperability before more advanced analytics and decision-support systems can be implemented.

From a digital twin perspective, Geo Slovenija functions as the connected data and service layer that enables scalability. It does not replace thematic systems, but rather enables them to be linked consistently. This aligns with the shift from SDI thinking towards a broader geospatial ecosystem, where value stems from cross-querying, integration, and reuse, rather than isolated dataset publication. Consequently, the national digital twin should be viewed as an analytical and operational extension of the national geospatial ecosystem rather than an alternative to it (Lisec et al., 2026).

3.2 Core data and service components

Figure 1 summarises the conceptual architecture of the national geospatial digital twin of Slovenia. The base comprises authoritative national reference geospatial data, including cadastral parcels, topographic databases, land use and land cover data, orthophotos, and other official registers. These datasets provide the positional, semantic, and legal consistency required for multi-sector integration. A second group comprises terrain and 3D data sets derived from repeated photogrammetric and laser scanning programmes. These data sets have two functions: they support physically meaningful spatial analysis and provide the geometric basis for 3D visualisation and object-based interpretation.

A third group contains dynamic observations. EO sources, such as Sentinel-1 and Sentinel-2, as well as PlanetScope and updated orthophotos, offer synoptic observations of land and water dynamics (ESA, 2025a). In contrast, in situ hydrological and meteorological observations provide temporally denser forcing and state information. These heterogeneous inputs are linked through analytics and simulation services that derive

flood-state layers, Earth observation (EO) water masks, exposure overlays, change products and potentially AI-assisted reporting products. The final user-facing layer is a web-based DT environment that supports 2D/3D visualisation, querying, time-enabled layers and plug-in applications. In the current Slovenian context, such an environment already supports hazard-oriented pilots, replay-style analysis, and integration with external EO services.

An important architectural feature is the connection to external EO ecosystems. The Slovenian DT is intended to connect not only to national authoritative data services, but also to European data spaces and pre-operational digital twin environments. This enables national applications to utilise broader EO resources while maintaining national context, semantics and governance. In this sense, the national twin acts as an interoperability layer and downstream application rather than a closed internal system.

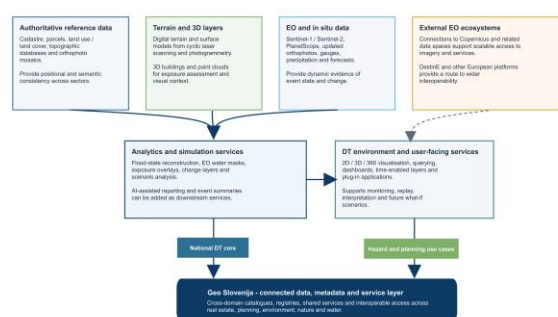


Figure 1. Conceptual architecture of the Slovenian national geospatial digital twin. Geo Slovenia acts as the governance and interoperability foundation that links authoritative reference data, EO, in situ observations, analytics and user-facing applications.

3.3 Temporal model and operational maturity

The temporal organisation of the twin is as important as its thematic structure (Figure 2). Static reference layers include data whose geometry and semantics change slowly, such as cadastral data, topographic data, base terrain models and national 3D building data. Periodically updated structural layers include orthophotos, repeated laser-scanning campaigns, updated land-use data and EO archive snapshots. Near-real-time observations are primarily provided by hydrological measurements, precipitation data and meteorological forecast services, while satellite acquisitions supply event snapshots whenever available. On top of these layers, the DT produces event-driven outputs such as inundation masks, water-depth rasters, change layers, alerts, dashboards and reports.

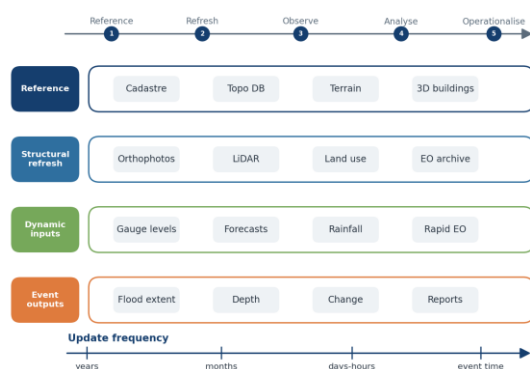


Figure 2. Simplified temporal model and operational maturity pathway of the DT. The diagram distinguishes four temporal/update groups - reference layers, structural refresh, dynamic inputs and event outputs - and links them to an operational pathway from reference capture to analysis and service delivery.

This temporal model is consistent with the maturity pathway of the Slovenian twin. The system begins with reality capture and 2D/3D representation, then links static national datasets, adds higher-frequency feeds, and progressively moves towards two-way and more automated operation. The current prototype should therefore be regarded as pre-operational rather than purely conceptual: it already supports 2D/3D integration, scenario-oriented visualisation, replay of flood situations, long-term water-dynamics analysis and exploratory AI-assisted risk reporting. This is a significant distinction because it means that the twin already behaves as more than a static geoportal, even though several operational functions still require further hardening and automation.

4. Flood pilot application: Lake Cerknica

4.1 Study area and input data

The flood pilot scheme was implemented in the Lake Cerknica area in southwestern Slovenia. Lake Cerknica is a large, intermittent karst lake and one of the country's most distinctive floodplain systems. The combination of a shallow topographic basin, strong water-level sensitivity and relatively rich observational support makes it particularly suitable for a digital twin pilot. Even small changes in the water level can result in significant differences in the area inundated, making the site ideal for testing terrain-based reconstruction of the flood state and Earth observation (EO)-based validation.

The pilot uses three main data sources. First, a high-resolution digital terrain model provides the microtopographic basis for identifying potential inundation areas. Secondly, long-term gauge observations from the Dolenje Jezero station provide the hydrological forcing. In the current implementation, the available series spans the period from 1954 to 2025. Thirdly, multispectral PlanetScope scenes provide independent observations of water extent for selected dates between 2023 and 2025. All layers used in the analytical workflow are harmonised to the national spatial and vertical reference frames (i.e. D96/TM in plan and SVS2010/Koper in height). This harmonisation is essential because even minor vertical discrepancies can significantly distort a flood-state reconstruction based on terrain thresholds.

4.2 Terrain-constrained inundation modelling

The flood-state reconstruction is deliberately lightweight. For each time step t , the observed gauge values are first transformed into absolute water-surface elevations (h_t) in the national vertical reference system. Then, for each terrain cell i with elevation z_i , inundation is inferred from the condition that $h_t > z_i$ and the relative water depth is computed as $d_i = \max(0, h_t - z_i)$. This approach does not attempt to resolve the full hydrodynamics of flood propagation; rather, it reconstructs the spatial state implied by the observed water level and detailed topography. Such terrain-constrained methods are computationally efficient when high-quality elevation data is available and rapid state estimation is more important than resolving all local flow processes.

To support long time series, the relationship between water level and inundated area ($A(h)$) is precomputed from the terrain model. Once this relationship is available, daily flood masks can be efficiently generated for the entire gauge record. Additional derived layers include relative water depth, flood frequency, cumulative flooded area, and event-specific spatial products. For comparison with PlanetScope imagery and web delivery, the daily masks are resampled to a 5 m grid and exported as raster products. Figure 3 summarises the workflow from study-area inputs to DT publication.

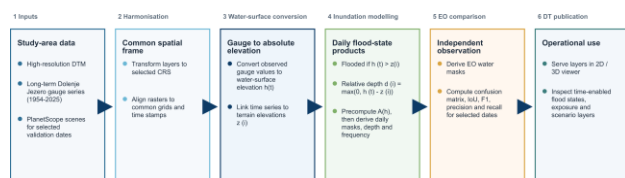


Figure 3. Flood pilot workflow for Lake Cerknica. Gauge observations are converted to water-surface elevations, linked to the DTM, transformed into daily flood-state products and compared against EO-derived water masks before publication in the DT environment.

4.3 Integration into the DT environment

The outputs of the flood pilot are stored and explored as time-enabled layers within a web-based DT environment. In practice, this environment supports 2D and 3D visualisation, spatial querying, timeline navigation, Earth observation (EO) overlay, and the inspection of terrain, flood state, and contextual layers within a shared scene. This allows users to transition from water-level observations to spatially explicit flood states, which can then be interpreted relative to land cover, settlement patterns, and other reference information. As the Lake Cerknica study area is dominated by open karst floodplain dynamics, 3D buildings mainly serve as contextual objects in this pilot and are not yet used as explicit hydraulic obstacles.

Integration into a DT environment is significant because it converts otherwise separate raster products and time series into an operational, decision-supporting representation. Therefore, the pilot can be used not only to reconstruct historical states, but also support the replay of selected events, compare EO observations with modelled states, and test scenario-oriented workflows. In principle, the same structural logic can be transferred to other hazard domains and parts of Slovenia where high-resolution terrain and dynamic observations are available.

4.4 Representation of buildings and vertical obstacles

Ultimately, a national geospatial digital twin should represent not only terrain and water, but also the built environment. Structured 3D building data is important because it provides spatial context for exposure analysis and enables object-based intersection with hazard layers, improving interpretation in 3D scenes. In Slovenia, repeated photogrammetric and laser scanning data facilitate systematic national 3D building production, although the level of geometric and semantic detail will vary depending on the application and production cycle.

In the current Lake Cerknica pilot, however, buildings have not yet been modelled as explicit vertical hydraulic obstacles, as regularly inundated areas are dominated by open karst floodplain dynamics, and the most pertinent analytical question concerns the water-level-driven expansion of open water. Nevertheless, buildings remain useful as contextual elements in the 3D environment, reminding us that the same DT architecture

must later support settlement-oriented cases, in which exposure, accessibility, and infrastructure impacts are much more central. It is important to note that the Lake Cerknica pilot validates one core flood-state component, whereas future urban pilots should extend the same framework towards obstacle-aware modelling and stronger asset-impact analysis.

4.5 DT outputs for flood management

The most important outputs within the DT environment are the time-enabled inundation extent, relative water depth, long-term flood frequency, cumulative flooded area, and the precomputed $A(h)$ relation linking water level to inundated area. These outputs can be examined alongside authoritative reference layers, Earth observation (EO) imagery and contextual 3D data. This allows users to swiftly transition between synoptic event interpretation and local spatial detail. Therefore, the same flood state can be represented as a raster, as a long-term temporal product, or as a layer within a broader 2D/3D decision-support scene.

This representation adds value for multiple user groups. Civil protection actors can use it for event awareness and replay; municipalities and planners can see where recurrent inundation overlaps with assets and land uses; and researchers can compare modelled and observed states through the same interface. In this sense, the Cerknica pilot is not only a hydrological case study, but also a methodological demonstrator showing how national geospatial layers, Earth observation (EO) evidence and hazard-state analytics can be assembled into an operational digital twin workflow.

5. Validation and results

5.1 Validation design

The validation process involved an independent comparison between modelled flood masks and EO-derived water masks. For each of the 26 PlanetScope dates used in the assessment, the modelled raster was aligned to the EO grid and resampled to 5 m, before being compared at a pixel level. A confusion matrix was used to derive the number of true positives, false positives, false negatives and true negatives. From these values, the following were computed: Intersection over Union (IoU), F1 score, precision and recall. The Intersection over Union (IoU) metric was prioritised because it directly represents spatial overlap and is less misleading than overall accuracy in situations where the ratio of water to non-water areas is highly imbalanced.

The benchmark is intentionally limited to agreement with EO-derived reference water masks only. This should not be interpreted as a full comparison against 2D/3D hydrodynamic baseline models, depth observations or velocity measurements. Therefore, the present evaluation tests whether the DT component reconstructs observed flood-state geometry at a landscape scale, rather than whether it resolves all flow processes, local obstacle effects or detailed water depths.

5.2 Flood state reconstruction and EO agreement

Long-term reconstruction confirms a distinctly non-linear relationship between water level and inundated area. At lower water levels, inundation gradually expands to fill depressions and the Strzen channel system. At a gauge level of around 281.5 cm, a clear threshold is reached, after which the broader floodplain becomes active, and the increase in flooded area

steepens (Figure 4). At higher levels still, expansion slows again due to the morphological limits of the polje. This behaviour indicates that microtopography exerts a strong control over the spatial response of the Lake Cerknica system.

Lake Cerknica (Slovenia)

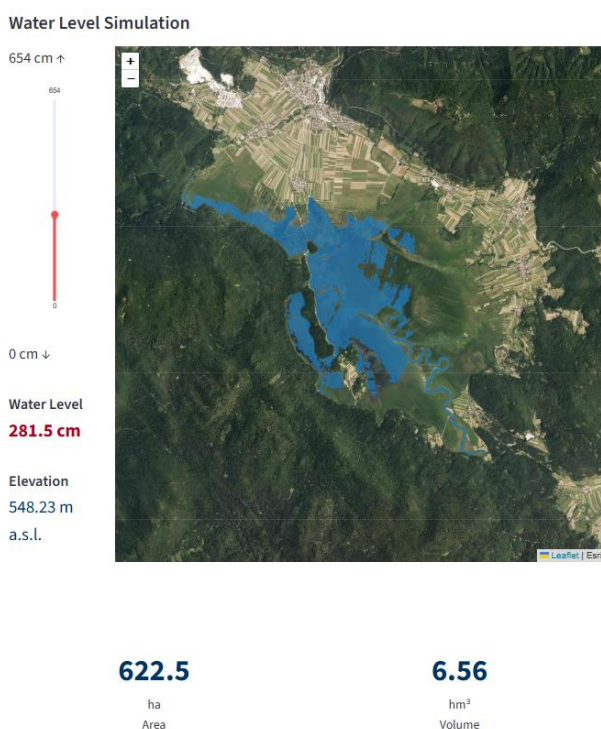


Figure 4. DT Lake Cerknica.

Across the full validation sample, the terrain-based model achieved a mean Intersection over Union (IoU) of 0.62 ± 0.26 and a mean F1 score of 0.75 ± 0.22 . Precision was high (0.90), indicating that areas labelled as flooded by the model were usually observed as water in PlanetScope images. However, recall was lower (0.67), suggesting that the EO masks sometimes identified additional wet or spectrally water-like areas that were not represented by the terrain-threshold model. During stable lake phases, performance improved substantially, with mean IoU increasing to 0.72 ± 0.18 and mean F1 to 0.86 ± 0.05 . During this time, precision increased to 0.93 and recall to 0.77.

Relative dispersion also decreases in stable phases. The IoU coefficient of variation falls from 0.42 for the full sample to 0.25 for stable states, and the F1 coefficient of variation falls from 0.29 to 0.06. Therefore, performance is not only higher on average during stable phases, but also markedly more consistent.

The pattern of agreement is hydrologically plausible. Stable open-water conditions are well represented because the terrain threshold closely corresponds to the physical water surface. During transitional drying phases, however, EO-derived masks may include shallow water, saturated soils, wet vegetation, and spectrally ambiguous surfaces, which the terrain-based approach does not classify as open water. Therefore, some disagreement reflects different observational definitions of the target phenomenon rather than model failure alone.

5.3 Performance and limitations

From a computational perspective, the prototype is designed to be efficient. Once the terrain model and the A(h) relation have been prepared, large numbers of daily flood masks can be rapidly generated from gauge values. In operational terms, the main latency does not arise from the flood-state calculation itself, but from the update cycle of external observations, particularly EO acquisitions, which are used for validation and interpretation. This distinction is important for digital twins: near-real-time awareness can be driven by gauges and forecasts, whereas EO data is often sparser but provides independent evidence.

The main sources of uncertainty are terrain accuracy, the conversion of gauge values into absolute elevations, the temporal discrepancy between the model state and EO acquisition, and the ambiguity of EO water masks in areas with shallow water, vegetation, wet soil, clouds or shadows. Additionally, Cerknica is not a representative urban flood case. While it is highly suitable for testing terrain-water level-EO coupling, it is less suitable for evaluating obstacle-aware urban hydraulics, local drainage controls, or detailed damage estimation in densely built environments. Therefore, the current pilot should be interpreted as a validated building block within a wider national digital twin (DT) programme, rather than as a universal flood-impact model for all Slovenian settings.

The following summary of uncertainties can therefore be stated:

- Vertical error in terrain or in the gauge-to-datum conversion primarily shifts the reconstructed shoreline.
- Temporal mismatch between gauge time and EO acquisition affects rapidly changing stages.
- EO ambiguity in shallow, vegetated or cloud-affected areas tends to reduce recall.
- Transferability beyond the Lake Cerknica pilot area is strongest for terrain-dominated open-water settings rather than urban, obstacle-controlled floods. Confidence in the reported metrics is accordingly highest for stable open-water phases and lower for transitional wetness conditions.

6. Discussion

6.1 Scientific contribution of the DT approach

The main scientific contribution of this work is integration. Rather than treating flood analysis, EO interpretation, authoritative reference data and 3D visualisation as separate tasks, the proposed Slovenian DT approach unites them within one coherent architecture. Instead, they are placed within one coherent architecture, with Geo Slovenija providing the interoperability foundation and authoritative data providing the semantic and positional backbone. Analytical services then generate temporally explicit hazard-state products. This transforms the twin into something more than a 3D scene or a mere collection of web services; it becomes a structured analytical environment in which the same state can be explored across spatial, temporal, and thematic dimensions.

A second contribution is methodological. The Lake Cerknica pilot demonstrates that a computationally lightweight, terrain-constrained inundation workflow can be incorporated into a national digital twin and verified using independent EO data. This is useful because many discussions about flood-related DTs focus on complex hydraulic engines without considering operational latency, reproducibility, or national-scale

transferability. In the Slovenian case, the combination of terrain data, gauge observations and EO-based validation provides a robust starting point for national hazard state reconstruction. Compared to urban flood twins and sensor assimilation systems, the Slovenian pilot is best understood as a lightweight but nationally interoperable component that prioritises datum consistency, reproducibility, and transferability over full hydrodynamic detail.

6.2 Implications for national-scale deployment

There are several implications for national-scale deployment. Firstly, the coexistence of different temporal layers must be explicitly addressed: slowly changing authoritative layers require governance and versioning, whereas higher-frequency observations necessitate automated ingestion and harmonisation. Secondly, hazard-specific components must be modular. The same DT environment should be capable of hosting flood-state reconstruction, drought indicators, landslide susceptibility layers, wildfire information, and related reporting products, without forcing all hazards into a single, comprehensive model. Thirdly, stronger urban and infrastructure-oriented test cases are needed to benchmark the framework in settings where buildings and engineered barriers influence the behaviour of hazards.

The current Slovenian prototype already demonstrates this broader applicability. Beyond the Lake Cerknica pilot, the same environment has been used for replay-oriented analysis of the August 2023 flooding and for future services relating to flooding, drought, landslides and wildfires. AI-assisted risk reporting is also a plausible downstream capability, given that the system already organises information into structured spatial states and time slices. The remaining challenge is not a lack of conceptual direction, but rather the operational work involved in automation, service hardening, access management, security, and systematic validation across multiple cases.

From a European perspective, the Slovenian digital twin is therefore best understood as a national pre-operational digital twin aligned with Digital Twin Earth, powered by Earth observation (EO) data, and moving progressively towards resilience-oriented service pathways (ESA, 2025b; ESA, 2025c). This positioning clarifies where the Slovenian system can contribute, namely as a national downstream EO application layer and as a national interoperability counterpart for European digital twin efforts. In the longer term, it could also serve as a client of more secure and resilient operational services.

6.3 Data governance, versioning and service readiness

Operational digital twins depend on data governance details that are often overlooked in conceptual diagrams. Dynamic layers must be versioned, traceable and reproducible. Users need to know which terrain model, water-level observation, Earth observation (EO) scene and processing rule produced a given flood-state layer. This requires explicit lineage metadata, temporal tagging and robust reference system management. Without such controls, a national twin could appear visually convincing yet be analytically fragile.

Service readiness is equally important. National deployment will likely require differentiated access paths for public use, professional planning, research workflows and public authority operations. Standardised APIs, stable identifiers, authentication mechanisms and clear update expectations are therefore integral to the digital twin architecture. In this respect, the current

Slovenian prototype can be viewed as a pre-operational stage that already demonstrates scientific value and interoperability logic. The next phase must then transform these strengths into reliable national services.

7. Conclusions

This paper presented a framework for a Slovenian national geospatial digital twin, demonstrating a validated, flood-related component via a pilot application in the Lake Cerknica system. The proposed architecture is based on Geo Slovenija, combining authoritative national reference data, terrain and 3D layers, Earth observation (EO) data, in situ observations and analytical services within a shared digital twin (DT) environment. Methodologically, the Lake Cerknica pilot demonstrated that a terrain-constrained inundation workflow, driven by a long-term gauge record, can reconstruct temporally explicit flood states and be independently validated against EO-derived water masks.

The validation results indicate moderate to good overall agreement and notably stronger performance during stable lake phases, confirming the usefulness of the approach for open-water state reconstruction. Equally importantly, the pilot demonstrates that the added value of the digital twin (DT) lies not only in the flood solver, but also in the coupling of simulation, observation and authoritative geospatial context. As the workflow relies on a nationally relevant terrain backbone and modular dynamic inputs, the underlying principle can be transferred beyond the Cerknica case.

Taken together, the findings provide answers to the three research questions posed in the introduction. RQ1 is addressed by a Geo Slovenija-based architecture that organises authoritative, EO and analytical layers into a single, coherent DT environment. RQ2 is addressed by the EO benchmark, which demonstrates moderate-to-good spatial agreement overall, as well as notably stronger and more consistent performance during stable lake phases. RQ3 is answered conditionally: while the workflow can be used as a national DT building block for terrain-dominated flood-state reconstruction, broader deployment requires additional urban pilots, fuller benchmarking and service hardening.

Future work should extend the framework to additional flood types, more urbanised environments, and other hazard domains while improving automated ingestion, access control, reporting, and service robustness. Even in its current form, however, the pilot provides a scientifically sound and operationally relevant building block for developing a national geospatial digital twin in Slovenia more broadly.

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