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Article

Spatial Insights for Building Resilience: The TErritorial RIsk Management & Analysis Across Scale Framework for Bridging Scales in Multi-Hazard Assessment

Francesca Maria Ugliotti *, Muhammad Daud and Emmanuele Iacono

Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy; muhammad.daud@polito.it (M.D.); emmanuele.iacono@polito.it (E.I.)
* Correspondence: francesca.ugliotti@polito.it

Highlights:

What are the main findings?

- The TERIMAAS framework successfully integrates BIM, GIS, and IoT data to enhance multi-hazard risk assessment, bridging scales from territorial impacts to individual structures.
- A public building case study in a critical natural hazards area in northwest Italy demonstrates real-time flood risk assessment to improve resilience and disaster management strategies.

What is the implication of the main finding?

- The scalable approach equips different types of stakeholders with actionable insights for enhancing critical infrastructure resilience against evolving environmental risks.
- Policy-makers and asset managers gain a dynamic decision-making tool, fostering proactive disaster preparedness and optimised resource allocation.

Abstract: In an era of increasingly abundant and granular spatial and temporal data, the traditional divide between environmental GIS and building-centric BIM scales is diminishing, offering an opportunity to enhance natural hazard assessment by bridging the gap between territorial impacts and the effects on individual structures. This study addresses the challenge of integrating disparate data formats by establishing a centralised database as the foundation for a comprehensive risk assessment approach. A use case focusing on flood risk assessment for a public building in northwest Italy demonstrates the practical implications of this integrated methodology. The proposed TErritorial RIsk Management & Analysis Across Scale (TERIMAAS) framework utilises this centralised repository to store, process, and dynamically update diverse BIM and GIS datasets, incorporating real-time IoT-derived information. The GIS spatial analysis assesses risk scores for each hazard type, providing insights into vulnerability and potential impacts. BIM data further refine this assessment by incorporating building and functional characteristics, enabling a comprehensive evaluation of resilience and risk mitigation strategies tailored to dynamic environmental conditions across scales. The results of the proposed scalable approach could provide a valuable understanding of the territory for policymakers, urban planners, and any stakeholder involved in disaster risk management and infrastructure resilience planning.

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1. Introduction

This paper examines how Digital Twin (DT) challenges can enhance multi-hazard risk assessments by integrating Building Information Modelling (BIM), Geographic Information Systems (GIS), and the Internet of Things (IoT) domains. This study presents the TErritorial RIsk Management & Analysis Across Scale (TERIMAAS) framework, using a flood risk case study to illustrate the practical application of these integrated technologies enabled by implementing a consolidated centralised database.

1.1. Background and Motivation

In the modern era, the DT [1,2] paradigm disrupted the idea of representing the world through simplified models that describe its behaviour. A DT is a real-time digital replica of a physical entity. The fundamental parts can be mirrored in a virtual environment and continuously updated from multiple sources for various purposes [3]. Rapid advances in telecommunications and information technology in recent years have led humans to want to achieve more accurate and detailed descriptions of the built environment. The goal is to reach the twin copy of the system—a building, a city, or a territory in the field of investigation—and interrogate it concerning its real-time state. The most cutting-edge enabling technologies, including Big Data, cloud computing, the IoT, and artificial intelligence (AI), now make it possible to collect, store, and handle an ever-increasing amount of data by facilitating cross-domain access. Data have become so relevant in the information society that it is seemingly the only thing that matters. The creation, distribution, use, dispersal, integration, and management of information have become the most significant cultural, economic, and political tasks to achieve competitive advantages [4]. In line with this understanding, the Dutch architect Maas provocatively published a book at the end of the last century that reflected on the futuristic "Datatown", a city-based exclusively upon data, a city to be described only by the flow of information [5]. Data appears to be the most reliable tool for providing an accurate view of social interactions from our daily activities and the environment that staged those interactions [6]. Now up to fourteen [7], the characteristics of Big Data were initially defined according to the 3Vs model—volume, variety, velocity—by analyst Doug Laney, based on a 2001 study [8]. Volume concerns the amount of data collected and stored. Data creation follows an exponential process. According to the global data and business intelligence platform "Statista", about 328.77 million terabytes, or 0.33 zettabytes, of data are created daily [9]. Moreover, 90 percent of the world's data have been created in the past two years alone [10]. Variety concerns the diversity of formats, sources, and structures. Velocity allows it to be readily available for real-time management and use.

Within this framework, using interoperable platforms is crucial to converting data into usable information to ensure fruitful collaboration among stakeholders and make sense of the data through their interpretation. A system aimed at a data-driven approach in the built environment, in a transition process such as the current one, must be able to develop an ecosystem of services [11] by responding to queries related to the synchronic state of affairs of diachronic scenarios [12]. This aspect is particularly crucial when examining resilience in the age of climate change, as numerous dimensions need careful monitoring. Improving the understanding of disaster risk and strengthening disaster risk governance, as suggested by the Sendai Framework of 2015 [13], represents another goal to be achieved. According to the United Nations Office for Disaster Risk Reduction

(UNDRR), disasters are indeed reversing global development at unprecedented rates; therefore, urgent actions are needed to build resilience to withstand and respond to shock in every decision we make. With current climate projections, the world could face 560 yearly disasters by 2030 [14]. As tools nowadays enable a more performant multidisciplinary knowledge of the built heritage, pragmatic experimentation to guide the handling of complexity is essential in structuring and graphical and visual representation of the data. The perspective lies in experimenting with ways to relate heterogeneous, static and dynamic data to each other, interrogate them concerning specific objectives, and visualise them through intuitive presentation modes.

One of the most relevant aspects of a multi-hazard assessment is considering the continuous transition in scale, from the general to the particular and vice versa. Data have become increasingly accurate over time, assuming greater complexity and resolution; however, they consider the specific areas of investigation. To predict the impacts of the environment on individual works, as well as the effect of individuals concerning the surroundings, the availability of large-scale spatial and temporal data must cross that of high-resolution detail, as depicted in Figure 1. The perspective of making effective decision support systems [15] to predict pre- and post-extreme event impacts requires the interpretation of data derived from spatial knowledge of buildings, territory, and hazards.

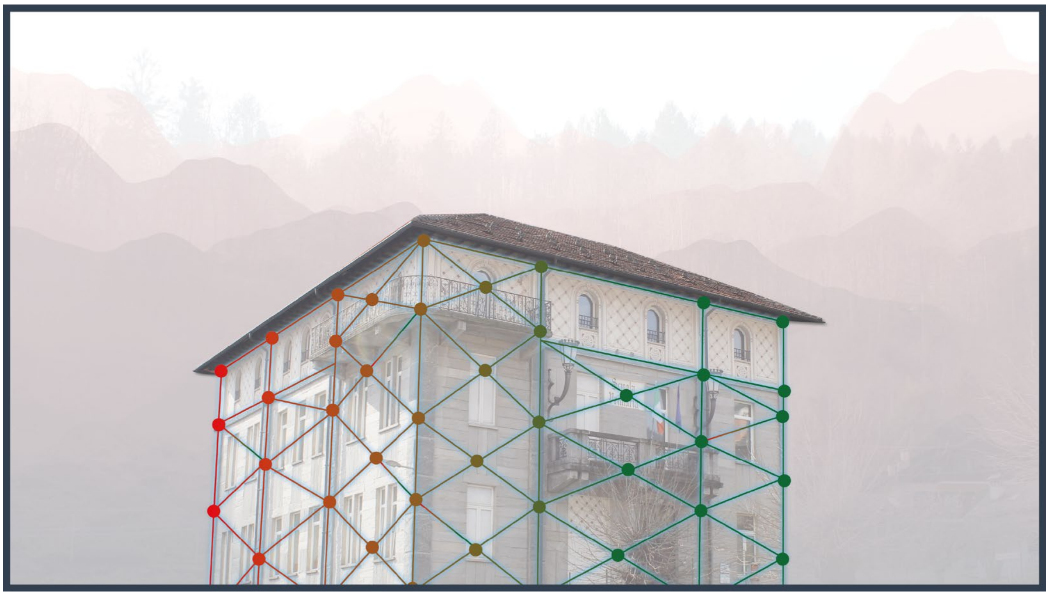

Figure 1. Strengthening building resilience through IoT-driven environmental data integration.

1.2. Literature Review

BIM and GIS are critical technologies in the architecture, engineering, and construction (AEC) and geospatial industries. The possibility of cross-reading data from these domains has emerged as a promising practice for enhancing spatial data analysis and infrastructure management efficiency and scope. BIM offers highly detailed, three-dimensional representations of buildings, integrating comprehensive datasets on architectural, structural, and mechanical systems [16,17]. Conversely, GIS excels in spatial data analysis and visualisation, offering a broader macro-level view of natural and built environments [18]. Their integration leverages the micro-level detail of BIM with the macro-level spatial analysis capabilities of GIS, offering a transformative advancement for improved data utilisation, collaboration, and decision-making capabilities for various sectors.

The application that finds the most exhaustive discussion in the literature is undoubtedly related to the realisation of urban models for the management of Smart Cities. The different granularity of geometric, spatial, material, and functional information favours advanced analyses, accurate simulations and more informed decision-making processes to address complex urban challenges related to sustainability and resilience. This approach yields a two-fold value. On the one hand, it enriches the management of point infrastructures that can benefit from a more effective contextualisation of works. On the other hand, it is critical for disaster management [19,20], which is increasingly central to international policies in the ever-more pressing context of climate change.

The GIS-BIM fusion enables a holistic assessment of a critical asset, particularly in managing natural hazards and disasters at different levels [18] and evaluating mitigation actions. In fact, GIS is particularly adept at hazard risk assessment and management due to its robust spatial data analysis capabilities, which include terrain modelling, hydrological analysis, and infrastructure visualisation [15,21]. BIM complements this by providing detailed data on building structures and systems, allowing for the precise evaluation of vulnerabilities and the development of targeted mitigation strategies [22]. When integrated, BIM's granular building information and GIS's broad spatial context enhance emergency response efforts, improve situational awareness, and support more informed decision-making [23]. This integrated approach is crucial for effective disaster management, where timely and accurate data are imperative [24]. The STORM project exemplifies such integration by offering a comprehensive multi-hazard risk assessment and management tool tailored for cultural heritage sites, addressing both natural hazards and climate change impacts [24].

Despite the promising potential of GIS-BIM urban modelling, several limitations hinder its widespread adoption and operational efficiency. These challenges span technological, methodological, and institutional dimensions. Recent research has focused on various approaches to achieve effective BIM-GIS integration focusing on data interoperability, standardisation, and processing techniques.

- Data interoperability and integration challenges*:* as the two systems were designed for different purposes, one of the most significant limitations lies in the difficulty of seamless data exchange between BIM and GIS platforms, leading to isolated data silos and impaired comprehensive analysis [22,25]. Although open data standards such as IFC (industry foundation classes) CityGML or GeoJSON aim to bridge this gap, they are not universally implemented and may lead to information loss during conversion. Differences in data formats, coordinate systems, and semantic representations often lead to compatibility issues. Although BIM can utilise global coordinates, it frequently defaults in practice to local coordinate systems for detailed design, whereas GIS typically employs global coordinate systems for spatial analysis. Furthermore, the extent and accuracy of georeferencing in BIM models may vary substantially across standards, model versions, and authoring tools [26]. In cases where a BIM model is already georeferenced, GIS integration may be indeed simplified because geographic alignment tasks can be slightly more straightforward. However, assessing the building's position data is critical regardless of whether a BIM model includes global coordinates by default. Efforts to overcome data incompatibilities include the development of middleware tools, standard conversion protocols, and hybrid platforms. Nonetheless, data conversion between these formats can lead to data loss and reduced accuracy [27] and can be resource-intensive and prone to errors [28].
- Semantic mapping and ontologies: semantic discrepancies between BIM and GIS models constitute a significant hurdle. Ontological frameworks [29] have been developed to establish mappings between BIM's detailed, object-oriented semantics and GIS's spatially referenced data. The granularity of BIM data often mismatches the broader spatial scope of GIS. BIM models typically focus on individual buildings or infrastructure elements, while GIS operates at scales encompassing neighbourhoods,

cities, or regions. Reconciling these different levels of detail to ensure meaningful integration without oversimplifying or overloading the system is a significant challenge.

- Level of detail: one of the key aspects of BIM-GIS integration is considering the different levels of detail (LOD) used in each domain. In BIM, the LOD is used to categorise the level of completeness of the graphic and alphanumeric information contained in a model, ranging from basic geometry with a low amount of associated data to highly detailed 3D building components with large amounts of additional parameters [30]. On the other hand, GIS data adopt a different approach to LODs (ranging from LOD0 as simple building footprints to LOD4 as 3D buildings with modelled interiors) [31], which are based on spatial resolution and typically reach a lower amount of detailed geometries if compared to the higher LODs of BIM, because of the larger territorial scope for which they are used. A proper BIM-GIS integration would therefore need to take into account these discrepancies without sacrificing the essential data of each domain nor overloading the emerging integration with redundant specificities. The concept of the level of information need (LOIN) introduced by the ISO 19650 [32] can be useful for implementing models (i.e., level of detail, dimensionality, location, appearance, parametric behaviour, accuracy, and reliability of model elements) that fulfil certain information purposes, even though they are not characterised by a high level of graphics or information. In fact, the level of information need framework defines the extent and granularity of information according to its purpose.
- Computational complexity and performance: integrating BIM and GIS often results in highly complex datasets that can be computationally demanding to process. The level of detail required for BIM models may overwhelm GIS systems while simplifying BIM data for GIS applications risks losing critical architectural or engineering details. Managing and visualising these large datasets requires an advanced computational infrastructure, which may not be accessible in many urban planning contexts.
- Cost and resource constraints: developing and maintaining integrated BIM-GIS models is resource-intensive, requiring significant software, hardware, and skilled personnel investment. These costs can be prohibitive for smaller municipalities or projects with constrained budgets.
- The lack of standards and workflow: international efforts, such as ISO 19650 and Open Geospatial Consortium (OGC) standards, aim to harmonise the BIM and GIS ecosystems. However, there is no universally accepted framework or workflow for integrating BIM and GIS, which leads to inconsistencies in implementation. The lack of standardised protocols makes collaboration among stakeholders more difficult, especially in multidisciplinary projects involving architects, engineers, urban planners, and policy makers. Furthermore, data ownership, privacy, and lack of standardised workflows hinder adoption.
- Limited scalability for urban dynamics: while BIM-GIS models excel in static analyses, they often struggle to incorporate temporal and dynamic urban processes, such as population growth, traffic patterns, and environmental changes. Current models frequently lack the flexibility to update in real-time, limiting their utility for adaptive urban management.

While significant progress has been made, continued research and standardisation efforts are crucial to address the existing challenges and unlock the full potential of BIM-GIS integration. Currently, great research interest is focused on implementing web-based and cloud platforms for data exchange and visualisation. A recent systematic review highlights that centralised databases and integrated webGIS platforms significantly contribute to informed decision making in disaster risk management by enhancing capabilities in risk data collection, processing, and the dissemination of natural disasters [33].

Despite the advantages of integrating BIM and GIS, traditional systems often rely on static data, posing significant limitations for real-time hazard assessment and responsive disaster management. In the context outlined above, emerging opportunities that may offer interesting insights in the coming years are oriented towards the development of Digital Twins, with the integration of dynamic data and automatic data analysis procedures using Artificial Intelligence and Machine Learning techniques. The IoT can enable continuous, real-time data collection and transmission, which provides up-to-date information on environmental conditions and structural integrity [34].

As shown in the "House of Digital Twin" framework [35] illustrated in Figure 2, the system architecture should support data interoperability, standardisation, and real-time data integration, incorporating automated data transformation, validation, and updating processes. It should also provide a centralised data repository to streamline data management and improve stakeholder accessibility [36,37]. Standardised data protocols and interoperable systems to enhance the usability of risk information [38] are in fact highlighted as requirements by studies and the reviews of risk web platforms.

Integrating IoT with BIM and GIS facilitates dynamic model updates and enhances hazard assessment and response capabilities [39]. As an example, the InSPiRE project demonstrates the efficacy of combining IoT with BIM for predictive maintenance, improving lifecycle management through real-time data acquisition and analysis [12].

Through the literature analysis, it is clear that this research addresses a critical knowledge gap by adopting a multi-hazard approach that provides a more realistic and comprehensive understanding of the impacts. A well-designed, interoperable framework will enhance data sharing, improve decision making processes, and optimise resource management in disaster risk management. It will also facilitate the development of innovative, resilient cities capable of effectively withstanding and recovering from natural hazards and disasters [40–43].

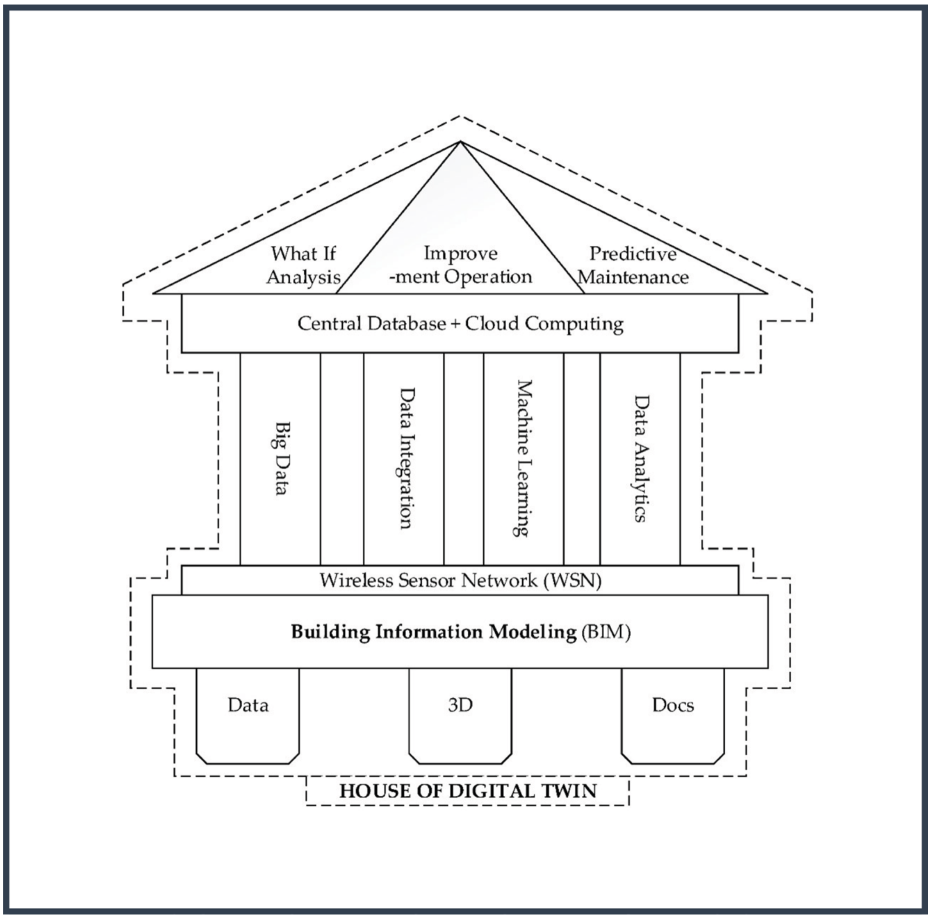

Figure 2. The "House of Digital Twin", illustrating the essential components of a DT [17].

1.3. Significance of the Study

Effective resilience planning for multi-hazard scenarios requires integrating territorial and building-scale analyses, especially as environmental risks continue to evolve dynamically. Current methodologies often fail to comprehensively address these interconnected scales, resulting in fragmented data utilisation and less effective disaster management strategies. This study makes key contributions, including the following:

- Macro- and micro-scale integration: combines GIS-driven territorial data with BIM-based building models to deliver comprehensive resilience insights.
- Centralised database: employing PostgreSQL [44] to unify GIS, BIM, and IoT data, ensuring consistency across different scales.
- Real-time risk monitoring: integrates IoT updates to continuously evaluate hazards, vulnerabilities, and exposures, enabling proactive interventions.
- Operationalising Digital Twin: merges static models with dynamic environmental data to support decision making across multiple scales.
- Validated framework: demonstrates effectiveness through a flood risk case study, linking regional hazards with building vulnerabilities.
- Scalable and modular design: adapts to various hazards and geographic contexts, supporting both urban resilience and localised infrastructure protection.
- Addressing research gaps: overcomes the critical limitations in GIS-BIM integration, offering a comprehensive approach to resilience planning [15].

To achieve these features, this study is guided by clearly defined objectives that translate TERIMAAS's contributions into actionable outcomes. These objectives ensure that the framework's theoretical foundations align with practical applications, effectively addressing real-world challenges in disaster resilience and multi-hazard risk management:

- Develop a centralised database: create a PostgreSQL-based system to integrate GIS, BIM, and IoT data for unified macro- and micro-scale analyses [44].
- Define risk indicators: implement dynamic metrics for the real-time assessment of vulnerabilities and hazards across territorial and building scales.
- Validate through application: demonstrate the adaptability and reliability of TERIMAAS through a flood risk case study in Piedmont, Italy, connecting regional hazard data with localised vulnerabilities.
- Propose a modular framework: establish a scalable and adaptable methodology suitable for diverse natural hazards and geographic contexts.

TERIMAAS goes beyond existing approaches by unifying territorial and building-level analyses into a cohesive, dynamic framework. Its ability to integrate GIS, BIM, and IoT data while providing real-time insights attempts to set a standard for multi-hazard resilience planning. The contributions of this study will allow stakeholders to make informed decisions, optimise resource allocation, and protect both communities and infrastructure.

The methodology developed in this study is scalable and adaptable to various study areas, thereby enhancing the generalisability and practical application of the findings. This approach is visually represented in the framework shown in Figure 3, which links building-scale resilience with territorial-scale hazards.

The research is organised as follows: Section 2 describes the methodology and technical framework of TERIMAAS, highlighting software and data management processes; Section 3 presents the method's application in a case study, focusing on a specific use-case; Section 4 includes the discussion, findings, and future works; and Section 5 provides a summary of the study.

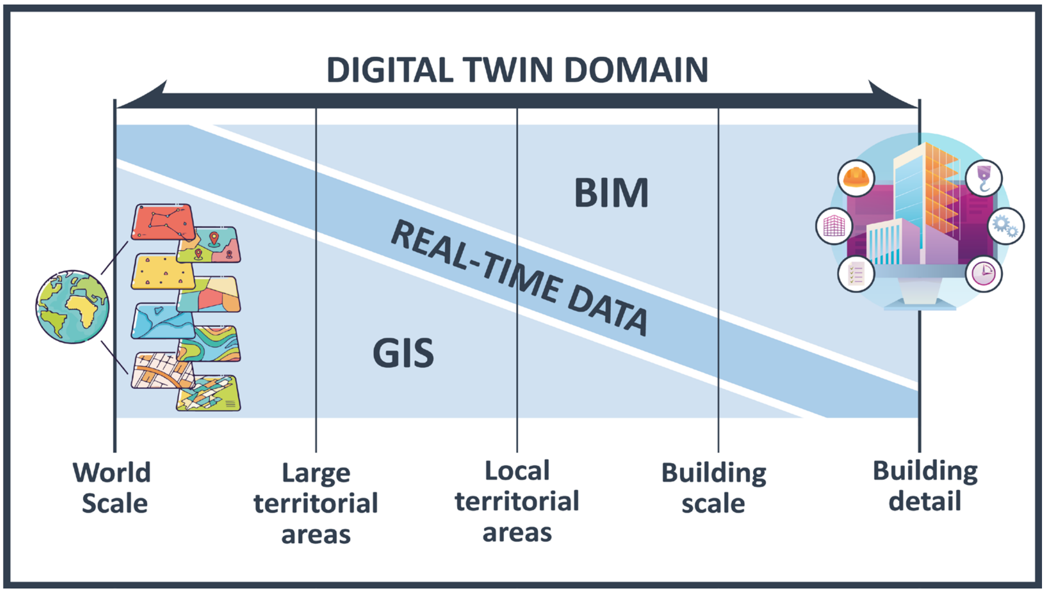

Figure 3. The DT domain: connecting the building detail with world scale for integrated hazard assessment.

2. Methodology

The volume and variety of information to be achieved and managed in the perspective of obtaining a representative twin model of the territory crucially configure data collection and visualisation activities. The outlined complexity must recognise the need to intelligently converge highly heterogeneous data sources such as type, format, discipline, and granularity. Accessing a comprehensive consolidated database is essential for correlating multidisciplinary and cross-scale data and paves the way for new testing and approaches.

The TERIMAAS framework employs a structured and integrated approach to multi-hazard risk assessment, addressing data interoperability challenges, temporal variability, and cross-scale analysis. The methodology is designed to unify macro-(territorial) and micro-(building) scale perspectives, combining IoT, GIS, and BIM data into a centralised and dynamic system. The framework ensures precise and actionable insights for disaster risk management by focusing on real-time adaptability and cross-domain data integration.

The architecture of TERIMAAS is presented in Figure 4. The core of the proposed solution is an infrastructure-as-a-service, consisting of a collection of virtualised resources for storage, processing, and visualisation purposes. The idea is to combine static and dynamic data of interest through a relational database management system (RDBMS). In this way, it is possible to make information datasets generally managed with dedicated environments interact with each other. IoT, GIS, and BIM systems constitute the primary databases that implement the central storage unit. The monitoring and analysis method for territorial resilience is therefore structured into three interconnected processes.

The first process focuses on dynamic data management, leveraging IoT sensors and automated pipelines to ingest real-time geotagged data. These data are validated and processed to create high-resolution hazard maps that adapt dynamically to evolving scenarios, enabling timely decision making.

The second process emphasises geospatial data management, employing high-resolution vector and raster datasets to analyse regional hazard impacts. By utilising scalable cloud infrastructure, this process facilitates the efficient handling and visualisation of data for multi-hazard scenarios.

The third process centres on building-scale data management, integrating enriched BIM models with the centralised database. Advanced bidirectional tools, such as Dynamo and FME, enable dynamic updates to building vulnerabilities while linking them to broader regional hazard data.

Together, these processes bridge temporal hazard monitoring, geospatial precision, and building-level assessments. Dynamic updates, powered by trigger functions, transform incoming data into actionable insights, which are visualised through intuitive dashboards and platforms. This cohesive methodology sets the stage for the detailed explorations in Sections 2.1–2.3, showcasing how TERIMAAS effectively integrates data to advance multi-hazard resilience planning.

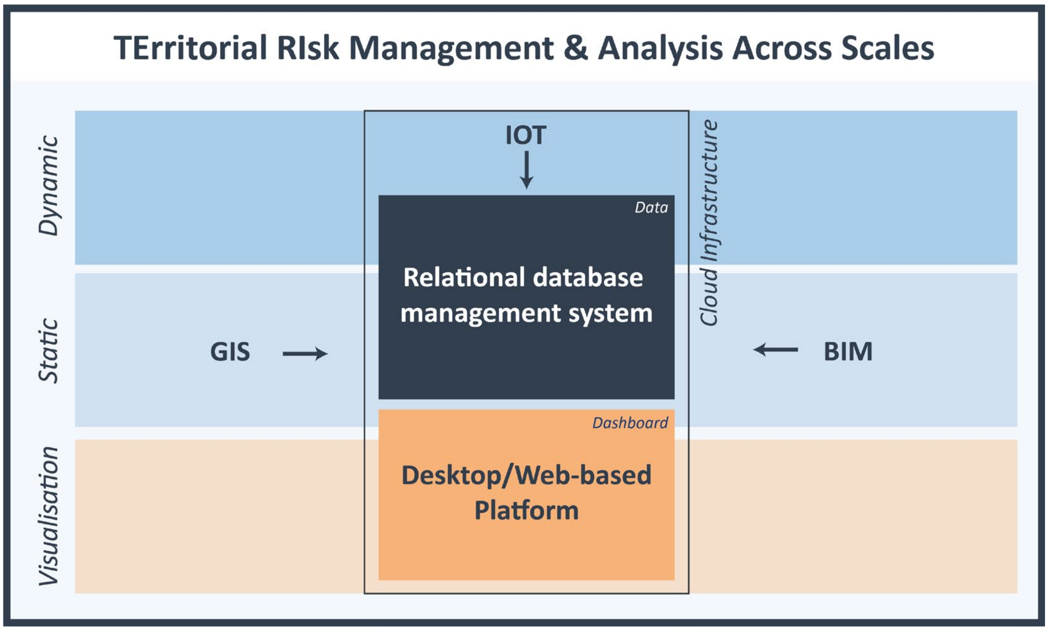

Figure 4. Conceptual design of the TERIMAAS multi-hazard framework.

2.1. Dynamic Data Management at the Temporal Scale

Natural hazards, such as earthquakes, floods, or wildfires, necessitate real-time assessment, a capability often limited by the static nature of traditional GIS and BIM datasets collected post-event [45]. TERIMAAS addresses these challenges in hazard scenarios through a robust and continuous data ingestion pipeline. Application programming interfaces (APIs) and webhooks serve as gateways, facilitating the constant influx of high-frequency, geotagged data streams from IoT sensors. These sensors provide real-time data, which can originate from diverse sources such as national meteorological agencies, regional hazard monitoring networks, or open source weather data providers.

The raw data undergo a multi-stage validation process, which includes outlier detection, spatial interpolation, and plausibility checks against historical data, and real-time observations. Subsequently, validated data are integrated into a spatially enabled PostgreSQL/PostGIS geodatabase.

The ingestion of fresh data triggers a cascade of automated processes using Trigger functions tailored to the specific hazard. Real-time sensor data are spatially interpolated and integrated with external data sources to generate high-resolution hazard maps for hazard events. These estimates are fed into distributed physical models running on a scalable cloud infrastructure to dynamically simulate the hazard's evolution. These models incorporate factors relevant to the specific hazard, such as terrain, weather patterns, and infrastructure vulnerability. The resulting hazard maps are then used to assess risk at various scales, from individual buildings to entire regions. A rule-based alert system can disseminate targeted warnings to relevant stakeholders through multiple channels, enabling timely evacuations or other mitigation actions if pre-defined risk thresholds are exceeded. This IoT-driven methodology empowers TERIMAAS to furnish a continuously updated and multi-layered view of the unfolding hazard situation, which is vital for making informed decisions at various spatial scales, from individual properties to the entire territorial landscape.

It is essential to observe that, when moving from single-hazard to multi-hazard analysis, the temporal and spatial scale of the risk may drastically change. Figure 5 from Gill et al. 2014 shows the spatial and temporal scales over the 16 natural hazards on logarithmic axes. Here, the spatial scale refers to the area that the hazard impacts, and the temporal scale refers to the timescale on which the single hazard acts upon the natural environment [46].

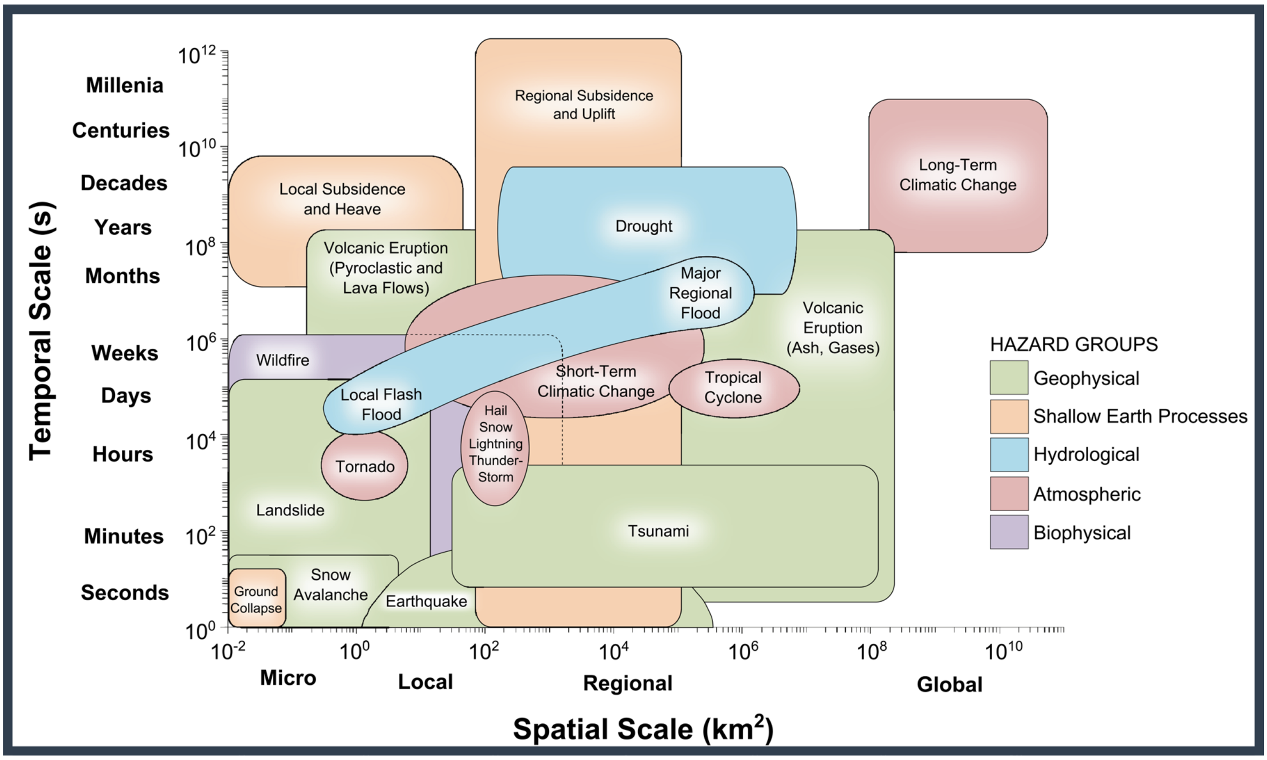

Figure 5. Natural hazard types mapped by spatial and temporal scales [46].

2.2. Geospatial Data Management at the Territorial Scale

GIS are integral to the TERIMAAS framework, providing the tools necessary for comprehensive multi-hazard risk assessments. As GIS data advances in resolution and density, the capability to capture and analyse spatial information has significantly improved. This enhanced data quality allows for the more precise and detailed evaluation of natural hazards and their impacts on natural and built environments.

The TERIMAAS framework leverages vector and raster data to conduct thorough hazard analyses. Vector data, which include discrete features such as roads, buildings, and land parcels, complement raster data that represent continuous variables like elevation and temperature. These dataset's high-resolution and high-density nature supports detailed local-scale analyses, which are crucial for understanding vulnerabilities at the level of individual structures and natural features. For instance, flood risk assessments may utilise detailed hydrological models and terrain attributes derived from raster data. At the same time, earthquake studies might focus on vector-based seismic fault lines and building inventories. Integrating these diverse datasets—high-resolution digital elevation models (DEMs), land use and land cover classifications, infrastructure networks, and historical hazard footprints—ensures a comprehensive approach to risk assessment. The combination of proprietary and open source data sources, including satellite imagery, Unmanned aerial vehicles (UAVs) and handheld devices further enhance the richness and applicability of the geospatial data.

The TERIMAAS framework employs cloud-based GIS solutions from Amazon Web Services (AWS) to manage substantial volumes of high-resolution data. AWS provides scalable infrastructure for handling extensive datasets and facilitating advanced web visualisation for hazard management. Essential services include Amazon S3 (Simple Storage Service) for scalable object storage, and cloud-optimised GeoTIFFs (COGs) for efficient data access and processing. AWS EC2 (Elastic Compute Cloud) offers the computational power required for complex spatial analyses, while AWS Lambda enables serverless computing to automate and streamline data processing workflows. These cloud-based solutions address the challenges associated with large, high-resolution datasets, improving data management efficiency and real-time visualisation capabilities.

In addition to cloud infrastructure, GeoPython libraries [47] are pivotal to the analytical processes within TERIMAAS. Libraries such as GeoPandas, Rasterio, GDAL (Geospatial Data Abstraction Library), and Shapely are utilised for various tasks. GeoPandas supports the high-performance manipulation of geospatial data frames, Rasterio specialises in raster data operations, GDAL facilitates format conversion, and Shapely enables advanced geometric operations and spatial queries. Pyproj aids in coordinate transformations, and Fiona manages spatial data files. Tools like HydroSHEDS and HEC-RAS are integrated for hydrological and flood analysis to model and analyse water flow and floodplain dynamics. The automation of these processes is achieved through AWS Lambda, which ensures the accurate and timely geospatial analyses by executing Python 3.11 scripts and workflows with minimal manual intervention.

2.3. Data Management at the Building Scale

Regarding the building scale, BIM methodology [48] provide a digital representation of an asset, focused not only on its graphical 2D and 3D features but, most importantly, the quantitative and qualitative information related to any of its constituent elements. Therefore, it serves as a common source of information about a facility, allowing users to have a reliable basis for decision making. When integrated into DTs, BIM provides an accurate geometric and semantic model of a built asset. This allows for a more granular analysis of potential impacts and vulnerabilities, enabling a potential element-by-element type of assessment.

Specifically, to encourage interoperability between the various systems used, it was decided to use the industry foundation classes (IFC) format, an open exchange format through which both the data and the geometries of a model can also be read outside of any BIM authoring software, almost all proprietary, used to create the model itself [49].

The methodological approach proposed within the TERIMAAS system uses a series of connections, some made in real-time by the tools and software capable of managing the BIM methodology available on the market. Among these, an essential component of an integrated system such as the one proposed is undoubtedly made possible by tools based on a visual programming language (VPL) [50], i.e., systems thanks to which a user, even if not an expert in any specific programming languages, can prototype any functionality from scratch, not already present among the basic ones of the software used, and completely customised based on the needs of the project or application to be created. Furthermore, since these are tools that, in most cases, are integrated, in the form of plugins, within the software used in the AEC industry, the interoperability of data relating to these domains is already optimal. In the case of the system proposed here, there were two tools based on VPL that it was suggested to integrate within the developed methodology, both currently part of proprietary software (while maintaining the aim of also exploring further similar solutions coming from the ecosystem of open source tools): feature manipulation engine (FME, version 2024.1.3) and dynamo (version 2.12, the latter an integral part of the Autodesk Revit 2022 software). There are many similarities in the use of the two tools for integration with the proposed methodology, certainly including the numerous possibilities for exchanging data, both incoming and outgoing, between the model and the database, as well as between these and any module of additional calculation that is intended to be part of the system's structure.

Specifically, the Dynamo plugin [51] has been tested and prepared for bidirectional data exchange with the database: in the model-to-database direction, all data and alphanumeric parameters relating to each component of the model can be transferred within the database, in dedicated tables, with writing and/or updating operations, thanks to the fact that, among the functions available in the plugin above, there are some specific ones for making connections to databases and sending any command to them, effectively allowing the execution of any CRUD (create, read, update, delete) operation. Furthermore, again using certain features made available by Dynamo, it is also possible to make web connections, for example, to external servers using specific HTTP endpoints, to send data relating to the model to said servers, or receive from them, for example, real-time information from sensors placed on site. Both mentioned functions have been successfully used and tested within the TERIMAAS system methodology. In addition, in the database-to-model direction, the connections made possible by Dynamo have also allowed us to experiment with the reception of updated data coming from the PostgreSQL database, following processes triggered by lambda functions every time the database itself receives updated data from IoT sources. The result and related visualisation are shown in the following sections. Ultimately, once again, taking advantage of the functionality made available by Dynamo to execute SQL (structured query language) commands against relational databases, it is possible to obtain updated data processed by the server and receive them directly within the Dynamo script. Similarly, if necessary, it is also possible to directly execute web requests to external services and obtain input data from sensors or public databases. Once the data, as mentioned earlier, have been received within the VPL script, it is possible to process it further, for example, as was done in the use case presented later, by compiling (or updating) appropriate parameters associated with the spaces of a building, as well as each component of the BIM model created.

Similarly to Dynamo, the FME tool [52] was also tested for the purpose of integration into the proposed methodology. In this case, the specific objective was integrating the alphanumeric data and geometric information within the database. This approach was motivated by the fact that FME provides the possibility of exporting a BIM model (in this case, in IFC format) into numerous other spatial formats and environments thanks to its multiple available converters. Currently, the results of this process are still very experimental, and further tests are being carried out due to some emerging critical issues relating to the compatibility of the geometric encoding adopted by the BIM model, the one allowed within the PostgreSQL database, and the necessary further conversions needed in the case of geometry export from the database toward other 3D viewers. However, other intermediate solutions, which can potentially be integrated into the methodology, are currently being tested [53].

With all this considered, as shown in Figure 6, the TERIMAAS framework comprises a series of domain-specific functionalities that make it possible to have GIS (territorial scale), BIM (building scale), and IoT (dynamic) data converged into a single environment. This allows the system to perform specific risk calculations that consider data coming from these different domains and store the raw data and the processed results in a shared integrated database. Finally, this can be visualised through dedicated viewers, potentially using locally installed software and browser-based web viewers.

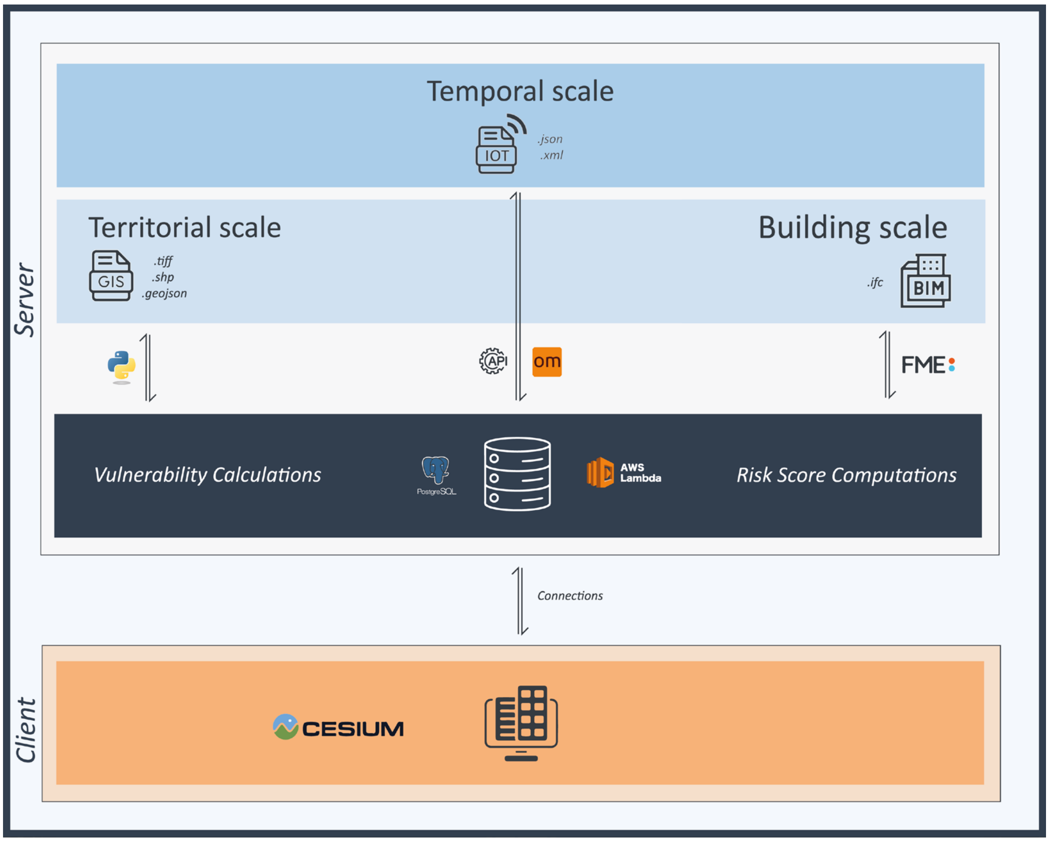

Figure 6. Technical framework of TERIMAAS, highlighting software and data management processes.

3. Use Case Implementation

The methodology presented above is tested through an illustrative use case to clarify the practical application considering a specific environmental risk. This approach can also reflect the modular nature of the TERIMAAS system, outlining its potential in multi-hazard management.

The prototype phase of our study focuses on flood risk by assessing the vulnerability of an actual public building. By cross-referencing the data merged in the centralised Postgres database prototype, the characteristics of the hazard can be related to the area and, specifically, to the characteristics of the building and its activities. Integration is aimed at correlating a relevant precipitation event's effect on the built environment. From the dynamic rainfall dataset, the precipitation height has been derived and related to the construction BIM data, allowing the identification of all model elements affected by the phenomenon to assess potential damage. The focus is not only on the envelope and structural building components but also on the interior environments. With regard to potential flooding, it will, therefore, be possible to identify in detail the functions and assets affected, for example, sensitive rooms such as archives and libraries or IT equipment such as servers often located in basements.

The methodology included the following steps: (i) case study selection, (ii) data collection, (iii) integrated database implementation, (iv) data processing, (v) data visualisation.

3.1. Case Study Selection

Among the many possible areas of interest for this kind of analysis, the Val d'Ossola territory, in the northwest of Italy, was chosen for its susceptibility to several types of natural hazards. In fact, this area, included within the administrative territory of the

Piemonte Region, is among the ones characterised by relatively high seismic activity, at least compared to the rest of the Region [54,55]. Moreover, in this area, surrounded by many mountains and rivers, the probability of flood events is also exceptionally high [56,57]. Finally, another important criterion for choosing the case study area was the relative proximity to the authors, which could have allowed the possibility of performing visits and surveys at any needed time.

Based on the aforementioned reasons, a school building located in Val d'Ossola was selected as a typological case study due to its sensitivity and strategic importance in flood-prone areas (Figure 7). School buildings are a considerably sensitive type of asset, given that, from the perspective of safeguarding human lives, users are primarily children, and therefore, the impact of a disaster event is likely to be extremely high. Moreover, significant public buildings like schools, hospitals, sports halls, and police stations are usually considered "strategic" buildings, meaning that these are types of structures that need to remain operational even in case of disaster events because they might be used, among other things, to host injured and displaced people temporarily. Specifically, the chosen building was the Primary School of Crodo (VB), one of the schools located in its municipality. This building, dating back to the first decades of the 20th century, comprises four levels, the lowest of which hosts a post office, a public music room, and a series of unused empty spaces in the back. The remaining floors above host all the main spaces of the school, such as classrooms, labs, offices, and restrooms. In particular, the school spaces include five classrooms, two laboratories, an office, and a storage space and restrooms for each floor. There is also a minor construction on the side of the building, hosting the central heating unit and a small terrace at the back of the last floor.

3.2. Data Collection

The first phase involves collecting data on the case study and the relevant contextual information needed to approach the use case. Documentary research was carried out to understand the building and its construction phases by investigating the historical and municipal archives in the area, and an on-site visit was made to understand its current state.

Several GIS and IoT data sources were identified and used to enhance the flood risk assessment. The GIS data include DEMs, vegetation soil curve number raster, land use/land cover classifications, infrastructure networks, historical flood footprints, and flood maps. These datasets are primarily sourced from national and regional government agencies and are updated regularly to ensure accuracy and relevance.

OpenMeteo [58,59], an open source meteorological data platform, has also been used. It compiles real-time weather observations and forecast models, providing easy access to critical parameters such as precipitation, temperature, humidity, and wind via RESTful APIs.

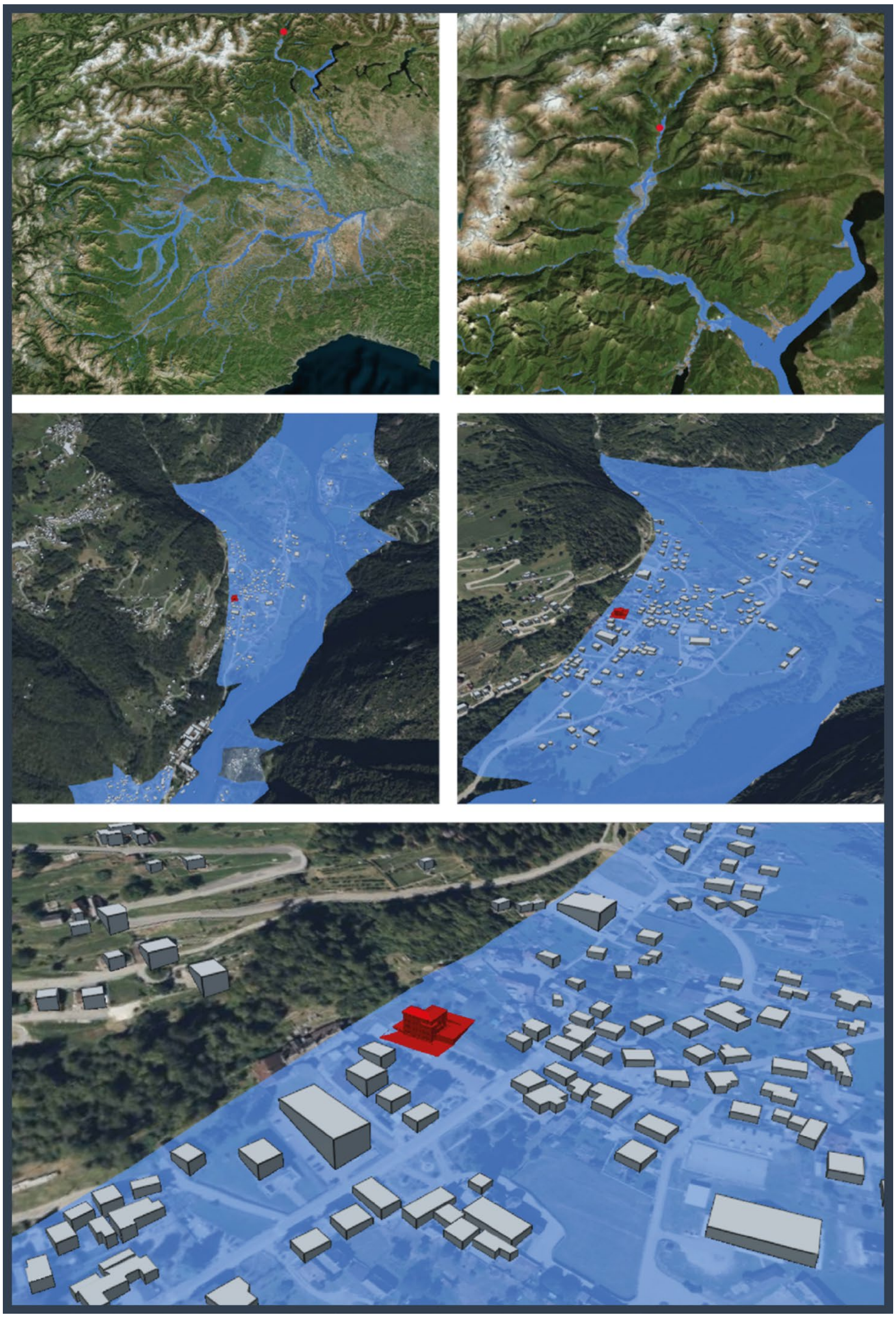

Figure 7. The selected case study building (marked in red) and its related territorial context. The figure highlights how the area is interested by medium-high probability of flood events.

While these data were already available in open format, the building-specific information was implemented entirely from the creation of a BIM model. As shown in Figure 8, it consists of a relatively high LOD [30] for the architectural discipline. In contrast, the structural and systems disciplines have a lower LOD because of the lack of data. Specifically, the level of geometry is consistent enough across architectural and structural disciplines, giving sufficient detail about the geometric characteristics and proportions of individual building elements and their components. On the other hand, the amount of information, i.e., the level of information, is much higher for architectural elements and spaces, giving insights about materials and functional uses, while information about the structural materials and performance were not available at the time, and therefore, only assumptions could be made about it. The parameters entered in the model are functional to the purpose of the use case, so even if the overall LOD is not rich, valid and interesting considerations can be drawn from the analysis.

Table 1 below outlines the various datasets used, their purposes, formats, sources, frequency of updates, and accessibility, offering a comprehensive view of the data integration necessary for this flood analysis. This GIS and IoT data integration ensures a robust flood risk assessment and management framework, facilitating effective decision making and planning.

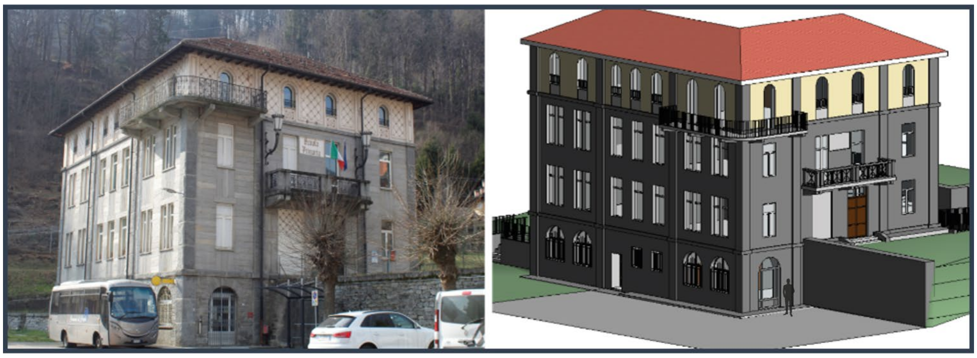

Figure 8. (**a**) The school building used as a case study, and (**b**) its corresponding BIM model for assessment and visualisation purposes.

Table 1. Summary of the data sources, purposes, and formats.

Type	Purpose	Format	Data Provider	Accessibility
DEM	Digital elevation model for mapping and analysis	Raster (GeoTIFF)	Online (API)-National Mapping Agency [60]	Open
DTM	Digital terrain model for hydrological and topographical analysis	Raster (GeoTIFF)	Online (API)-National Mapping Agency [61]	Open
Soil Curve Number	Soil curve number raster for runoff calculation in hydrological models	Raster (GeoTIFF)	Online (API)-Environmental Agency	Open
Precipitation Data	Real-time precipitation measurements for flood forecasting	Time-series (CSV)	Online (OpenMeteo API)-Weather Stations [58]	Open
Meteorological Data	Weather parameters (temperature, humidity, wind) for detailed flood impact analysis	Time-series (CSV)	Online (OpenMeteo API)-Weather Stations [59]	Open
Soil Moisture Data	To assess soil saturation levels which impact runoff and flooding potential	Time-series (CSV)	Online (API)-National Weather Service [59]	Open
Building Information	Detailed architectural and structural data for flood risk assessment of buildings	IFC	Offline-Local/Architectural Firms	Closed
Land Use/Land Cover	Classification of land cover types for flood impact analysis	Vector (SHP)	Online (GIS)-Environmental Agency [62]	Open
Historical Flood Footprints	Records and extent of past flood events for risk assessment and planning	Vector (SHP)	Historical (GIS)-National Disaster Agency [63]	Open
Hydrological Models	Simulation models for predicting flood behaviour and water flow dynamics	Model (HEC-HMS)	Offline-Hydrological Institutes [64]	Closed

3.3. Integrated Database Implementation

The TERIMAAS framework is built on a centralised PostgreSQL database enhanced with PostGIS, providing a robust infrastructure for managing diverse spatial and temporal datasets critical to multi-hazard flood risk assessment. This database supports the seamless integration of GIS, BIM, and IoT domains, forming the foundation of the school building case study. The database schema organises four primary datasets:

- Meteorological inputs: real-time weather data ingested at 15 min intervals, retaining spatial (e.g., station coordinates) and temporal (e.g., timestamps) details.
- Topographic layers: high-resolution DEMs and soil conservation service (SCS) curve number rasters, essential for terrain and runoff analysis.
- Building attributes: structural information from BIM models, including basement elevations, material properties, and equipment locations.
- Hazard metrics: outputs from hydrological simulations, such as flood depth and velocity grids, used to assess building-level and regional risks.

To support high-performance processing, the database employs advanced optimisation techniques. Spatial indexing using GiST indexes enhances the efficiency of query operations, particularly for large geospatial datasets, ensuring the rapid retrieval of relevant information. Additionally, time-based partitioning segments meteorological inputs into temporal intervals, streamlining data retrieval and simplifying the maintenance of continuously growing datasets. These optimisations ensure that the database can handle dynamic, real-time data flows while maintaining fast and reliable performance. The database's robust security framework includes the following:

- Role-based access control (RBAC): restricts access to authorised users.
- Encryption: secures sensitive information during storage and transmission using SSL/TLS protocols.
- Audit logging: tracks all data access and modifications for traceability and accountability.
- Backup and replication: safeguards against data loss, ensuring availability during disaster scenarios.

This centralised database ensures data consistency, enabling validated datasets to be readily available for advanced modelling and real-time risk analysis. Figure 9 illustrates the seamless integration of GIS, BIM, and IoT datasets within the TERIMAAS database architecture.

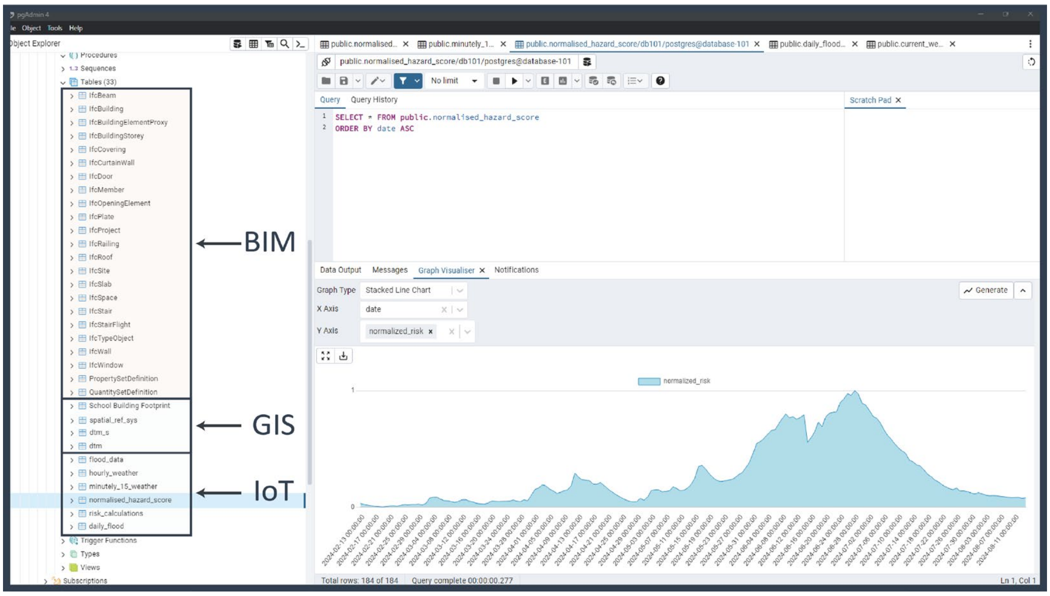

Figure 9. Integrated database demonstration including all GIS, IoT, and BIM domains.

3.4. Data Processing

The data processing pipeline in the TERIMAAS framework transforms validated inputs from the centralised database into actionable insights for flood risk assessment. By integrating meteorological, geospatial, and structural datasets, this pipeline provides high-resolution, dynamic hazard evaluations tailored to the case study.

Real-time meteorological data [65] are retrieved every 15 min via AWS Lambda functions and undergo a rigorous validation process. The data are checked against baselines and thresholds stored in the meteorological thresholds table to ensure only high-quality data are used for analysis. The cleaning process includes the following steps:

- Outlier detection: identifies and removes anomalies using statistical methods like Z-score analysis.
- Missing data imputation: addresses gaps through spatial and temporal interpolation techniques.
- Spatial alignment and temporal synchronisation: ensures consistency with the database schema.

Validated data initiate downstream workflows through PostGIS triggers, which automate critical spatial operations to streamline the processing pipeline. For example, meteorological inputs are intersected with topographic and hydrological layers, including DEMs and SCS Curve Number rasters. This intersection generates updated boundary conditions required for hydrological models. The outputs from these operations, such as refined data for flood simulations, are stored in the hazard metrics table, ensuring the immediate availability for subsequent analysis and decision-making processes.

Hydrological simulations are performed using the HEC-HMS model, deployed on AWS Fargate for scalable cloud-based computation. This model dynamically simulates runoff and flood extents based on updated conditions. The outputs, including flood depth and velocity grids, are passed to 2D hydrodynamic models, which simulate floodwater propagation across terrain. These models incorporate the following:

- Infiltration rates, surface roughness, and channel conveyance for accurate flood dynamics.
- GIS datasets, including terrain elevation, land use patterns, and watershed delineations, enhance flood simulations by accounting for local characteristics. These factors refine flood risk assessments and help tailor interventions to specific regional conditions.
- Building-level risk assessments integrate hazard metrics with BIM attributes, dynamically recalculating structural vulnerabilities. Basement elevations, equipment locations, and material properties are evaluated against updated flood depth and velocity thresholds to identify specific risks. These recalculations allow stakeholders to prioritise interventions and allocate resources effectively.

The hazard risk score is normalised to ensure consistency across regional and building-level assessments. Updated flood maps and risk scores provide actionable insights for stakeholders, enabling informed decision making for disaster risk mitigation.

3.5. Data Visualisation

The database mentioned above is a central repository accessible to the BIM system, enabling dynamic flood risk recalculations and accurate hazard mapping for emergency planning and disaster response. After obtaining the results of the calculations, there was the need to represent them graphically so that any potential stakeholder could easily and immediately understand. As a first test of representation of the calculation results carried out, the Autodesk Revit 2022 software was tested as a viewer (the same one also used for the modelling of the school) thanks to the communication possibilities of the Dynamo plugin, already illustrated previously, with the system server set up.

A series of example tests were carried out on the BIM model with Dynamo (Figure 10) to simulate the data update after a request to the database to retrieve hazard calculation results on the area. These included a risk assessment of the building's functional spaces and a few building component categories (namely walls, windows and doors), of which their respective vulnerability and exposure factors were computed. Through the proper functional categorisation of spaces and a view filter applied to the visualisation of building components within the 3D view of Dynamo itself, it was possible to represent a selection of flood risk scenarios which, based on the intended use of each space and the type and height of the related components of the envelope, the model is themed to immediately and directly show the risk to which the various parts of the building are subject.

The example tests considered the three simple standard parameters related to the most common and consolidated risk assessment practices. The risk is, therefore, split into hazard, vulnerability, and exposure.

The hazard factor comes from the calculations performed at the territorial scale, which are directly saved into the database and retrieved by Dynamo through a dedicated call. The vulnerability factor is a parameter associated with each building element and space; therefore, dedicated calculation criteria were set up based on the category of each building component to assess this parameter. For the sake of structuring examples to test the data exchanges, simple assessment expressions were set up. For building spaces, the vulnerability index was a value directly dependent on the function of each space (i.e., classrooms have a remarkably high vulnerability while unused or storage spaces have the lowest). On the other hand, the vulnerability of wall elements was based on a calculation set up to compute their thickness and the elevation of their base. Moreover, a combination of sill height and elevation over the ground was used, considering openings like walls and doors. The result of each component's assessment is then automatically compiled back into the model on a dedicated "vulnerability index" parameter assigned to each element instance. Lastly, the exposure factor is a parameter based on the time and date, meaning that it is considered lower when the spaces of the building are not used, as opposed to when it is crowded with people. These three parameters are collected and computed together in the final script. The results are shown graphically by colouring the desired building elements according to a predefined gradient, as shown in Figure 11.

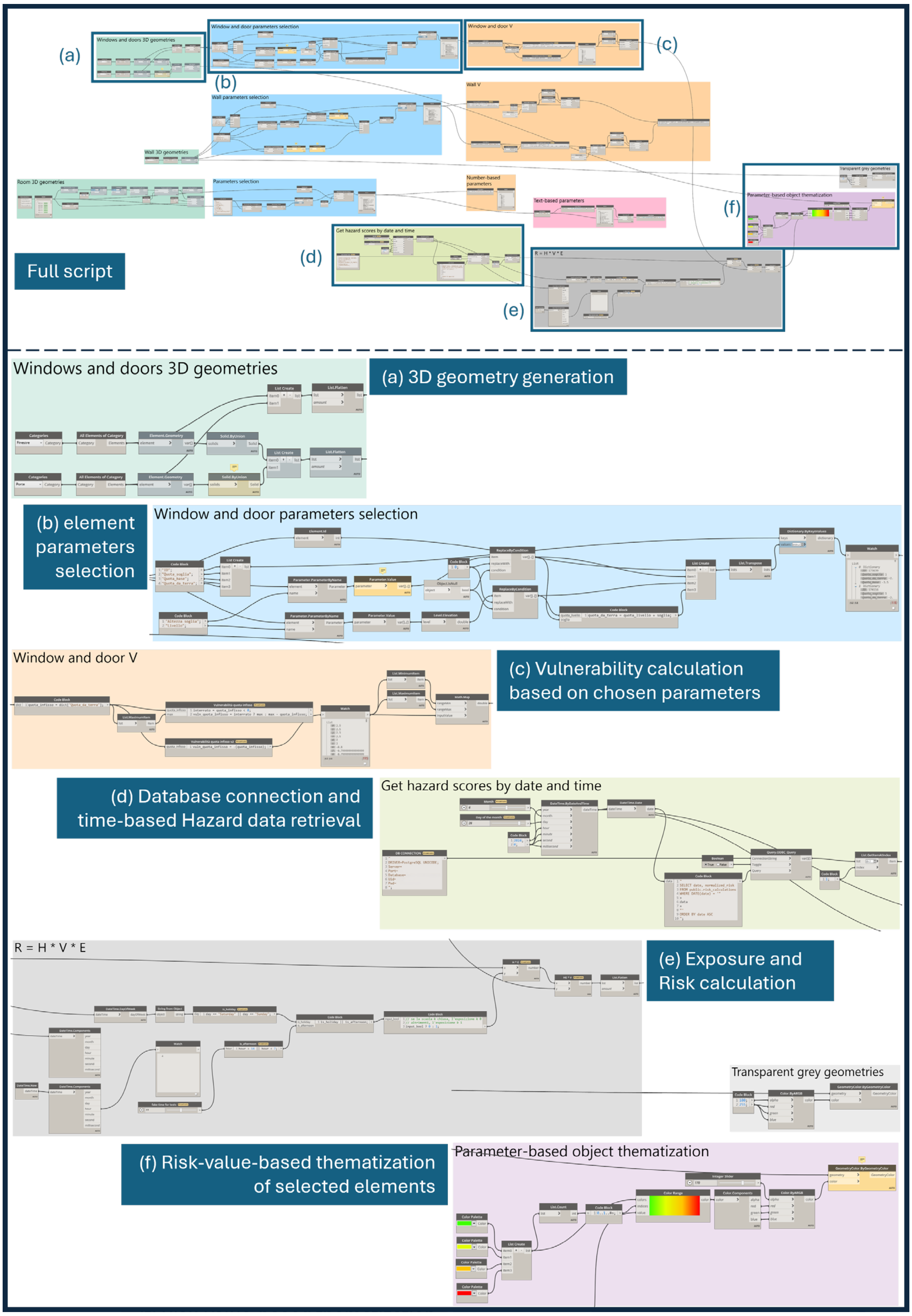

Figure 10. Dynamo script for the vulnerability and exposure assessment calculations of selected BIM model elements, and the colour-coded visualisation of the risk results.

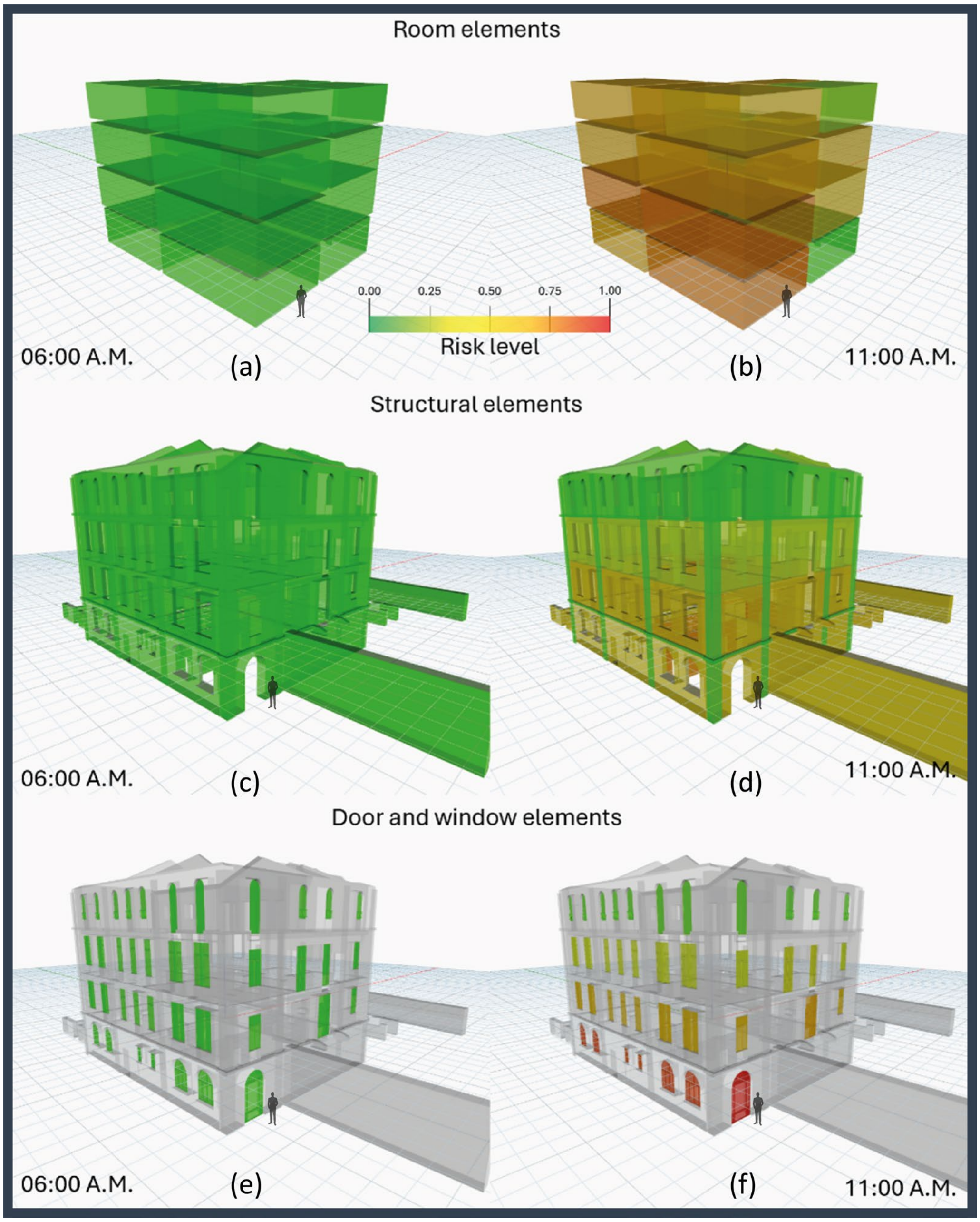

Figure 11. Probability-based flooding risk visualisation for building elements on weekdays, accounting for exposure due to building occupancy: room elements (**a**,**b**), structural elements (**c**,**d**), and door/window elements (**e**,**f**) at 06:00 A.M. (**a**,**c**,**e**) and 11:00 A.M. (**b**,**d**,**f**). Increased occupancy during working hours contributes to higher overall risk.

4. Discussion

The TERIMAAS framework presented in this study provides a robust and comprehensive approach to bridging the gap between environmental and building-centric scales by integrating diverse temporal and spatial data sources. It harmonises GIS, BIM, and IoT domains to deliver consistent, multi-level, granular information. The established integrated database links static hazard-related GIS data for specific areas with dynamic hazard monitoring from IoT sensors. This enables an accurate analysis of the hazard's impact on a specific infrastructure by leveraging the detailed information available in BIM data. This approach supports a multi-dimensional, multi-scale risk assessment to evaluate asset vulnerability effectively. It is critical to understanding the interplay between broader environmental hazards and their localised effects on individual structures, a long-standing challenge in disaster risk management. The method's effectiveness has been rigorously validated through a real-world case study, considering the flood impact assessment on a public building in a critical area of northern Italy.

4.1. Findings

The proposed database integration in the use case aims to assess the impact of flood events on a public-school building. The building is in a high-risk area, as identified by GIS hydrogeological hazard maps, and its characteristics are detailed through a parametric digital model. Data processing determines the precipitation's maximum ground accumulation height relative to the structure. Integrating multiple information domains makes it possible to identify the affected building levels, assess potential damage to components and equipment, and determine unusable spaces. Although BIM modelling provides very detailed asset information, a very high level of detail is not always necessary for meaningful analysis. While geometric detail offers an immediate visual representation of the building, excessive complexity can overload visualisation systems within the framework. Regarding information detail, a higher level allows for more in-depth assessments, yet a well-curated selection of key data may be sufficient to access critical insights unavailable through other systems quickly. However, ensuring data reliability—its accuracy and trustworthiness—remains essential.

Particular attention has been paid to investigating the possible display of the phenomenon, as it is considered essential for an easy and immediate understanding by users. By numerically—but most importantly visually—representing hazard, vulnerability, and exposure factors, computed using data from a combination of the different domains addressed above, within a 3D model, several concrete benefits emerge. School administrators and facility managers can use these outputs to identify high-risk zones within the school—particularly vulnerable functional spaces (e.g., classrooms, labs)—and evaluate in advance the possible reallocation of functions in the event of a critical event. If the probability of a room being flooded is high, consideration should be given to ensuring that no equipment or material is present that may deteriorate in contact with water. This could enable the formulation of more targeted evaluation procedures as well as careful resource allocation to reduce potential flood damage and safeguard users. The identification of critical structural or architectural components (e.g., doors, windows, walls with low elevation) most susceptible to flood events can represent a valid support for local authorities and decision makers to prioritise retrofitting actions or adjustments to interior layouts. This kind of approach can support public policies aimed at mitigating the potential long-term impacts of flood events on public facilities, like the one from the current case study, reducing repair costs over time and enhancing resilience.

This study provides an example related to possible interactions with a centralised database, that can become part of a multi-risk management system, where several types of risk can be considered. These would become system modules, further reinforcing the robustness of the proposed framework. Finally, since the system connects to real-time data sources, the framework carries out continuous updates to hazard parameters, allowing stakeholders to perform near real-time risk estimations. This also means being able to monitor how risk factors might evolve over time, during the life cycle of a building or infrastructure.

However, integrating multi-domain data streams remains a challenge. Studies on BIM-GIS integration [18,27] focus on data interoperability, semantic transformations, and lifecycle applications, but lack real-time hazard tracking, which is crucial for disaster response. Similarly, BIM-IoT research [37,43] explores sensor-based monitoring and automation but remains largely conceptual or prototype-based, struggling with scalability, interoperability, and bidirectional real-time updates.

Hazard management requires both spatial intelligence and real-time responsiveness, yet existing studies fail to integrate dynamic hazard modelling with sensor-driven real-time data. BIM-GIS provides urban-scale context but lacks real-time adaptation, while BIM-IoT offers real-time sensing but remains fragmented. These disconnects hinder an effective hazard response. This shows a clear gap addressed by the TERIMAAS methodology, and tested via a case study, attempting to deliver impactful results that advance disaster management strategies, as follows:

- Seamless integration across scales: GIS-driven territorial data and BIM-based building models are harmonised within a centralised PostgreSQL database, enabling comprehensive multi-scale analyses.
- Dynamic risk monitoring and assessment: real-time IoT updates enhance the evaluation of hazards, vulnerabilities, and exposures, ensuring proactive and adaptable risk assessments.
- Enhanced decision making: the integration of static and dynamic data supports a digital twin approach, empowering stakeholders with actionable insights for both territorial and building-level resilience.
- Proven effectiveness: the case study demonstrated the framework's ability to link regional hazard data with building-specific vulnerabilities, validating its utility in real-world applications.
- Scalability and adaptability: a modular design enables the framework to address diverse hazards and geographic contexts, making it a versatile tool for multi-hazard resilience planning.

While the TERIMAAS framework shows significant promise, several challenges and limitations must be addressed. First, implementing the method requires substantial resources, including technical expertise, robust data infrastructure, and high-quality GIS, BIM, and IoT datasets. These requirements may pose barriers for resource-constrained regions or organisations. Additionally, data privacy, uncertainty, and security concerns associated with the centralised repository and real-time IoT inputs must be managed to ensure compliance with regulations, clear communication and maintain stakeholder trust. Second, the framework's scalability and adaptability to other hazard types and regions warrant further exploration. Although the study focuses on flood risk assessment, its applicability to other hazards, such as earthquakes, landslides, or wildfires, should be investigated. Similarly, evaluating its performance in diverse geographic and socio-economic contexts is essential to establishing its broader utility. Finally, while integrating GIS and BIM offers substantial benefits, managing and processing such diverse datasets involves significant complexity. Developing standardised workflows and tools to streamline these processes will be critical for the widespread adoption of the TERIMAAS framework.

By leveraging GIS for spatial risk analysis and BIM for detailed building-level assessments, the study offers actionable insights for stakeholders. Specifically, four potential users have been identified that may benefit from this kind of platform, both for management and training/education purposes:

- Policymakers and urban planners: the insights can inform decisions on infrastructure investments and resilience strategies. Given the dynamic nature of vulnerability across hazard cascade scenarios, it is essential to understand the potential implications on housing or infrastructure developments [46].
- Critical infrastructure players: by overcoming spatial and temporal scales barriers, players like facility managers and operators gain a deeper understanding of the ongoing works, maintenance procedures, and safety protocols, supplementing with information that returns the current operations of the infrastructure in real-time, and cast about the characteristics and conditions of the territory in which they are located.

This allows them to tailor risk mitigation measures to the specific needs of individual structures.

- Emergency management and disaster risk reduction practitioners and policymakers: simplifying complex data through visualisation schemes empowers these stakeholders to anticipate and respond to hazards at various levels. Specifically, it provides valuable insights for detailed building-specific information, enhancing preparedness and response strategies.
- Scientific community: this research provides a mechanism for contextualising single-hazard studies within the broader scope of multi-hazard scenarios. [46]. The framework fosters improved communication between hazard specialists and critical infrastructure experts, encouraging a more interdisciplinary approach. By continuously refining the TERIMAAS framework, it is possible to equip communities and decision-makers to better anticipate, mitigate, and respond to the growing challenges posed by natural hazards and environmental risks.

4.2. Future Works

Future research and development should focus on several technical advancements to enhance the TERIMAAS framework. A critical area of exploration is comparing centralised and decentralised databases for managing sensitive data. Centralised databases, currently in use, offer unified data management and streamlined access but pose risks related to data security and single points of failure. Future work should investigate implementing advanced security measures and redundancy protocols to mitigate these risks. Additionally, exploring decentralised databases, such as blockchain or distributed ledger technologies, can enhance data security and resilience, ensuring data integrity and availability even in localised failure scenarios.

Expanding the framework to incorporate multi-hazard assessment capabilities is essential. The system's design is scalable and modular, enabling new risk assessment modules to be added without disrupting existing functionality. Future research should develop algorithms and models capable of dynamically assessing and prioritising risks from various natural hazards, including earthquakes, wildfires, and landslides, alongside floods. This integrated approach will facilitate a transition from single to multi-hazard analysis, providing a more comprehensive risk assessment and enabling more effective mitigation strategies and optimised resource allocation.

Integrating open source BIM tools into the TERIMAAS framework is another crucial area of future work. While proprietary tools provide extensive out-of-the-box functionalities, they can be restrictive due to cost and limited flexibility. Open source BIM solutions offer significant customisation options and allow developers to manage their projects better and adapt them over time. Evaluating the performance and interoperability of various open source BIM tools within the existing framework will be vital for broad adoption and flexibility.

Incorporating AI techniques, such as machine learning (ML) and deep learning (DL), can significantly enhance the analytical capabilities of the TERIMAAS framework. Using ML algorithms on datasets will enable the accurate forecasting of extreme events, allowing for a comprehensive assessment of their environmental, economic, and social impacts. For instance, it will be possible to evaluate necessary actions based on the specific characteristics of building occupants and equipment concerning flooding events. This approach recognises that an event's impact is determined by the extremeness of a climate or weather variable and by people's exposure and vulnerability. Future research should focus on developing and integrating these AI techniques to enhance predictive analytics and decision support systems, thereby improving the efficiency and effectiveness of resilience planning and disaster management.

By addressing these areas, future research can build on the foundations laid by this study, driving forward the capabilities and impact of integrated risk management systems.

5. Conclusions

The research highlights the significance of data interoperability by creating a centralised repository that harmonises and automates diverse data formats while integrating both past and real-time IoT-derived inputs. This approach enables the TERIMAAS framework to perform dynamic risk assessments that adapt to changing environmental conditions across multiple scales, as demonstrated in the case study. Incorporating real-time IoT data further enhances the system's responsiveness, continuously updating vulnerability and risk scores to reflect evolving hazards. This adaptability is particularly crucial in the context of climate change, where the increasing frequency and severity of natural disasters demand more proactive risk management solutions.

In conclusion, this study introduces a novel and effective approach to natural hazard risk assessment, providing valuable insights for disaster risk management and infrastructure resilience planning. By addressing key challenges and broadening its scope, the TERIMAAS framework presents a scalable methodology with potential for improving risk analysis and mitigation strategies across various environmental and geographic contexts.

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request. Access to the data is subject to compliance with ethical and legal restrictions.

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