CI-RES: A GIS-Based Platform for Critical Infrastructure Resilience Analysis in Urban Environments

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Abstract. Urban critical infrastructures (such as power grids, water networks, transport systems, and telecommunications) provide essential services to citizens and experience a continuous growth and complexification. Moreover, they are increasingly interdependent and exposed to a wide spectrum of threats, ranging from natural hazards such as earthquakes, floods, and geological instabilities to deliberate anthropogenic attacks. Assessing and improving their resilience and especially the resilience of the resulting system of systems, requires simulation platforms capable of modelling complex interdependencies and evaluating the impact of disruptive events at the city scale. This activity is strictly in line with the so called "CER Directive": the Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities that repeals previous Council Directive 2008/114/EC. This paper describes CI-RES (Critical Infrastructure Resilience), a GIS-based platform developed at ENEA for the collection, visualisation, and simulation of critical infrastructure behaviour in urban areas. The platform integrates geo-referenced data layers with containerised simulation codes covering multiple hazard scenarios. Furthermore, it exposes a meta-modelling interface through which domain experts can compose simulation workflows, evaluate consequences, and estimate dynamic risk and resilience metrics. The ongoing evolution of CI-RES towards a Kubernetes-based deployment is described, together with its roadmap as a foundational component for future Urban Digital Twin implementations. Preliminary results and the platform's potential for supporting municipal authorities and infrastructure protection agencies are discussed.

Keywords: Critical infrastructure · Resilience · GIS · Urban simulation · Kubernetes · Digital twin · Risk assessment · Interdependency modelling

1 Introduction

Modern cities rely on a tightly coupled set of critical infrastructures (CIs) whose correct functioning underpins the delivery of essential services to citizens. Power

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distribution, water supply, transportation, healthcare, and telecommunications are not independent systems: they interact through complex physical and functional interdependencies, so that a failure in one sector risks to propagate rapidly and non-linearly to others [1]. This *cascade* behaviour makes city-scale resilience assessment a fundamentally multi-system problem.

The frequency and severity of disruptive events affecting urban CIs is continuously increasing. Climate change are also expected to amplify the incidence of extreme weather events—floods, heatwaves, and landslides—while the growing digitalisation and automatization of infrastructure control systems exposes them to cyber-physical threats. Seismic hazard remains a dominant concern in many European and Mediterranean urban areas. At the same time, deliberate attacks targeting infrastructure components introduce an adversarial dimension that purely natural-hazard models cannot capture.

Effective resilience management requires tools that can: (i) represent the spatial layout and interdependencies of urban CIs in a georeferenced environment; (ii) simulate the propagation of disruptions across multiple hazard types and infrastructure layers; (iii) estimate the resulting impact on service availability; and (iv) support decision makers in identifying optimal resource allocation strategies to minimise vulnerability and accelerate recovery.

This activity is strictly in line with the Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities that repeals previous Council Directive 2008/114/EC [2] (the so called "CER Directive"). It is worth stressing the CER Directive requires both Critical Entities (Operators, Authorities etc.) to perform risk analysis and to build up resilience plans. The CI-RES platform represents a versatile means to perform those activities, while presenting synthetic outcomes in a friend format.

CI-RES (Critical Infrastructure Resilience) is a platform developed by ENEA within the Italian Programme Agreement for Electric System Research (WP2, Line of Activity LA8) to address precisely the former requirements. Building on a GIS-based data model and a modular simulation architecture, CI-RES provides an integrated environment for urban CI analysis. This paper describes the platform's current capabilities, the ongoing migration to a cloud-native Kubernetes deployment, and the extensions under development that will enable hybrid scenario analysis and meta-modelling through a user-facing web interface.

A reduced set of capability is demonstrated at https://resilientity.enea.it web portal. That web server is also endowed with a private chat-bot that allows users to ask information about critical infrastructures and essential services. This facility will be described in a separate work.

The remainder of this paper is organised as follows. Section 2 reviews related work on CI resilience modelling and urban simulation platforms. Section 3 describes the architecture of CI-RES. Section 4 presents the simulation capabilities and the hazard scenarios currently supported. Section 5 describes the meta-modelling interface. Section 6 discusses the Kubernetes migration and its operational benefits. Section 7 outlines the Urban Digital Twin roadmap. Section 8 presents preliminary results, and Sect. 9 concludes the paper.

2 Background and Related Work

2.1 Critical Infrastructure Interdependency Modelling

The very early study of CI interdependencies was formalised by Rinaldi et al. [3], who identified six classes of interdependency (physical, cyber, geographic, logical, social, and political) and showed that cascade failures across interconnected systems could produce consequences far larger than those attributable to any single infrastructure in isolation. Subsequent work has explored graph-theoretic representations [4], agent-based models, and system-of-systems approaches to capture the dynamics of failure propagation. Starting from the former seminal paper, the "System of Systems" (or Network or Networks) became a central topic in the Complexity Science [5]. The theoretical approach allows to understand the emergent behaviors, that is the universal phenomena ruling interdependent networks, regardless of their details. However, usable models, need to enter in deeper details based on the functional behavior of infrastructures and especially their geographical distribution on the territory.

GIS-based methodologies are particularly suitable for identifying the portions of land where disasters triggered by natural hazards of various kinds may occur. The possibility of producing enhanced maps starting from different geospatial layers (e.g. natural hazards, CI topology, territorial features, etc.) is one of main advantages of GIS applications. The development of GIS-based platforms have emerged as a natural framework for urban CI analysis, since the spatial dimension is central both to infrastructure topology and to the geographic footprint of hazard events. In particular, such platforms allow to solve complex spatial decision problems by integrating GIS with other techniques or tools (e.g., decision support systems).

Tools such as HAZUS [6] provide standardised loss estimation models for earthquakes, floods, and wind events, but are primarily oriented toward physical damage assessment rather than service-level resilience quantification.

Beyond HAZUS, several platforms have been developed to support CI resilience assessment. The Infrastructure Resilience Analysis Framework (IRAF) developed by Argonne National Laboratory provides a systematic methodology for characterising infrastructure dependencies and estimating restoration times [7].

OpenQuake, developed by the Global Earthquake Model Foundation, is an open-source seismic hazard and risk calculation platform widely adopted for infrastructure vulnerability assessment [8].

The SYNER-G project developed a comprehensive methodology for the systemic seismic vulnerability and risk assessment of urban infrastructure systems, explicitly addressing interdependencies among buildings, transportation networks, utility networks, and healthcare facilities [9].

Further, the EU-funded RESILIENS project produced a European Resilience Management Guideline and an associated toolbox for CI operators [10], while the DARWIN project focused on resilience management guidelines for crisis response organisations [11].

CI-RES distinguishes itself from these platforms through: (i) the integration of hybrid natural-anthropogenic scenarios; (ii) a fully containerised simulation architecture; (iii) a meta-modelling interface allowing non-programmers to compose custom workflows; and (iv) direct alignment with the operational requirements of the CER Directive.

2.2 Resilience Metrics and Simulation

Resilience is commonly operationalised as the ability of a system to absorb a disturbance, adapt, and recover to an acceptable performance level within an acceptable time [12]. Quantitative resilience metrics typically integrate performance loss over the disruption and recovery period, requiring time-resolved simulation of post-event system response. This is particularly challenging for urban multi-infrastructure systems, where recovery in one sector depends on the partial recovery of others. Strictly speaking, the 'real' resilience of a system, as compared to its robustness, is related to its recovery capabilities. However, the term is currently employed in a wider sense as stated by the CER Directive [2]. The CI-RES platform enables a comprehensive assessment of system resilience across all its dimensions.

2.3 Urban Digital Twins

The concept of the Urban Digital Twin (UDT) extends the industrial digital twin paradigm to the city scale, combining real-time sensor data, physics-based simulation, and data analytics to create a dynamic virtual replica of urban systems [13]. UDTs are increasingly recognised as a strategic tool for urban planning, emergency management, and infrastructure investment prioritisation; but their enforcement requires a scalable, interoperable simulation backbone of the kind that CI-RES is designed to provide.

3 CI-RES Platform Architecture

3.1 Overview

CI-RES is structured around three main layers: a *data layer*, a *simulation layer*, and a *presentation layer*. The data layer stores geo-referenced representations of urban critical infrastructures and their interdependencies in a GIS-compatible format. The simulation layer hosts a suite of containerised codes that implement hazard-specific and consequence models. The presentation layer exposes both an interactive map-based visualisation environment and a meta-modelling interface for workflow composition.

3.2 Data Layer

The data layer integrates multiple geo-referenced datasets describing the topology and attributes of urban CI components: electrical substations and distribution lines, water treatment and pumping stations, road and rail networks, bridges and viaducts, hospitals and emergency services, and telecommunications infrastructure. Interdependency links—both physical and logical—are encoded as directed graph edges connecting components across infrastructure layers.

Infrastructure data are acquired from multiple authoritative sources. Data about electrical network, telecommunication, gas pipelines, and other CI systems are derived from utility operators under data-sharing agreements. Transportation network data, strategic structures and point of interest (e.g. hospitals, public buildings, etc.) originate from OpenStreetMap.

Hazard data sources include: the Italian Seismic Hazard Map (MPS04) [14] produced by INGV for seismic scenarios; the ISPRA IdroGEO [15] platform for landslide inventories and flood hazard maps; the European Ground Motion Service (EGMS) [16] for subsidence monitoring; and the Italian Civil Protection Department for meteorological bulletins and alerts.

Data ingestion currently follows a semi-automated workflow: authoritative datasets are periodically retrieved from source repositories, processed through validation and format conversion pipelines, and integrated into the platform database.

Data ingestion pipelines support standard geospatial formats (GeoJSON, Shapefile, GeoTiff, etc.) and are designed to be updated incrementally as new infrastructure data become available. All spatial data are referenced to a common coordinate system (WGS84, EPSG:4326) to ensure consistency across datasets of different provenance.

3.3 Simulation Layer

The simulation layer is implemented as a collection of Docker containers, each encapsulating a self-contained simulation code together with its dependencies. This containerisation approach ensures reproducibility, eliminates dependency conflicts between codes, and facilitates independent versioning and updating of individual models.

Current container types include: seismic fragility and damage estimation codes; buildings and infrastructures multihazard assessment; geological instability models covering subsidence and landslide scenarios; and network flow models for estimating service degradation given component damage states. Additional containers are under development for cyber threat scenarios and for consequence models that estimate the impact of infrastructure outages on population welfare indicators.

3.4 Presentation Layer

The presentation layer provides an interactive WebGIS environment in which territorial features, hazard maps, infrastructure components, interdependency

links, simulation inputs, and simulation results are visualised within the browser (Fig. 1). Non-specialist users—including municipal planners and civil protection officers—can navigate the interface, select scenarios, launch pre-configured analyses, and inspect results through thematic maps and summary dashboards without requiring direct access to the underlying simulation codes.



Fig. 1. CI-RES Platform: WebGIS interface.

4 Simulation Capabilities and Hazard Scenarios

4.1 Seismic Scenarios

The seismic simulation pipeline accepts a ground-motion intensity map (expressed as peak ground acceleration or spectral acceleration) and applies component-level fragility functions to estimate damage states for each CI element. Damage states are propagated through the interdependency graph to estimate service disruption at the system level. The pipeline supports both scenario-based analysis (a specified earthquake event) and probabilistic hazard analysis (aggregated over a range of possible events).

While this paper primarily describes the platform's architecture, evaluating its predictive capabilities and result reliability is essential. The platform supports diverse simulation workflows, though their constraints are dictated by the underlying computational modules. For seismic scenarios, rather than simulating detailed wave propagation, we utilize heuristic amplification laws [17] to approximate propagation behavior. The accuracy of this approach varies by context:

it is highly effective for homogeneous seismic zones but may deviate in more heterogeneous environments.

To assess post-event structural damage, we may employ both deterministic and stochastic methodologies. The deterministic approach applies specific 'PGA thresholds' (to each structure) based on available census data regarding construction materials and techniques; exceeding these thresholds implies structural failure. Conversely, the stochastic approach offers greater realism by assigning failure probabilities to individual components and generating combinatorial damage scenarios. While this yields a more robust impact estimate through ensemble averaging, it increases computational demand by several orders of magnitude. Similarly, sensitivity analyses—which require iterative simulations with perturbed parameters—remain computationally intensive.

4.2 Multihazard Analysis

This tool combines geospatial analysis with the Weighted Linear Combination (WLC) method [18] for multi-hazard assessment, understood as the simultaneous presence of multiple hazards within the same territorial area [19]. The six hazards considered are: earthquake, flood, landslide, volcanic, wildfire and tsunami. The assessment is carried out for selected relevant critical infrastructures (roads and bridges, electric power stations, etc.) and is based on the definition of weights through a pairwise comparison matrix, according to the AHP (Analytical Hierarchy Process) approach [20]. To perform the multihazard calculation, the user can insert the relative importance between hazards in the matrix (Fig. 2): the values range from 1 ("equal importance") to 9 ("extremely more important"). Alternatively, the user can load preset values (e.g. all hazards equal, focus on seismic, focus on floods/landslides, focus on seismic/floods/landslides). The results are presented in the form of maps, charts, and statistics, and the outputs can be downloaded in GIS formats.

The reliability of the multi-hazard approach is highly sensitive to the parameter selection, defining the weight of the different hazards. In this framework, the selection process relies on expert judgment to ensure the analysis is tailored to the specific context. The multi-hazard assessment approach adopted in CI-RES builds upon established methodologies for spatial hazard interaction analysis at the European scale [21] and has been validated in recent Italian case studies demonstrating its applicability across different spatial scales [22].

4.3 Geological Instability Scenarios

Subsidence and landslide models estimate differential ground deformation and slope failure probabilities across the urban area, and translate these into damage likelihood for surface (e.g., bridges) and buried (e.g., pipelines) infrastructures. The tool intersects selected critical infrastructure components with the European Ground Motion Service (EGMS) [16] validated dataset (Fig. 3). It calculates the average displacement velocity (mm/year) for both vertical (UP) and horizontal (EAST) components within a specific buffer, identifying potential structural

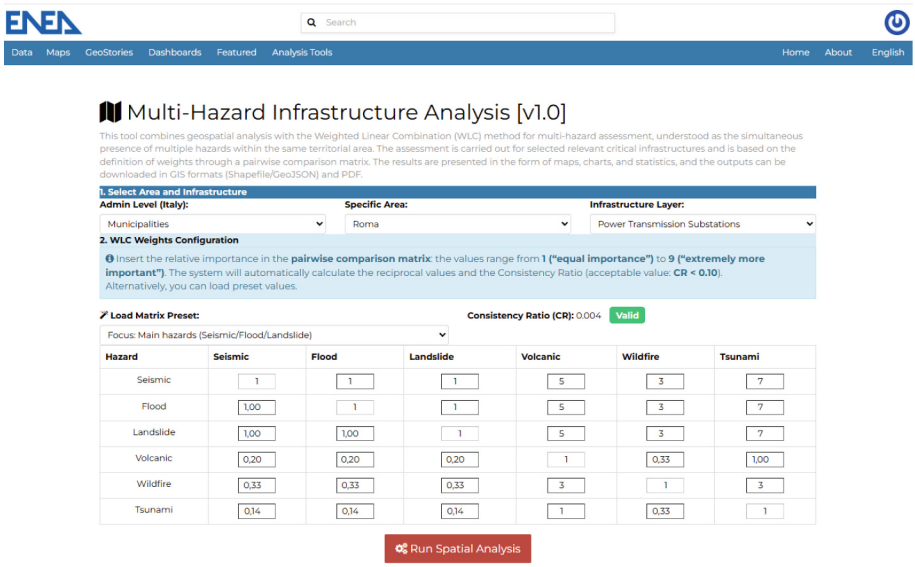

Fig. 2. CI-RES - Multihazard tool: input mask.

"alerts" due to subsidence, uplift, or lateral movements. Moreover, the analysis takes into account the landslide hazard zones (Source: ISPRA-Idrogeo [15]) and the Italian Landslide Inventory (source: ISPRA-IFFI [23]). This model is particularly relevant for Italian urban contexts, where geological hazard is a significant contributor to infrastructure risk.

4.4 Hybrid and Anthropogenic Scenarios

A distinctive capability of CI-RES is the support for *hybrid scenarios* in which natural hazard events are combined with deliberate anthropogenic actions—for example, a flood event coinciding with a targeted attack on a water pumping station, or a seismic event exploited to mask a cyber intrusion into grid control systems. Hybrid scenario analysis requires the simultaneous activation of multiple simulation containers and the aggregation of their outputs through a consequence model, which is orchestrated by the meta-modelling interface described in the following section.

5 Meta-modelling Interface

5.1 Workflow Composition

The meta-modelling interface, can be implemented as a web application, thus allowing authorised users to compose simulation workflows by selecting and connecting simulation containers, consequence models, and optimisation modules

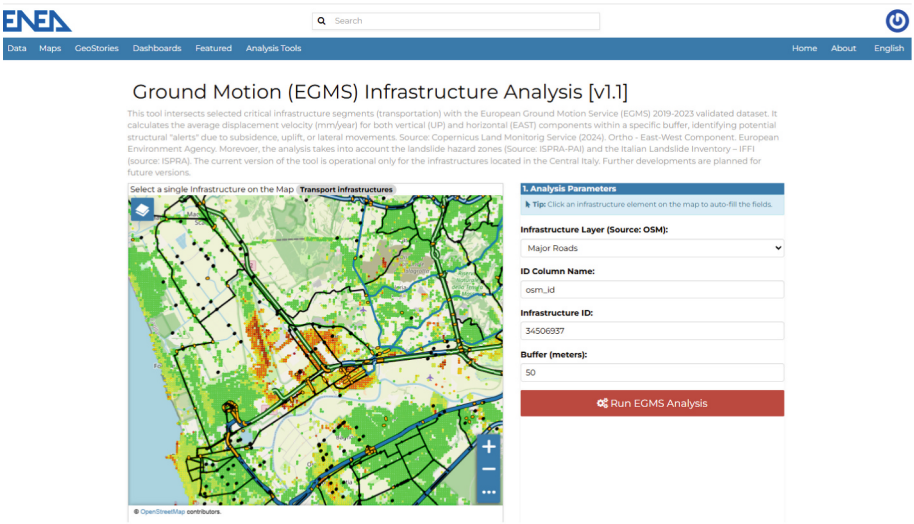

Fig. 3. CI-RES - Ground motion tool: input mask.

through a graphical interface. The resulting workflow is represented as a directed acyclic graph in which nodes correspond to simulation components and edges define data dependencies between them.

This approach enables domain experts to:

- **Customise models:** Adapt simulation parameters and consequence functions to the specific urban context and stakeholder requirements.
- **Create new scenarios:** Define bespoke simulation scenarios to evaluate the impact of new infrastructure investments or risk mitigation interventions.
- **Share workflows:** Publish composed workflows for reuse by other platform users, fostering a community of practice among CI resilience analysts.

It is worth noting that the former approach does not require deep knowledge of the employed codes, for their composition, but just their I/O data format. In other words, the 'meta-modeler' may design their application disregarding the details of calculations performed by each module.

5.2 Dynamic Risk and Resilience Estimation

Beyond static damage assessment, the meta-modelling layer supports time-resolved simulation of post-event system behaviour, enabling the estimation of dynamic risk and resilience metrics. Users can specify recovery models for each infrastructure sector and observe how service availability evolves over time following a disruptive event. The platform computes standard resilience indicators—such as the area-under-the-performance-curve metric—and presents them alongside spatial maps of residual service coverage.

5.3 Optimisation Module

An optimisation module, callable from within the meta-modelling interface, applies resource allocation algorithms to identify the intervention strategies that maximise post-event resilience given a budget constraint. Outputs take the form of prioritised lists of infrastructure components to reinforce or protect, which can be directly communicated to municipal authorities and infrastructure operators.

6 Kubernetes Migration

6.1 Motivation

The current CI-RES deployment relies on two independent physical machines hosting development and production environments respectively. This architecture limits operational continuity: hardware failures or software malfunctions in either machine can cause extended service interruptions, and the manual synchronisation of the two environments introduces operational overhead and the risk of configuration drift.

6.2 Kubernetes-Based Deployment

The platform is being migrated to the existing Kubernetes cluster managed by the ENEA Laboratory for the Analysis and Modelling of Critical Infrastructures and Essential Services. Kubernetes provides container orchestration capabilities that directly address the limitations of the current deployment:

- **High availability:** Service redundancy across multiple cluster nodes and automatic failover ensure that the platform remains operational even in the event of hardware failures or software malfunctions.
- **Scalability:** Horizontal pod autoscaling allows the platform to accommodate peaks in simulation demand—for example, during emergency response operations—without manual intervention.
- **Continuous deployment:** Kubernetes simplifies the rollout of updated container images, enabling new simulation codes and interface features to be deployed rapidly and safely with zero downtime.
- **Self-healing:** Automatic restart of failed containers and rescheduling of workloads to healthy nodes minimise the impact of transient faults on platform availability.

The migration also establishes the technical foundation for the future integration of real-time data streams—from sensor networks, smart meters, and emergency communication systems—that will be required by the Urban Digital Twin implementation described in the following section.

7 Towards an Urban Digital Twin

The Kubernetes-based CI-RES platform constitutes the simulation backbone of a broader Urban Digital Twin (UDT) initiative. In the UDT framework, CI-RES will be extended with:

- **Real-time data integration:** Live telemetry from infrastructure monitoring sensors will continuously update the platform's representation of infrastructure state, enabling near-real-time situation awareness during emergencies.
- **Predictive analytics:** Machine learning models trained on historical event data will augment physics-based simulations with rapid probabilistic forecasts of disruption propagation and recovery trajectories.
- **Decision support:** Automated alert generation and scenario precomputation will allow the platform to provide actionable recommendations to emergency managers within minutes of an event onset.
- **Smart City Platform integration:** [24] Selected CI-RES applications, packaged as lightweight services, will be integrated into the municipal Smart City Platform, making resilience indicators accessible to a broader audience of non-specialist users.

This evolution positions CI-RES as a foundational infrastructure for evidence-based urban governance, supporting both routine infrastructure investment planning and crisis response operations.

8 Preliminary Results

The CI-RES platform has been applied to a pilot urban area to validate the integrated simulation pipeline and the meta-modelling interface. The pilot focused on the interaction between the electrical distribution network and the water supply system under a seismic scenario, assessing the cascading impact of substation damage on pumping station operations and the consequent degradation of water service availability across the city.

The simulation identified a set of critical nodes whose failure produces disproportionately large reductions in overall service availability, consistent with the theoretical predictions of interdependent network models [4]. The optimisation module suggested a prioritised reinforcement strategy that, applied to the five most critical nodes, reduced the expected service loss by approximately 30% under the reference seismic scenario.

The georeferenced visualisation of results (Fig. 4) was positively evaluated by a group of domain experts from the civil protection sector, who highlighted the intuitive accessibility of the map-based interface as a key advantage for operational use. Full quantitative results and a detailed case study will be reported in the accompanying technical report [25].

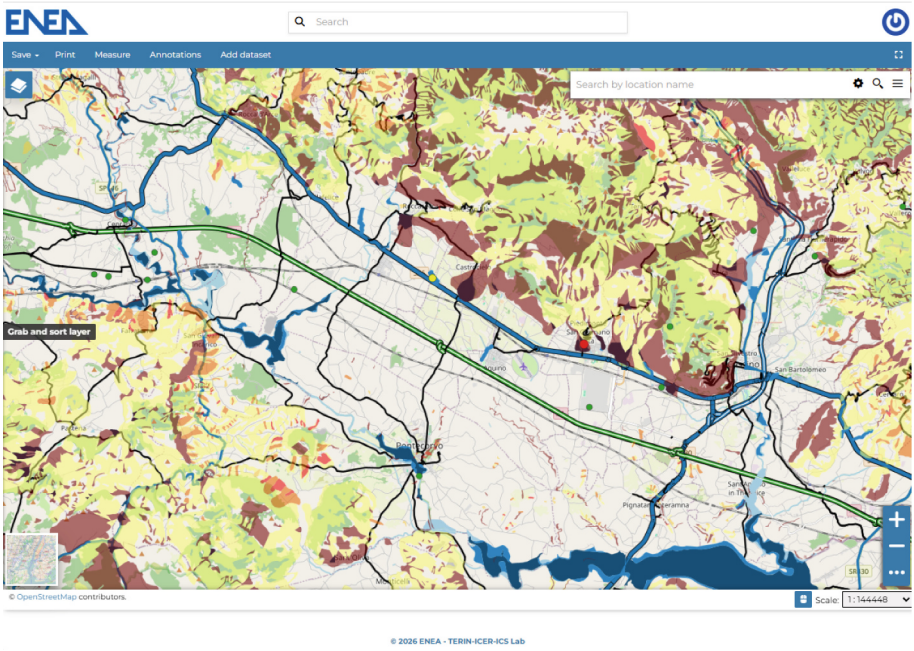

Fig. 4. CI-RES: example of visualisation of results.

9 Conclusions and Future Work

This paper has described CI-RES, a GIS-based platform for the analysis and simulation of critical infrastructure resilience in urban environments, developed by ENEA within the Italian Programme Agreement for Electric System Research. The platform integrates geo-referenced infrastructure data, a suite of containerised hazard and consequence simulation codes, a meta-modelling interface for workflow composition, and a georeferenced visualisation environment. The platform is also endowed with a Intelligent Private Chat interface that allows users to ask information about critical infrastructures and essential services. The workflows employed require the coordinated execution of various simulation codes. Each code, in turn, relies on a set of parameters tuned through expert judgment or data adaptation. Among these, thresholds play a critical role; their precise calibration can significantly influence both quantitative outcomes and even emergent behaviors. For example, thresholds for structural failure during earthquakes are often estimated using census data, which are frequently outdated or imprecise. Furthermore, physical structures often deviate from the construction specifications recorded in such databases. This dependency on parameter accuracy is even more pronounced in multi-risk analyses, where the reliability of results remains an unresolved challenge.

The ongoing migration of CI-RES to a Kubernetes-based deployment will substantially improve platform availability, scalability, and dependability, while

establishing the technical foundation for the integration of real-time data streams required by future Urban Digital Twin implementations.

Future work will focus on: (i) expanding the simulation container library to cover additional hazard types and infrastructure sectors (e.g. wildfires and floods); (ii) integrating real-time sensor data feeds to enable live situation awareness (and early warning thereby); (iii) developing machine learning components for rapid disruption forecasting; and (iv) deploying selected platform services within the municipal Smart City Platform to broaden access to resilience indicators among non-specialist stakeholders.

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