

VISU4EO: A METAVERSE-BASED FRAMEWORK FOR SCENARIO EXPLORATION, CAUSAL ANALYSIS, AND URBAN RESILIENCE PLANNING

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ABSTRACT

The Visu4EO platform demonstrates how extended reality, immersive visualization, and metaverse technologies can enhance the exploitation of Earth Observation data for “what-if” analysis and decision-making support. The system integrates real-time parameter manipulation, scenario simulation, and 3D immersive exploration to support the assessment of environmental conditions and urban planning strategies in a scenario of flood risk and mobility disruptions.

Index Terms— EO, XR, DT, Decision-Making Support

1. INTRODUCTION

The Visu4EO platform [2], developed within the Immersive Visualization Metaverse for EO Applications (IMMERSEON) study, an ESA Future EO activity at the Φ-lab in ESRIN, demonstrates how extended reality, immersive visualization, and metaverse technologies can enhance the exploitation of Earth Observation (EO) data for what-if analysis and decision-making support. The system integrates real-time parameter manipulation, scenario simulation, and 3D immersive exploration to support the assessment of environmental conditions and urban planning strategies.

As a demonstration case, Visu4EO focuses on flood risk and mobility disruption in Copenhagen, Denmark, where climate change and land-use transitions jointly exacerbate both coastal and inland flooding. Increasing heavy precipitation and global sea-level rise intensify storm surges, while urbanization increases runoff and exposure. These combined factors significantly affect traffic flows and congestion, underscoring the need for resilient infrastructure and climate-adapted mobility planning.

Visu4EO retrieves simulated hydrological and mobility data from CityNexus [3], a Digital Twin application on the DestinE platform. Users can interactively explore how variations in rainfall duration and intensity, sea-level projections, land-use configurations, and flood-defense measures influence flood behavior. Simultaneously, changes

to road-network accessibility, population levels, and point-of-interest distribution reveal mobility impacts under each scenario. This integrated view enables the assessment of cascading effects across environmental and mobility systems. Beyond visualization, the platform incorporates explanatory and decision-support capabilities. Root-cause analysis and counterfactual comparisons help users understand how their choices affect outcomes, while an Explainable AI (XAI) analysis provides actionable explanations during the immersive experience. Additionally, intelligent assistance suggests parameter adjustments and scenario refinement, enabling users to iteratively converge toward more effective and resilient solutions.

The VR component transforms the user experience from passive observation to active, cognitive decision-making. The system is engineered to do more than just display graphics; it can read, parse, and visualize complex simulation data directly from external sources. By processing heterogeneous datasets, including advanced heightmap-based flooding algorithms and street-level interpolation, the application translates numerical inputs into a topographically accurate, immersive environment.

2. THE VISU4EO PLATFORM

The Visu4EO platform enables users to define and manipulate various environmental parameters to simulate urban planning interventions to evaluate their impacts on urban mobility, flooding and pollutant concentration through an immersive visualization experience. The application allows users to navigate a 3D representation of the scenario and, using advanced VR techniques, to seamlessly transition from a global overview to a local, street-level perspective.

The platform is structured around three main building blocks, which also define the operational workflow (Figure 1). First, users define scenarios by manipulating flood-related and urban planning parameters through a GIS-based web interface. Once a scenario is configured, simulations are executed directly from the interface through the CityNexus Digital Twin Application.

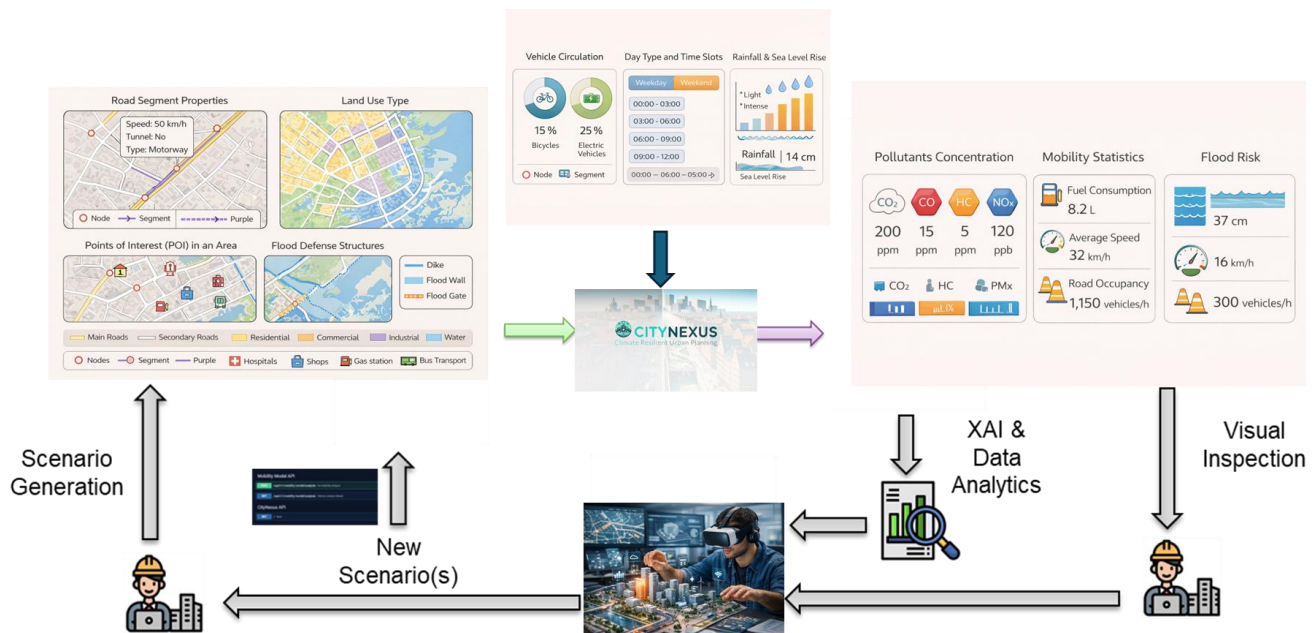


Figure 1 - Visu4EO Architecture

Simulation flooding results are then rendered visualizing factors such as rainfall, river and canal flooding, sewer discharge capacity, traffic conditions, and road closures. Finally, an Explainable AI (XAI) component performs model-agnostic analysis to assess the impacts of hydrological parameters and flood events on the road network, as well as the effects of changes to road segment characteristics. These explanations are integrated into the immersive experience to provide users with actionable insights during navigation.

3. SCENARIO AND SIMULATION

While Visu4EO is a **general framework for analyzing diverse flood scenarios and their impacts on urban mobility**, the present demonstration focuses on a specific use case addressing a concrete need of the City of Copenhagen: simulating and assessing urban flood risk under evolving environmental conditions.

In Denmark, flooding risk is increasingly driven by the combined effects of climate change and land cover transformation, intensifying both coastal and pluvial flooding. More frequent and intense precipitation events—such as the 2011 Copenhagen cloudburst, which delivered 150 mm of rainfall in less than two hours—demonstrate the growing exposure of urban areas to extreme rainfall. At the same time, ongoing sea-level rise, currently averaging

approximately 3.5 mm per year, is amplifying storm surge impacts in low-lying coastal zones. Projections of up to 1.2 m of sea-level rise by the end of the century suggest that events currently considered rare could become near-annual occurrences, as evidenced by the extensive coastal flooding in Southern Jutland in 2017.

Urbanization further exacerbates these risks by increasing impervious surfaces, thereby reducing natural infiltration and accelerating surface runoff. The resulting flood events have substantial implications for urban mobility, as inundated or damaged road infrastructure disrupts traffic flows, increase congestion, and prolong travel times. Addressing these interconnected challenges requires resilient infrastructure planning and adaptive traffic management strategies. By simulating flood scenarios and evaluating their impacts on mobility networks, city planners can identify critical vulnerabilities, prioritize interventions, and design targeted measures to enhance the resilience of urban transportation systems.

Visu4EO builds on top of and extends CityNexus, an urban mobility DestinE's service to model environmental, social, and economic impacts of road network, mobility and urban fabric interventions [1,3]. Using the CityNexus service within the DestinE platform, users can configure a range of parameters to simulate diverse flood scenarios and assess

their impacts. By adjusting hydrometeorological conditions, boundary inflows, land-use configurations, and flood defence measures, the system enables the modelling of multiple interacting factors that influence both coastal and inland flooding dynamics under varying environmental conditions.

The key configurable parameters include the following. **Rainfall duration and intensity** can be defined to represent pluvial events of varying severity. Rainfall duration may range from 1 to 24 hours of uninterrupted precipitation, allowing the simulation of short, intense storms as well as prolonged rainfall events. Hourly rainfall intensity can be adjusted between 0 and 150 mm/h, covering conditions from moderate precipitation to extreme cloudbursts. **Sea discharge** is prescribed as an increase in seawater level (in metres) applied at predefined open-sea boundary locations. Values can be set from 0 m upward, controlling the volume of seawater entering the model domain and enabling the simulation of coastal flooding under different sea-level conditions. **River discharge** is defined as a volumetric inflow (m^3/s), regulating the amount of upstream water entering the domain and supporting the analysis of fluvial flooding across a range of flow regimes.

In addition, users can modify **land-use policies** by specifying the fractional coverage of different land-cover categories at pixel level, including agricultural, commercial, industrial, natural (non-forested), forested, water, residential, and other land-use types. These adjustments allow the representation of varying degrees of imperviousness, infiltration capacity, and runoff behaviour associated with urban development patterns. Finally, **flood defence systems** can be incorporated into simulations, including thin dams (e.g., floodwalls or embankments) to redirect water flow and protect specific areas, and weirs to regulate water levels and mitigate flood risk.

By combining these parameters, the CityNexus service enables the creation of customised, policy-relevant flood scenarios that support risk assessment and resilience planning.

The Visu4EO framework integrates multiple advanced modelling components to support the simulation of coupled flood and mobility dynamics. Urban mobility patterns are generated using **MindGravity**, a deep learning-based model that analyses large-scale datasets to produce accurate origin-destination matrices and simulate traffic flows. These mobility dynamics are further processed within SUMO [4], an open-source, agent-based traffic simulation platform capable of handling large multimodal and intermodal transport networks. Flood processes are simulated using the **SFINCS model** [5], a high-performance hydrodynamic

engine designed to represent compound flooding in urban and coastal environments and to deliver fast, large-scale flood assessments under varying environmental conditions. To enhance transparency and user trust, an **Explainable AI (XAI)** module is incorporated, providing interpretability of AI-driven outputs and supporting informed decision-making in urban planning contexts.

4. VR EXPERIENCE

The VR experience is organized into three main scenes. In the opening scene, users are presented with a rotating globe displaying selectable cities. For demonstration purposes, only Copenhagen is currently active, though additional cities can be enabled simply by updating a configuration file.

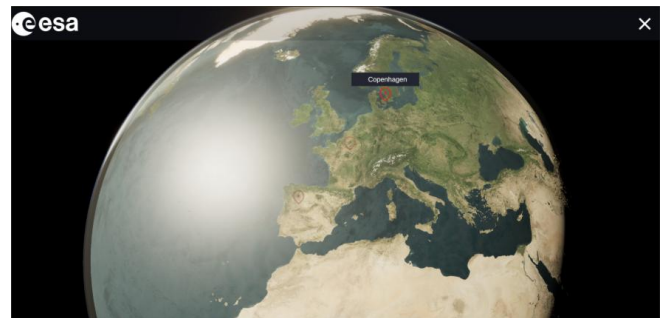


Figure 2 - Landing Scene

After selecting a city, users enter the area selection scene, which displays a 2D offline map generated from bundled GeoJSON data. From this view, users can select an area and load up to three scenarios for comparison or import new scenarios from the simulation engine.

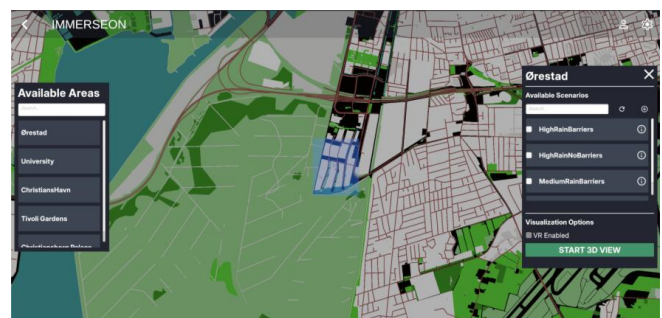


Figure 3 - Area Selection

The simulation scene presents a fully navigable 3D reconstruction of the selected area. Flooding is visualized using Unity's Water System, driven by GeoTIFF simulation data that **dynamically adjusts water levels across the scene to reflect the simulated flood profile accurately**. Interaction within the simulation is managed through a multi-tab user interface. The Map tab provides a top-down view,

elevation control, and scenario switching; the Edit tab enables inspection and modification of flood defenses, time-slot navigation, and simulation setup; the Info tab displays contextual street-level flood and traffic data; and the XAI tab presents explainable-AI insights for the currently observed street.



Figure 4 - 3D Rendering

The virtual environments used in Visu4EO are **generated through a structured, multi-stage pipeline that combines geo-referenced data import, AI-assisted texturing, and performance-oriented 3D modelling**. This approach ensures both geographic accuracy and high visual fidelity, while remaining suitable for real-time immersive applications.

The process begins with the creation of a geo-referenced base model using open geospatial data, providing accurately scaled terrain and building footprints. Visual realism is then enhanced through an **AI-augmented texturing pipeline**, where reference imagery is used to generate façade textures consistent with real-world architecture. These textures are efficiently managed through texture atlases to support real-time rendering. Architectural detail is added using a combination of modular and non-modular modelling techniques, allowing both efficient replication of repetitive

structures and accurate representation of complex or landmark buildings. Finally, models are optimized for VR performance and exported using conventions that support dynamic rendering, asset replacement, and seamless integration into the Unity-based Visu4EO platform.

5. ANALYSIS AND SUPPORT

This immersive experience provided by Visu4EO aims at innovative and **advanced support for policy and decision-makers, allowing them to experience and assess the consequences of planning decisions**. By simulating alternative scenarios and their effects on mobility, city planners can identify vulnerabilities and develop strategies to enhance the resilience of urban transportation networks. To support this goal, the Visu4EO XAI module leverages state-of-the-art Explainable AI techniques for:

- **Providing insights on which driver matters** to explain the effects on flooding and traffic observed in the simulations (global sensitivity analysis). This analysis aims at explaining, for each street in the map, in which percentage the rain, sea and river discharge affects the simulation.
- **Providing insights on scenario efficiency** (local explanation). This analysis supports the user in the evaluation of the effectiveness, pros and cons of the defenses implemented.
- **Providing decision making support**, to help the user in designing an effective defense system for a given area. The analysis provides suggestions on where to place defenses to reduce the impact of catastrophic events in a selected area. Regarding the global sensitivity analysis, to identify the main hydrologic drivers of urban flooding, the platform applies a **Sobol-based sensitivity analysis** to quantify how rainfall, river discharge, and sea discharge influence flood levels along the city's road network. By computing first-order Sobol indices, the analysis isolates the direct contribution of each input variable to local flood depth, enabling a clear understanding of which processes dominate flooding in different areas of the city.

The analysis is performed across a large set of simulated scenarios and produces road-segment-level indicators showing the relative influence of each hydrologic driver. Results are expressed as impact percentages and accompanied by automatically generated textual summaries that highlight the dominant flood drivers for each street. This information supports targeted mitigation and planning decisions, such as prioritizing river defenses, coastal protection, or drainage improvements where they are most effective.

Regarding scenario effectiveness and defense evaluation, the platform evaluates the **effectiveness of flood-defense**

scenarios by comparing flooding and traffic conditions against a baseline scenario with identical hydrological inputs but no defenses. This comparison can be performed at both global level (entire defense layout) and local level (individual defense segments), enabling fine-grained assessment of how specific measures influence flooding and urban mobility. The analysis integrates flood and traffic simulations across a 24-hour period and examines impacts street by street and overtime. It quantifies changes in flood depth, traffic speed, road occupancy, and closures, and combines these results with a spatial analysis that considers the distance and orientation of defenses relative to the road network. These factors are synthesized into efficiency indicators that describe how well each defense performs locally and across the wider area.

Results are translated **into human-readable, Explainable AI (XAI) summaries** that classify each street according to its response (from strongly improved to strongly worsened) and highlight peak benefits, trade-offs, and potential adverse effects. By **linking flood reduction, traffic impacts, and spatial configuration, the analysis provides actionable insights to support informed decision-making**, helping planners refine defense strategies and balance flood protection with mobility resilience.

The decision-support component assists users in designing effective flood defense systems by generating **data-driven recommendations for defense placement and configuration**. The approach explores a wide range of potential solutions by first evaluating randomly generated defense scenarios, distributed across space, orientation, and length, and assessing their impact on flooding and urban mobility. This allows the system to learn which defense configurations tend to perform best within a given area.

Defenses are then ranked using a composite efficiency–cost trade-off score, which **balances flood reduction benefits against traffic disruption** while accounting for spatial alignment with the road network. Based on this ranking, defenses are classified from highly beneficial to counterproductive. The resulting insights are translated into street-level recommendations, guiding users on where defenses should be kept, adjusted, or avoided in order to maximize flood mitigation while minimizing negative impacts on mobility.

The Explainable AI outputs are seamlessly integrated into virtual reality as shown in Figure 5. The identified flooding drivers and the estimated effectiveness of flood defense measures are projected directly onto the three-dimensional city model as dynamic heatmaps. These overlays use a color gradient to represent the relative magnitude of contributing factors and defense performance, enabling users to intuitively

distinguish high-impact areas from lower-risk zones within the spatial context of the built environment.



Figure 5 - XAI Result Integration in the VR

By embedding the XAI results directly within the interactive VR scene, the system moves beyond conventional chart-based explanations and instead supports spatially explicit interpretation. Users can navigate the digital twin, inspect specific streets or buildings, and immediately relate model explanations to physical urban structures and infrastructure elements. This tight coupling of explainability outputs with immersive visualization enhances transparency, improves cognitive understanding of complex flood dynamics, and facilitates informed decision-making in resilience planning and urban management.

6. CONCLUSIONS

Recent advances in EO combined with artificial intelligence and high-performance computing have enabled a new generation of Digital Twins capable of supporting urban

resilience, climate adaptation, and environmental management.

The increasing availability of high-resolution, long-term EO data from missions such as Sentinel and Landsat has transformed EO from a niche scientific resource into a foundational asset for decision-making across urban planning, disaster response, and sustainability policy. These developments allow Digital Twins to model complex systems, analyze long-term trends, and simulate what-if scenarios with unprecedented accuracy and relevance.

Building on this context, Visu4EO **demonstrates the potential of immersive, EO-driven Digital Twins by integrating hydrological models, land-cover data, and mobility datasets to simulate flood events and assess their cascading impacts on urban mobility.**

A key innovation of Visu4EO is its multi-scale and multi-domain approach, linking climate and weather dynamics with human activity through immersive visualization, Virtual Reality (VR), and Explainable AI (XAI). This **enables users to explore scenarios interactively, understand underlying drivers, and evaluate the consequences of planning decisions in a transparent and intuitive manner.**

The platform is designed with scalability, adaptability, and responsible innovation at its core. It relies on globally available datasets to ensure transferability across regions, supports continuous improvement through the integration of advanced forecasting systems, and is architected to expand into additional domains such as urban heat, air quality, public health, and emergency planning. Ethical principles, including data anonymization, bias mitigation, and environmental and social impact assessment, are embedded throughout the system to ensure trust, fairness, and compliance with international standards. Together, these elements position Visu4EO as a robust and forward-looking Digital Twin framework capable of supporting evidence-based policymaking and resilient urban development.

The integration of Explainable AI and immersive VR further enables **participatory intelligence, enhancing confidence, transparency, and inclusiveness in urban decision-making.** These technologies provide an intelligent assistance layer that supports planners, policymakers, and citizens through natural interaction and immersive exploration of scenarios.

7. REFERENCES

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