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Resilience quantification for critical infrastructure in urban areas including nature-based solutions

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In the face of increasing urbanization and climate change, the resilience of critical infrastructure is essential for maintaining the functionality and safety of urban areas. This study presents a framework for quantifying the resilience of critical infrastructure systems, with a focus of integrating nature-based solutions (NBS) to mitigate climate-related risks. NBS have attracted broad attention recently since they promise to not only increase the resilience of humanly build infrastructure but to also support environmental protection. However, considering that the implementation of NBS requires significant time and effort, and given that their effectiveness against, e.g., natural disasters, often depends on local details, modelling approaches, like the one presented in this study, are essential to analyse the effects of NBS on the protection of CIs against a broad set of disruptions.
To estimate resilience, we construct a network-based representation of the critical-infrastructures found for the region of Aveiro, Portugal, encompassing central supply components like power supply systems and essential facilities such as hospitals. The links of the network correspond to physical or logical connections of the components, enabling simulations of cascading failures triggered by extreme events. The methodology combines a comprehensive assessment of infrastructure vulnerabilities with the potential benefits of NBS such as natural flood management strategies. Focusing on climate-related threats, particularly flooding events, we simulate the time evolution of damage cascades to estimate the performance loss over time due to adverse events.
Case studies from urban areas at risks of flooding demonstrate the effectiveness of this approach, highlighting how NBS can enhance the resilience of the area by mitigating performance losses during adverse events. These findings contribute to a deeper understanding of the interplay between infrastructure resilience and ecological strategies, offering valuable insights for urban planners and policymakers aiming to foster resilient and sustainable urban environments.

Keywords: Nature-based solutions, resilience assessment, flooding.

1. Introduction

As urbanization accelerates and climate change poses escalating risks, ensuring the resilience of critical infrastructure has become imperative for the safety and functionality of urban environments. The European research project NBSInfra (NBSInfra 2024) focuses on the integration of nature-based solutions (NBS) in urban areas to enhance the resilience of critical infrastructure against climate-related threats, such as flooding. Good implementation practices as well as cost-benefit analyses for NBS, see Section 2, are evaluated in five designated CityLabs. This paper places a special emphasis on the CityLab of Aveiro, presenting its challenges and opportunities related to NBS in Section 3. In Section 4, we introduce a simulation framework designed to quantify the resilience of critical infrastructures in case of adverse events. Exemplary results from the simulation of a flooding event in the Aveiro CityLab are presented in Section 5.

2. Nature-based solutions for flood management

The agenda 2030 to the UN Sustainable Development called "Transform our world: Agenda 2030 of the Sustainable Development" was approved and focuses on the collective and transversal commitment to the planet sustainability (UN 2015; UNESCO 2017, Pombo et al. 2022). Engineering with nature and adopting NBS in infrastructure projects can effectively mitigate climate change impacts. However, key challenges must be addressed in combining traditional engineering with NBS. NBS support infrastructure solutions, complement existing infrastructure reducing maintenance needs, mitigate climate change impacts as flooding and coastal actions, improve habitat biodiversity and improve heat resilience through green surfaces. In the following, first, a specific example for an NBS in coastal areas is introduced, followed by a description of an inland study region, the area of Aveiro.

2.1. *Self-healing concrete*

Self-healing concrete presents opportunities for civil engineering in coastal areas, exposed to aggressive environments. It enhances durability by enabling autogenous or autonomous crack healing, which can restore the mechanical properties of structures. This technology utilizes crystalline admixtures, particularly in the production of Ultra High Performance Concrete (UHPC) tailored for such challenging conditions. UHPC has been exploited in the repair and strengthening of coastal structures. The reinforced concrete water tower at Malta's Grand Harbour was restored using advanced UHPC with self-healing crystalline admixture and nano-additives for the column jacketing and textile reinforced concrete for the strengthening of the tank (Borg, 2020). Self healing in concrete can also be achieved through Microbial-Induced Carbonate Precipitation (MICP), a natural process where bacteria produce enzymes that accelerate the precipitation of calcium carbonate. This is exploited for limestone consolidation and offers a sustainable alternative to cement as a binder for block production. Furthermore, MICP enhances aggregate properties. Coastal protection relies on civil engineering infrastructure, such as breakwaters and offshore structures, which mitigate wave energy and reduce coastal erosion. These concrete structures can also be integrated through hybrid solutions with reef regeneration as living breakwaters, to support ecosystem regeneration. The research activity explores the potential of different concrete types and different environmental conditions, in relation to ecosystems regeneration, as nature-based hybrid solutions in coastal infrastructure.

2.2. *Aveiro region*

In 2015, the "Sustainable Cities Strategy 2020" report was published, which realised the strategic options for the Sustainable Development of Portuguese cities (Pombo et al. 2022). This was constituted as a reference framework for municipalities and other urban agents in terms of territorial development. One of the cities that adopted this framework was Aveiro, with the initiative "Teach City". This initiative intends to use technology as a means to improve the citizens' quality of life and to help the authorities in collecting and sharing important information about new forms of acting and managing the city in areas like mobility, education, culture and environment (Pombo et al. 2022). The city of Aveiro is characterised by its coastal and maritime cultural patrimony and a culture rich in traditions, some of which can be considered sustainable. One of the examples is the *Moliço* harvesting, a traditional seaweed collection activity that has nearly disappeared. The boats originally used for this activity (*Moliceiros)*, are now repurposed for tourism, helping to preserve the traditional craftsmanship. Nowadays, to maintain sustainable practices, the motors of these boats are electrical ones (Pombo et al. 2022). On the other side, Aveiro has a natural and urban patrimony, called "Ria de Aveiro" and its channels, which enter inside the urban area and marked permanently the history, patrimony, culture and local identity of the city. This is one of the most expressive and biologically significant coast wetlands, with a higher value in a national and international panorama (Pombo et al. 2022). The requalification and preservation of this salty river are fundamental to preserve the natural ecosystems but also to control the flooding areas of the city. Aveiro is not introducing the Nature-based

Fig. 1: Electricity mapping for the Ribeira de Vilar basin area of the Aveiro CityLab. Legend: high medium voltage overhead line; transformer substation; street lights.

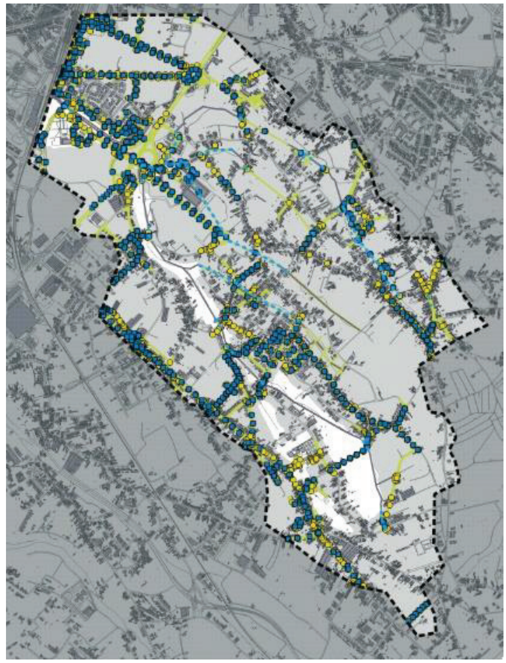

Fig. 2: Rain water drainage mapping for the Ribeira de Vilar basin area of the Aveiro CityLab. Legend Buried duct; Waterline duct; Rainwater manhole; Drain grids.

solutions directly in public spaces intervention projects, but there is a tentative effort of using some of the NBS principles in projects, as for example:

- Rehabilitation and Bank Stabilization of Streams: This involves manually removing invasive reed species (Phragmites sp.) from the banks and streambed while preserving biodiversity hotspots for mallard ducks (Anas platyrhynchos). Bank stabilization will use biomat (biodegradable PLA film on coconut fiber) and wooden staking with biologs.
- Rehabilitation of selected streets to recreational and leisure conditions with a pedestrian and cycle path. The aim is to combat the erosion of the banks of the Ria de Aveiro lagoon channels and salt marshes, guaranteeing their preservation.

Aveiro is also planning to directly introduce NBS in future projects, promoting the introduction or protection of nature.

3. Aveiro – Challenges and NBS opportunities

The city lab of Aveiro is predominantly susceptible to flash floods, exacerbated by its distinct geographical position and the presence of the Aveiro Lagoon. This creates particular challenges in managing simultaneously fluvial and estuarine hydrodynamics. Historical meteorological data from various weather stations indicate a maximum daily precipitation of 74 mm, with rainfall exceeding 10 mm in 15% of precipitation events. On an hourly scale, precipitation above 5 mm have occurred on 3% of the rain events. The risk associated with flash floods is particularly critical downstream of the study area, where multiple watersheds converge, resulting in the accumulation of various hydrographic contributions. The watercourse exhibits signs of numerous modifications and the riverbanks are severely degraded, with support mats in a state of disrepair. In intense rainfall conditions further damages occur in the riverbeds, endangering people passing through these areas. The lack of solutions to mitigate peak hydrographic flows leads to elevated flash flood risks downstream, causing flooding in both urban and agricultural properties.

Within the framework of the NBSInfra project, critical points have been identified for effectively mitigating flash flooding risks through NBS. One such area is the City Park Lake, facing low water flow in the summer, rising temperatures, and illicit wastewater discharges into the rainwater network. The proposed NBS intervention is to strengthen the control and monitoring of the run off and increase the shading by planation of trees compatible with local ecosystem and shrub species. Second critical point is the by-pass discharge of wastewater from pumping stations, which has a high impact on the quality of water specifically in Ria de Aveiro. The proposed NBS include retention basins and streets with drainage paving designed to have infiltration trenches and medium-to-high storage capacity to absorb and collect run-off during peak flows. For the Carregal-Requeixo area, the proposed solution involves connecting a nature trail between the two locations. This trail aims to establish a functional link along the Pateira de Requeixo lagoon, part of the RAMSAR wetland network, and will facilitate lagoon bed rehabilitation through the removal of invasive aquatic species and bank stabilization.

3.1. *Aveiro CityLab*

Aveiro is a young city that grew especially after the second half of the twentieth century, as most of the coastal areas of Portugal. The satellite images from 2003 to 2024 show a clear shift from a predominantly rural landscape to a heavily urbanised city. The overall trend is a steady reduction of agricultural land in favour of expanding urban infrastructure. According to Font's classification, Aveiro, located in Zone Parda I of maritime Mediterranean climate, exhibits distinct and marked climatic characteristics throughout the year (APA 2014). The city is predominantly influenced by north winds, which minimise significant latitudinal temperature variations. In winter, the temperature difference between the northern and southern extremes of the region is only 3 degrees Celsius (°C). In terms of land use, the study area of the Ribeira de Vilar basin contains soils with discontinuous urban fabric, agriculture with natural spaces, rainfed annual crops, and remnants of annual crops associated with permanent crops. The infrastructure mappings of Aveiro for energy, gas, water supply, and telecommunication are crucial, as these systems are identified as critical infrastructures which are essential for maintaining urban functionality and resilience. These mappings demonstrate varying degree of coverage throughout the city and give us a better understanding and in-depth insights how flooding will possibly affect and how proposed NBS should be designed accordingly. The energy supply and rain water drainage mappings are shown in Fig. 1 and Fig. 2. These mappings, including the spatial distributions of critical infrastructure, are valuable for analyzing interdependencies and assessing exposure to risks such as flash floods. They visually represent the proximity of critical infrastructure to hazard-prone areas, aiding informed decision-making for implementing NBS to enhance resilience and mitigate disruptions.

4. Resilience modelling framework and Digital Twins

We have seen in Section 3 for the CityLab of Aveiro how detailed local conditions can and need to be assessed to understand risks as well as their mitigation strategies. Still, given that those risks, flash flood in case of Aveiro, manifest only rarely, data on the practical outcome and consequences of those risks is only sparsely available. Consequently, model frameworks are essential to understand the impacts of adverse events for an encompassing set of starting conditions and disaster severity. Different modelling frameworks can be applied at this point (Ouyang 2014), including graph-based, flow-based and agent-based methods as well as combinations thereof. As example, this paper shows an application of a graph-based modelling approach that aims at understanding and quantifying failure cascades and restoration periods of diverse networks of interdependent critical infrastructures found for Aveiro and its surrounding region, see Fig. 3 (left). Such models can serve as the foundation of Digital Twins of the city or larger regions under investigation.

4.1. *Digital twinning*

Digital twins are virtual models of physical systems or assets that utilize real-time data for scenario modelling. In some cases, the digital twin can also control the system being modelled using actuators. They are useful for evaluating

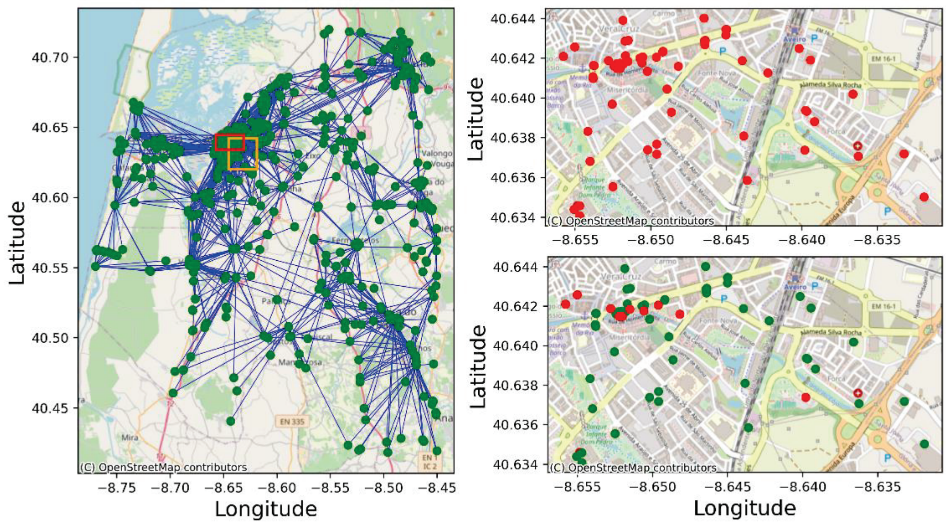

Fig. 3: Network of critical infrastructures for Aveiro and its surrounding. On the left, the full network is shown, the red box indicates the position of the sections shown on the right. The orange box indicates the position of the geographic region shown in Figure 1. On the right, the nodes targeted by the "severe flash flood" event are shown in red (top), the nodes damaged by the "mitigated flood" event (bottom) are also marked in red while the green dots represent the nodes which stay intact compared to the “severe flash flood”.

NBS, since key criteria can be monitored and spatially visualized in real time. For example, Helsinki’s digital twin simulates the effect of new green spaces on carbon emissions, stormwater, and temperatures during heatwaves, while also assessing green infrastructure's impact on climate resilience (Helsinki 3D, 2015).

The NBSInfra project develops a framework for the digital-twin modelling of critical infrastructure and nature-based solutions. These geospatial digital twins display GIS (Geographical Information System) data for the urban area being modelled, such as topography, land use and critical-infrastructure mappings (e.g., energy, gas and water supply). Scenario modelling reveals the impact of NBS on key performance indicators such as air quality, temperature or flood impact. Approaches like the graph-based modelling described in this paper below can be incorporated into the digital twin model, ensuring accurate scenario modelling through up-to-date data. The NBSInfra digital-twin framework specifies the core protocols for sharing data among collection points (e.g., sensors, satellite imagery providers, citizen scientists). Key protocols include those defined by the Open Geospatial Consortium (OGC), such as the SensorThings API for sensor data and API-Features for serving geographical features online. Adopting established standards facilitates the seamless integration of diverse sources into the digital-twin model and ensures consistency across CityLabs. Another key tenet of the NBSInfra framework is using open-source technologies where practicable. Utilizing tools such as Postgres plus PostGIS for GIS data storage and TensorFlow for AI-enhanced scenario modelling promotes software sharing and reuse. More details of the NBSInfra digital-twin framework are found in (M. Cullinane et.al, 2025).

4.2. *Resilience modelling for critical infrastructures*

Having specified the concept of digital twinning, we now investigate an exemplary graph modelling approach which serves as important part of the twin.

When assessing the impacts of disasters on the people of Aveiro, it must be kept in mind that the city’s infrastructure does not exist in isolation. Therefore, in case Aveiro is hit by a disaster, the population can rely on support from the surrounding cities and villages. For example, in case a hospital in the city of Aveiro is dysfunctional due to flooding, this does not mean that injuries cannot be treated since other hospitals, inside and outside of the city, can step in. This motivates the geographical extension of the network model shown in Fig. 3 on the left which encompasses the southern part of the district of Aveiro. The graph contains a selection of critical facilities and services inspired by a list of critical sectors defined by the European Commission (European Commission 2005) consisting of:

- Energy, e.g., electricity transmission
- Transport, e.g., road/rail/air transport
- Communication technology, e.g., internet
- Water, e.g., provision of drinking water
- Food, e.g., provision/control of food
- Health, e.g., hospital and medical care
- Finances, e.g., payment services
- Public/Legal order and safety, e.g., police
- Civil administration
- Chemical/nuclear sector
- Space and research, e.g., research facilities

Overpass Turbo (Raifer 2024) was used to extract the critical facilities and services from OpenStreetMap. The model parameters and specifications, which can also be found there, are only briefly introduced in the following. Interested readers might inspect (Lickert et al. 2024, CIRED) and (Lickert et al. 2024, ESREL) for more detailed explanations in the context of the application of the model concept to the use case of power blackouts.

The critical services and facilities are nodes of the model graph, which depend on other services to operate, e.g., a hospital node relying on functioning connections to the medium voltage (MV) grid as well as on an operative water supply. These dependencies are represented as edges, with some redundancies, e.g., hospital nodes may connect to two MV grid nodes but only one of them is necessary for the hospital to function properly. If a dependency fails due to events like flooding, the node won't fail immediately due to emergency measures, such as power generators for hospitals, which can supply the hospitals for about a week. This resistance is captured in the "lifetime" $t_{L,i}$, indicating the time from supply loss to emergency failure. More generally, the lifetime of certain structures can also be increased by NBS such as self-healing concrete, see Section 2.1. Conversely, once a dysfunctional node's supply is restored, it does not return to service immediately, but the repair times $t_{R,i}$ need to be considered. Both $t_{L,i}$ and $t_{R,i}$, can be adjusted for specific events. Due to the challenges in assigning exact lifetimes for critical infrastructures, this paper defines $t_{L,i}$ and $t_{R,i}$, using Gaussian distributions. For example, $t_{L,h} = 168h \pm 12h$ and $t_{R,h} = 72h \pm 6h$ was considered for the hospitals based on a study on the consequences of long, large-scale power blackouts (Petermann et al. 2011).

The temporal evolution of the disturbance affecting the model graph is simulated using a simulation setup, called CaESAR, developed at the Fraunhofer EMI (Fraunhofer EMI 2024). The iterative algorithm checks and adapts the state of nodes and edges of the considered network model in each timestep to produce a trajectory of the damage cascade. As input, it needs the list of network nodes collecting their attributes, the list of edges, and a definition of the threat representing the initial adverse event triggering the damage cascade. The failure cascade and the subsequent repair progress are based on $t_{L,i}$ and $t_{R,i}$ as explained above.

5. Exemplary spring flood simulation

To present an exemplary application of the cascade modelling introduced in section 4.1, a flash flood event, as mentioned as significant threat for Aveiro in Section 3, was simulated by approximating the flood damage based on elevation information. It is assumed that all nodes situated in the flooded area are damaged as initial step of the event simulation. In order to identify the network nodes prone to flooding, QGIS was used to extract data of the Copernicus Digital Elevation Model with a resolution of 30 m (European Space Agency, 2024) for Aveiro via OpenTopography. This data was analysed to identify low-lying areas close to the coast line. Fig. 3 (top right) shows all network nodes with an elevation below 18 m. It was assumed that these nodes will be flooded in case of a severe flash flood. No further changes in the elevation level were considered for the remaining simulation time, i.e. after the initial damage only cascading failures from the damaged region to the connected network components outside the flooded area were considered. Furthermore, it was assumed that the flood is receding quickly and the repair of

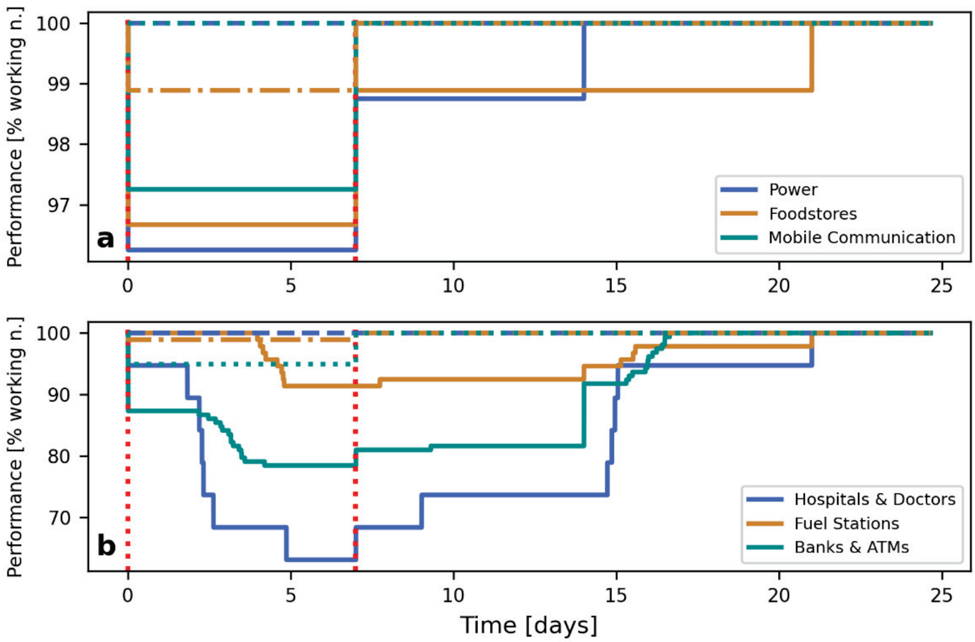

Fig. 4: Effects of the "severe flash flood" event (solid lines) and the "mitigated flood event" (dashed lines) on different categories of critical infrastructures. The events occur at Time = 0 (first red line), the repair of the flood damages take one week (second red line).

the initial damages caused by the flood would need one week.

Fig. 4 visualizes the time evolution of the cascade simulation for different node categories in solid lines. Since, in relation to the overall scale of the network model, the flooding event is comparably local, most parts of the network stay intact which explains why the drops that can be seen in Fig. 4 a for power, foodstores and mobile communication are only minor. Those infrastructures are well distributed over the full model region, i.e., only few nodes in these categories can be found in the flooded area. Additionally, we see that those categories are robust against cascading since only an initial drop can be observed. The repair of power and foodstores need more than one week since some of the damaged nodes depend on other nodes from the power category which need to be repaired first. Nevertheless, the overall behaviour of these categories is clear and coherent.

In contrast, the categories shown in Fig. 4 b behave more complicated. All three of them show delayed failures during the one week of flood damage repair since critical dependencies are not met. Especially the hospitals and doctors (solid blue curve) are harmed and drop relatively low. This is mostly caused by the flooding of one of the three hospital nodes, directly impacting the doctors that are assumed to depend on functioning hospitals. When inspecting the repair, on the other hand, we see that the infrastructures of both need roughly three weeks to fully recover from all damages, see Fig. 4 a and b.

As indicated in Section 3, flash flood events can be countered by different preventive measures, some nature-based, some conventional. To exemplarily depict the results of such interventions, a second simulation was performed where only the nodes with an elevation below 6 m were damaged, i.e., the flash flood was assumed to be significantly weaker. Fig. 3 (bottom right) shows that only a few nodes of the network model are targeted. As a result, we can see in Fig. 4 that the overall damage is significantly reduced (dashed lines). Power, mobile communication and health & doctors all stay completely unaffected while the other categories only reveal minor damages without any cascading. This indicates that the implementation of measures to reduce the height of the flooding significantly improves the resilience of Aveiro and the surrounding region.

6. Conclusions

In conclusion, this study showed how simulation frameworks can support the planning and implementation of nature-based solutions in enhancing the resilience of urban infrastructure against climate-related threats, particularly flooding. Our framework offers valuable insights for urban planners and policymakers aiming to create sustainable and resilient urban environments. We plan to enhance these results in the future by incorporating additional information on infrastructure components and exploring other climate related use cases.

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References

Agência Portuguesa do Ambiente (APA). (2014). Relatório de caracterização (Art.º 5º da DQA): Região hidrográfica do Vouga, Mondego e Lis (RH4). Agência Portuguesa do Ambiente.

Borg, R. P. (2020). Concrete heritage : challenges in conservation. Symposia Melitensia, 16, 35-52.

Cullinane, M. et al. (2025). Digital twins for nature-based solutions. IALCCE 2025, in process

European Commission. (2005). Green paper on a European program for Critical Infrastructure protection https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52005DC0576&from=EN, page 24, accessed on 19/12/2024

European Space Agency (2024). Copernicus Global Digital Elevation Model. Distributed by OpenTopography. https://doi.org/10.5069/G9028PQB, accessed: 19/12/2024

Fraunhofer EMI (2024). Analysis of the cascade effects in supply networks – software tool CaESAR. https://www.emi.fraunhofer.de/en/business-units/security/research/analysis-of-the-cascade-effects-in-supply-networkssoftwaretool-c.html, accessed: 20/12/2024

Helsinki 3D. (2015). Helsinki 3D | City of Helsinki. https://www.hel.fi/en/decision-making/information-on-helsinki/maps-and-geospatial-data/helsinki-3d

Lickert, B. et al. (2024). Modeling damage cascades in critical infrastructure for power outages. CIRED 2024, Chicago. Proceedings in process

Lickert, B. et al. (2024). Modeling Impact of power outages on interdependent critical infrastructure. ESREL 2024, Krakow.

NBSInfra (2024). Project homepage. https://nbsinfra.eu/, accessed: 20/12/2024

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliab. Eng. Syst. Saf. vol. 121,* 43-60.

Pombo, L. (2022). *Aveiro, cidade sustentável: EduCITY.* UA Editora. http://doi.org/10.48528/jtw2-k945

Petermann, T. et al. (2011). What happens during a blackout: Consequences of a prolonged and wide-ranging power outage. *Technology Assessment Studies Series. vol. 4,*

Raifer M. (2024). Overpass Turbo https://overpass-turbo.eu/, accessed on 19/12/2024

United Stations (UN) (2015). Transforming our world: the 2030 Agenda for Sustainable Development. https://sustainabledevelopment.un.org/post2015/transformingourworld/publication

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2017). Education for Sustainable Development Goals. Learning Objectives.https://unesdoc.unesco.org/ark:/48223/pf0000247444