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From Flood Risk Assessment to Blue-Green Infrastructure Evaluation in Urban Built Environments: A Holistic Workflow Definition

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From Flood Risk Assessment to Blue-Green Infrastructure Evaluation in Urban Built Environments: A Holistic Workflow Definition

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Abstract: *Urban areas face increasing flood risks due to climate change and urbanisation. A comprehensive approach is needed to assess flood vulnerability and enhance urban resilience. This study presents a holistic flood risk assessment workflow that integrates the assessment of blue-green infrastructure (BGI) as a mitigation strategy. The proposed methodology is developed within the framework of the CLIMRES project and consists of three key components: (i) flood vulnerability mapping, (ii) tactical flood management planning, and (iii) resilience-oriented recommendations for urban environments. The workflow uses the identification of flood-prone areas, measures to protect citizens and buildings, climate change projections, data collection and possible BGI measures to provide vital and clear information to stakeholders at district and building level. Two pilot studies: Ljubljana, Slovenia, and Senigallia, Italy - demonstrate the applicability of the approach in diverse urban settings with different environmental challenges. The pilot implementations provide critical insights into the integration of BGI in flood management, the role of real-time data processing, and the need for user-friendly decision support tools for stakeholders, including researchers, urban planners, and policy makers. The developed workflow is designed to be flexible and adaptable, allowing its application in different urban environments with varying levels of data availability and infrastructure complexity, thus ensuring its replicability in different urban contexts. The results highlight the need for flexible and scalable flood assessment frameworks that accommodate local conditions and data availability while supporting climate adaptation strategies. The workflow developed enhances the ability of decision makers to identify vulnerable areas, assess the impact of mitigation measures, and develop forward-looking flood resilience strategies.*

Keywords: *flood risk assessment, blue-green infrastructure, urban resilience, climate adaptation, decision-support tools, CLIMRES project.*

I. INTRODUCTION

Floods represent a significant threat to urban areas due to their high frequency and severity. It is important to note that, for example, over the past five years, floods have impacted approximately five million people and resulted in more than 23,000 deaths worldwide [1]. When considering the numerous factors that contribute to the issue of flooding in European cities, including high levels of urbanisation, infrastructure failures and inadequate risk reduction and mitigation measures, it becomes evident that the impact of flooding on these cities is a highly relevant subject [2], [3]. Climate change has been demonstrated to exacerbate the frequency and intensity of extreme flood events in urban areas [4]. This has resulted in an urgent need for a rapid, well-coordinated response from local administrations, designers and other relevant stakeholders, including private citizens [5], [6]. As demonstrated in [6], [7], the factors affecting flood risks in urban areas can be categorised as follows: (1) flood hazard and spreading, which essentially depends on the position of the urban area and on the type of flood event (e.g. fluvial, pluvial/flash flood, coastal/storm surge); (2) physical vulnerability, which comprises the features of the built environment, including buildings and open spaces, and its infrastructures; (3) exposure and social vulnerability, which concern the population and value of assets that can be affected by flood effects, and also include the features of the individual user at risk and the response of the population in case of a disaster.

Flood risk assessment methods and tools should be able to take into consideration the complexities of the interaction among these factors at different scales and dimensions (e.g. building, infrastructure, open spaces, community) [8], [9]. They can then also identify "hot-spots" in the urban scenario, support the analysis of key elements in risk reduction, allow the definition of pathways for climate-change adaptation and comprise the analysis of the positive effects of risk reduction actions and mitigation strategies [6]. In this sense, different structural and non-structural strategies can be implemented in cities to reduce flood risks by mitigating the effects of extreme events on the built environment and its users [10], [11]. Structural solutions are essentially centred on engineered interventions which can contribute to the reduction of flood volumes and the protection of urban areas. On the contrary, non-structural ones do not involve physical interventions, but are oriented towards education, awareness, preparedness, emergency management and, more in general, coordination between public-private entities (which can have effects on the built environment via land-use planning). Thus, structural strategies could have a relevant effects for risk mitigation and a direct impact on flood hazard and (physical) vulnerability of urban built environments, and they could be combined with non-structural strategies to increase flood resilience also from a redundancy perspective [7].

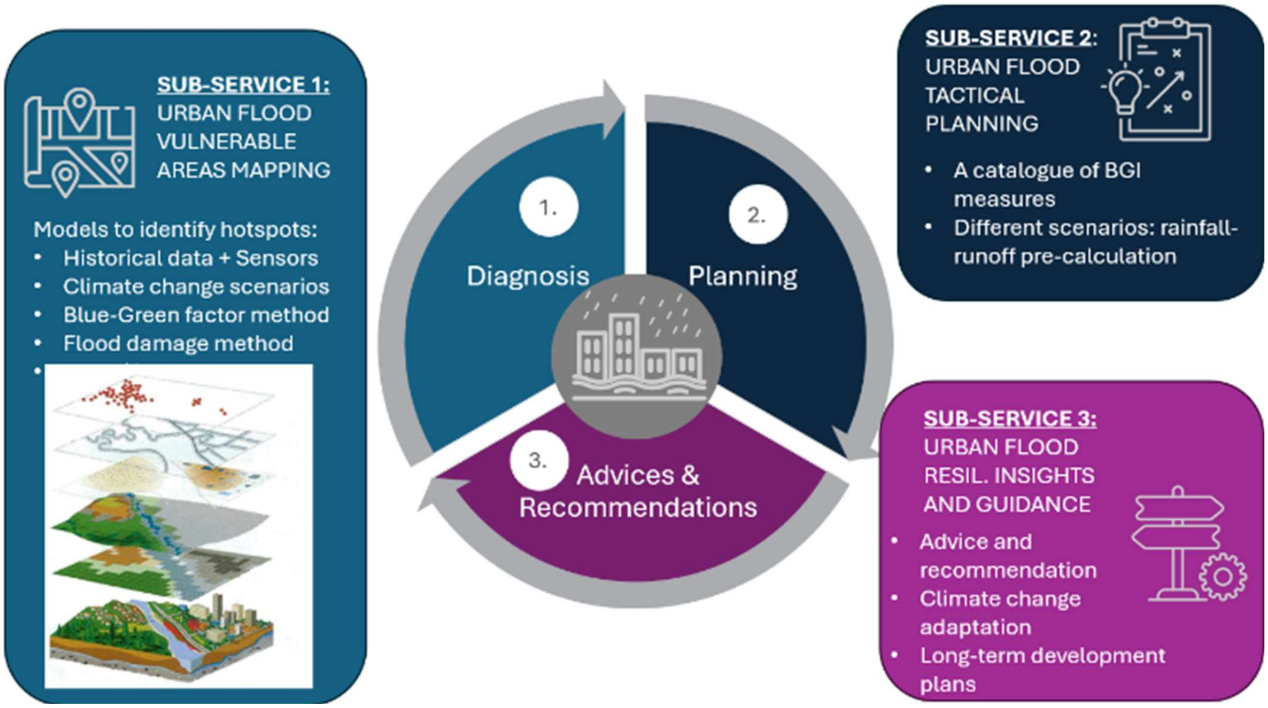

Fig.1. The diagram of the application for flood risk assessment analysis, which is being developed during the CLIMRES project.

Among structural strategies, blue-green infrastructure (BGI) emerges as a solution to enhance the resilience of urban areas and mitigate climate change impacts. The objective of BGI is to mitigate, restore and recreate a more natural flood response, thereby bringing hydrological responses closer to pre-urbanized conditions [10]. The integration of vegetation and water management has been demonstrated to be an effective strategy for mitigating the impact of urbanization on the water cycle [11]. It is evident that BGI plays a pivotal role in mitigating the consequences of flood damage, encompassing the following mechanisms: (i) decreasing the amount of stormwater runoff; (ii) decreasing the peak flow velocity; and (iii) boosting the storage capacity [2]. BGI, comprising green roofs, urban parks, street trees, ponds, permeable pavement, and wetlands, provides multiple benefits for urban water management and ecosystem services. Nevertheless, the effectiveness of BGI is frequently challenging to ascertain, as it is contingent on numerous factors.

Nevertheless, we can utilise simplified city-scale models integrating urban flood management with mapping and monitoring while evaluating building flood resilience through BGI implementation. Thanks to such analyses, it becomes possible to identify areas which are susceptible to urban floods, due to the morphology of the land and its development [13]. Concepts and approaches have been established [6], but their practical application by decision-makers and planners is lacking, and it is very valuable to know in detail their views and needs when making decisions. Local knowledge of flood-prone areas or past flood events can also be incorporated into the models, using the added value of data participation through participatory mapping [13] to provide a more nuanced understanding of risk. Efforts should be provided to accelerate the process of flood risk assessment from a holistic perspective, and to include the proactive analysis of mitigation strategies effectiveness, by taking into account the implementation of BGI as one of the leading structural solutions. To this end, it is necessary to study the use cases, including the aspect of decision-makers as key end-users, in addition to the already established concepts.

The objective of this study is to develop a tool that supports forward-looking urban flood resilience strategies. This tool will assist decision-makers at city level in identifying vulnerable areas, assessing resilience under different scenarios, and considering hydrological conditions and blue-green infrastructure measures. At the building level, the identification of less resilient buildings will enable the prioritisation of interventions and the provision of recommendations for climate change adaptation and retrofitting.

The objective of this study is to contribute to the "Leadership for climate resilient buildings" (www.climres.eu) project, which is funded by the European Commission under grand agreement No 101147777. The project aims to deliver guidelines, methods and tools to assist stakeholders in assessing and mitigating climate-change risk at various intervention scales. In the course of the assessment of potential hazards, flood risk has been identified as one of the most significant concerns, as outlined by CLIMRES.

II. MATERIALS AND METHODS

A. General framework and basic workflow logics

As illustrated in Figure 1, the comprehensive framework of the flood risk assessment application, which is currently under development as part of the CLIMRES project, has been delineated. The application is comprised of three key sub-services, derived from literature research [6], [8]: (1) mapping of urban flood vulnerability areas, (2) tactical planning for urban flood management, and (3) providing insights and guidance on urban flood resilience.

In *sub-service 1*, the results of the rainfall-runoff models are utilised for the identification of areas susceptible to flooding hotspots within the designation region. The subservice is driven by a range of data sources, including historical data and sensor data, such as: The Urban Atlas Cover, land cover data, urban planning, building cadastres, meteorological data, historical flooding events with statistical analysis, and imperviousness data. Additionally, climate change scenarios are incorporated, adjusting the meteorological data to reflect expected changes by the end of the 21st century. At this stage, various BGI measures are evaluated, offering potential solutions to reduce flood risk. Finally, a flood damage assessment is conducted, providing an economic outlook on the potential impacts of the projected flooding scenarios. All results can be calculated and visualized at both the district/city level and the building level, making the application suitable for urban planning as well as for the building climate adaptation strategies.

Sub-service 2 includes a catalogue of BGI measures that can be implemented to enhance flood safety in the modelled area. Additionally, various rainfall-runoff simulation scenarios are pre-calculated and stored within this sub-service. *Sub-service 3 is responsible for the storage of* insights, advice and recommendations for building renovations, as well as climate change adaptation strategies and long-term development plans.

In view of the above, the workflow considers three main different purposes for flood risk assessment and mitigation process related to the aforementioned sub-services [6]–[8]: (1) research interests towards understanding and analysing flood risk and mitigation measures, including BGI; (2) development, protection and retrofit of properties; (3) urban planning and emergency management, from the perspective of regulatory frameworks and interventions. These purposes are herein considered to differ in complexity, as target groups from these purposes have distinct needs and priorities. These sub-services are also supported by existing specific methods like outlines in Section II.B.

B. Existing methods outline

The methodology for flood risk assessment is designed to be flexible and tailored to the availability of data. As various pilots will use the flood risk application during the CLIMRES project, different use cases will be developed based on the data available for each pilot area and the specific assessment needs. However, the general frame for flood risk assessment remains consistent across all use cases, and follows these steps:

- Data library: Datasets for the pilot areas are pre-uploaded and accessible to various target groups. Users can upload their own more detailed data into the application for modelling purposes.
- Use case selection: Based on the available data and the specific requirements of the case, users choose the most relevant use case for their situation.
- Modelling: The utilisation of the selected use case entails the incorporation of the results of the rainfall-runoff modelling into the application. Models were operated, taking into account a range of meteorological scenarios, climate change projections, and the potential impact of BGI measures that could be implemented in the area. The SWMM computer model [12] is utilised for the purpose of rainfall-runoff modelling. Depending on the chosen use case, different datasets may be considered, such as population dynamics, building characteristics, infiltration capacity of the area, and more.
- Vulnerability assessment: The modelling results are used to create hotspot maps for flood risk, providing an assessment of flood risk at both the area and building levels.
- Flood damage assessment: Based on the vulnerability assessment, the economic impact of flood consequences is evaluated, resulting in a flood damage assessment for both the area and specific buildings.
- Scenario modification: Users can modify modelling scenarios and recalculate results, enabling them to visualize and compare the outcomes of different scenarios.

This approach allows flood risk assessment to be tailored to the specific needs of each case, providing multiple modelling options and the ability to compare different outcomes.

C. Pilot applications

Two pilot applications have been considered in view of the relevance within the climate-change contexts in the CLIMRES project.

The first pilot is located in Slovenian capital Ljubljana. Despite the construction of various structural flood protection measures for nearby rivers, Ljubljana continues to face frequent flood risks, most recently in 2010, 2014 and 2023. Due to significant urban growth over the past 25 years, reduced permeable surfaces, and diminished drainage capacity, the district remains highly vulnerable to pluvial flooding during heavy precipitation or rising water levels in nearby waterways. During the pilot activities, various measurement sites will be established. At these sites, different BGI measures will be implemented, including green roofs, green walls, and a rain garden. Data will be collected using both existing and additional sensors, such as rain gauges, humidity sensors, soil moisture, flowmeters and temperature sensors. Selected data will be used to model the impact of BGI measures on flood extent at both the district and building levels. According to literature review BGI implementation in selected areas could reduce surface runoff volume by approximately 25–30% compared to baseline conditions without BGI. Comparative simulations showed that, under future climate change scenarios (RCP 4.5 and RCP 8.5), areas equipped with BGI would experience 20–25% lower flood risk indices (combining depth and velocity thresholds) relative to non-BGI scenarios [9].

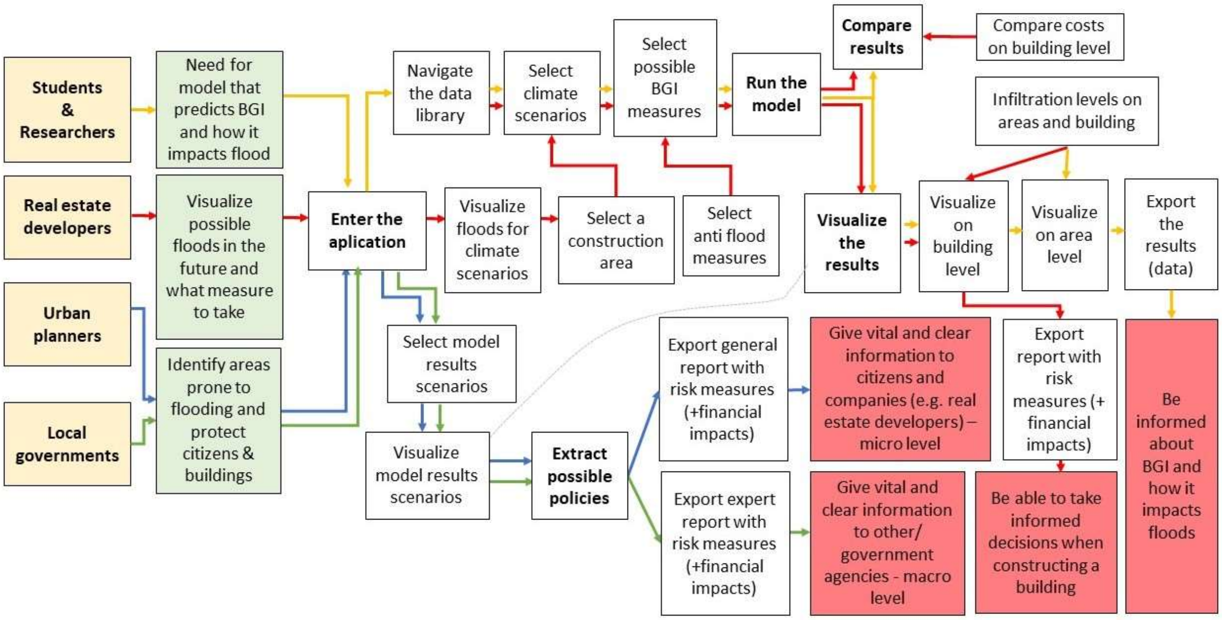

Fig.2. User workflow associated with the general framework in Fig. 1. Lines respresent the user flow. Yellow labels are users, green are starting points, white are intermediate actions, and red are output.

The second pilot is the municipality of Senigallia in the Marche region of Italy. This coastal and riverine Italian town on the Adriatic coast covers an area of about 118 km2 and has a population of about 44,000 inhabitants living in more than 6,000 buildings, with an average population density of about 375 inhabitants per km^2. The urban area is crossed by three main rivers, of which the Misa River is the most relevant one, and many secondary water channels, widely characterized by artificial embankments. Consequently, the water spreads during floods like in an open compound channel, increasing the overall risk levels at both macro and micro scale in the urban scenarios. The city centre is also widely characterized by a dense urban fabric, with limited permeability of ground surfaces and narrow streets, increasing the vulnerability to flood. One of the most flood-sensitive areas of this urban context is represented by the city centre, that is built on a floodplain and situated at the Misa River estuary, and hosts the historical town, composed of more than 600 structural units, including a wide number of buildings with cultural, artistic, social and strategic values. The city is also one of the most important touristic cities in the Marche region, and it was visited by more than 880,000 visitors just in 2024, both for the holidays season and for mass gatherings and frequent national and international events. Most of these events are carried out in the historical city centre, exacerbating user exposure and vulnerability. Finally, Senigallia has been also recently affected by many floods, of which the most significant ones occurred in May 2014, causing more than 5,000 homes flooded with 1,500 inhabitants forced to evacuate their homes, and 3 deaths, and in September 2022, impacting 22% of the city population (about 10,000 people) and causing 12 deaths, 1 missing and 50 injured. Such events also caused more than 180 million euros of damage. Within the project framework, activities in Senigallia do not focus on evaluating the benefits of Blue-Green Infrastructure (BGI), but rather on flood risk assessment to support early warning systems and evacuation planning. Thus, consistent risk indicators will be used across different scenarios, mainly based on riverine flood dynamics. Key indicators are expected to include maximum flood depth, water velocity, affected population density, and estimated evacuation times, in line with previous research outputs on flood risk and resilience metrics. For the quantitative assessment of Expected Annual Damage (EAD) and to support decision-making for flood risk mitigation measures, methodology, developed in Slovenia will be applied [9]. This method enables the estimation of damages across various sectors, including cultural heritage, natural environment, residential, agricultural, and business sectors. A simple equation is used for each sector to calculate damage costs, taking into account the intensity, duration, and extent of the expected flood event at different return periods, as well as the exposure, vulnerability, and values of the exposed elements in the target area.

Representatives from the pilots were involved in the user stories definition at the early stage of the CLIMRES project (during October and November 2024), and then into co-creation sections (carried out in January 2025) to revise the general user workflow and provide additional insights on their requirements.

III. RESULTS AND INSIGHTS ON PILOTS APPLICATIONS

A. User workflow

As illustrated in Figure 2, the user workflow for the flood risk assessment is delineated according to the following four identified user types. The user types are indicated by the colour of the lines. *Students and researchers* (yellow lines) and *real estate developers* (red lines) are considered the most 'expert' groups, and they need to be able to do complex operations and simulations through the assessment tools. They are respectively associated with research and properties-related purposes defines in Section II.A. About urban planning and emergency management purposes*, Urban planners* (blue lines) and representatives or technicians (public utility or water management experts) of *local governments* (green lines) are considered to need a more simple and effective application to disseminate results and evaluate strategical pathways from a wider perspective. It is evident that the green labels correspond to the initial points in the workflow, the white labels to the intermediate actions, and the red labels to the final points and outputs. It has been established that the users within the aforementioned two groups exhibit analogous workflows.

Students and researchers are associated with the use of the assessment tool to predict performance of selected BGI in respect to current conditions of the urban built environment. In order to achieve this objective, it is first necessary for the user to enter the application and then navigate the data library. This library is designed to provide all the necessary data for running scenarious. In the subsequent stage of the process, the user is permitted to select climate scenarios and potential BGI measures. Subsequent to the configuration of all parameters, the model is initiated. The results are then visualized, both at the scale of a reference urban area and at the scale of individual buildings. Within this visualization, it will be important to visualize infiltration levels, both for areas and buildings. User will also be able to compare results with other model runs and based on this information start new calculations. Finally, the user can export the results in data form. The same flow can be used by *Companies Specializing in BGI*, to support the evaluation of solutions effectiveness.

For *real estate developers*, the workflow is very similar and aims to assess flood risk at the current state and determine which mitigation measures (including BGI) can be implemented. After logging in to the application, they will first need to visualise flood impacts for different climate scenarios. Based on this, the user can select an area of interest where a possible construction project would take place. Then, the flow is the same as for the *students and researchers*. They will need to select data, climate scenarios and measures. For this user type, there will be extra anti-flood measures that can be selected, as those are more focused on the building level. For this user group, the results will be similar, although the focus will be more on buildings. Apart from the final impact on flood risk, they should be also aware and informed about costs comparison about different measures. Therefore, as an output, the export function will entail a report here with possible measures and their financial impacts.

It should also include criteria to make the flow more user friendly and accessible to the public. Citizens will be able to check the risk of flooding for their properties and will receive recommendations on how to reduce this risk by means of various BGI measures that can be implemented at the level of individual building.

Urban planners and representatives or technicians of *local governments* have largely a similar flow, pursued at a wide scale analysis of flood risk in pre-retrofit scenarios, and of the impact of mitigation measures, including BGI. After entering the workflow, they will need to select model result scenarios and visualize related data. Pre-modelled scenarios provided by researchers could be mainly selected. As an outcome, they will extract possible policies and plans to create resilience-increasing pathways at the level of the whole urban scenario or of the target areas. All these results can be exported as reports, assuming that the *local governments* could need more elaborated outputs than *urban planners*.

B. Insights on requirements from pilots and definition of basic elements for tool development

The overall workflow delineated in Section III.A is designed to be sufficiently flexible to accommodate both the flood risk assessment perspective and the analysis of the effectiveness of mitigation measures. In view of its applicability across a range of scales, from urban to building, it could also be reliably employed to support the analysis of hotspots in the city and to provide specific insights on them. In view of the aforementioned points, it is possible to specialise the workflow depending on the pilot requirements. These requirements have been defined according to user stories and the co-creation section, which involved stakeholders from Ljubljana and Senigallia seperately.

In the case of the Ljubljana pilot the firs co-creation session was attended by researchers, technical designers specialised in water management, water and sewer network planners and representatives of different municipal and government sectors related to urban water management. They expressed particular interest in the technical capabilities of the application, the risk assessment methodology, the utility of the data library, and technical recommendations at both the district (urban planning) and building levels (renovation recommendations for climate change adaptation). It was emphasised that particular emphasis should be placed on the future utilisation of the application, with specific reference to the incorporation of climate change scenarios and the enhancement of its applicability to diversity target groups. Maintenance of BGI remains a significant challenge; therefore, emphasis on this aspect should be included within the application. Further collaboration among stakeholders will be necessary to design appropriate solutions that contribute to long-term flood risk reduction and enhance the resilience of urban areas to climate change. Researchers specialising in the field of urban flood modelling have indicated that while the implementation of BGI measures at the level of individual buildings can be modelled within the application, the calculations of the flood protection measures, to be included in the application, will be taken from the results of the flood models already developed at city or district level for the different mitigation measures. It is imperative to recognise the necessity of undertaking meticulous computations, which, regrettably, preclude the possibility of implementing simplifications that would otherwise facilitate the integration of these computations into the application.

For the Senigallia pilot, stakeholders from the municipality (including representatives from the administration, emergency management and first responder teams) are expected to be primary interested in the flood risk assessment process. In this sense, operational remarks concern the possibility of including real-time data processing to support citizens, local authorities and first responders in the process of risk assessment and management of possible critical conditions, by considering different levels of information details. The collection of real-time data should be facilitated by in-situ monitoring systems, and risk assessment algorithms could also be developed according to risk analysis criteria used by first responders in case of an emergency. From this standpoint, it is posited that a web and mobile application should be utilised by the workflow to facilitate data visualisation for this cohort of end-users, who may select specific areas or locations within the urban fabric, for example. It could be assumed that the user flow is similar to that of the local government units in Figure 1, but mainly focused on easily calculable indicators. In this sense, moreover, the workflow should be also linked to early warning and communication solutions for flood risk management [6]. This would represent a shift from risk assessment to a direct contribution to disaster support systems.

It is evident that the requirements of the pilots present certain challenges, particularly in light of the intricacy of the assessment process (hydrological-hydraulic modelling). It is acknowledged that certain modelling calculations may be too complex for the application, in which case it would be necessary to pre-calculate the results. Furthermore, the application should be user-friendly despite its complex background.

IV. CONCLUSIONS

The objective of the present research is to develop an urban flood risk assessment application tailored to the needs of various stakeholders. This application will offer an integrated approach to flood modelling, risk assessment, and support in risk mitigation, also including issues about the implementation of BGI measures. Through the development and testing of the application in different pilot sites, key insights will be gained regarding its effectiveness in addressing both district-level and building-level flood risks. The utilisation of a variety of datasets, climate change projections, and flood management strategies will illustrate the potential for the application to provide valuable insights for urban planners, water management professionals, and policymakers.

The research emphasises the significance of a methodology that is adaptable and can be scaled up or down, in order to be applied to a range of urban contexts. It is evident from the feedback provided by the relevant stakeholders that there is a necessity for the application's capabilities to be refined on an ongoing basis. This is particularly true in relation to the adaptation to climate change and the relevance of the application to diverse target groups. The development of the application is currently at the stage of implementing pilot sites, developing the modelling framework, and refining the methodology for risk assessment and vulnerability analysis. The next steps involve enhancing the modelling capabilities, further developing the user interface, gathering stakeholder feedback through testing, tailoring the application to meet the specific needs of each pilot, and integrating early warning and communication solutions for flood risk management.

Insights from the pilot implementations highlight the critical role of high-resolution, real-time data in improving the accuracy and responsiveness of flood risk models. Lessons learned emphasize the importance of co-creating solutions with local stakeholders to ensure usability and applicability, as well as addressing operational challenges such as the maintenance of Blue-Green Infrastructure (BGI) in Ljubljana and the integration of risk metrics for early warning and evacuation planning in Senigallia. Challenges remain in scaling the modelling approach to larger urban areas with complex hydrological systems and in ensuring data harmonization across regions. Moreover, differing governance structures and regulatory frameworks between pilot cities highlight the need for adaptable and context-sensitive deployment strategies.

This research also offers valuable insights for replicating the urban flood risk application in other urban areas facing similar challenges. The key to successful replication lies in the adaptability of the application's framework to different datasets, geographic contexts, and stakeholder needs. By maintaining a flexible data library and ensuring the inclusion of local climate change projections and flood scenarios, the application can be applied to various urban settings with comparable flood risk factors. Furthermore, replicating the methodology across diverse scenarios will require careful consideration of each area's unique infrastructure, urban growth patterns, and flood mitigation strategies. Future directions include extending the application's functionalities to dynamic risk communication tools, integrating social vulnerability indicators, automating alert systems linked to real-time monitoring networks, and enhancing the capability to assess economic damage through flood damage assesment methodologies [9]. Ongoing pilot evaluations will support the iterative improvement process to ensure the application remains aligned with evolving climate risks and urban development dynamics. Future applications should also prioritize user-friendly interfaces and the integration of various stakeholders' feedback to ensure broad usability and relevance.

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