



A Holistic Framework for Flood Risk Assessment and Optimal Design of Mitigation Measures

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Received: 19 June 2025 / Accepted: 20 January 2026 / Published online: 7 March 2026

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Abstract

This study addresses the challenges of urban flood risk assessment using a holistic flood risk assessment methodology for the catchment area of the Garryllis River (Cyprus). This advanced methodology integrates hydraulic modeling, earth observation and geospatial information analysis, as well as socioeconomic data for risk-informed emergency planning. Two-dimensional hydraulic simulations have been conducted under three different return period scenarios (50, 100 and 1000 years). For the worst-case scenario, the highest water depth reached 6.2 m, most significantly affecting the urban regions in the southern part of the basin. Flood hazard was assessed and combined with both demographic vulnerability indicators (population density and age distribution) and economic exposure data (land economic value). To quantify flood risk, a risk matrix was developed in which hazard, vulnerability and exposure values were synthesized and classified into five risk categories. The results revealed that the highest risk levels are associated with the urban areas, since these areas are characterized by flat terrains, low surface permeability, dense population, and high land economic value. The resulting flood risk maps were used to identify safe emergency shelters and design optimal evacuation routes in the existing road network with adequate traffic capacity. The selection of emergency shelters was focused on public buildings located in zero-to-low risk zones, prioritizing accessibility for vulnerable and at-risk people. In this context, this study delivers a replicable decision-support framework that links hydraulic modeling and Earth Observation with actionable civil protection-oriented strategies, thus enhancing urban flood resilience and disaster preparedness.

Highlights

- Flood risk was estimated based on socioeconomic, earth observation, and hydraulic data
- High-risk flood areas are identified mainly in densely populated urban areas
- Optimal evacuation routes and safe shelters are proposed as flood risk mitigation measures
- The proposed framework is replicable in different contexts and geographical regions.

Keywords Flood risk assessment · Decision-making process · Garryllis river basin · Optimal evacuation planning · Disaster resilience

1 Introduction

Floods are one of the most significant types of natural disasters, with both its frequency and intensity increasing in recent years (European Commission 2025a). This increase is associated with several anthropogenic and climate change activities, including inadequate drainage systems, urbanization, and deforestation (Ramly and Tahir 2016; Kountouri et al. 2024). According to the latest available data for 2024, 142 floods were recorded worldwide, killing 5883 people, affecting the lives of 48.8 million people, and resulting in economic losses of 32.8 billion USD (Centre for Research on the Epidemiology of Disasters (CRED) 2025). At a European scale, flood events were directly responsible for 584 human deaths for the period 1980–2022 in the 32 countries of the European Economic Area (European Environment Agency (EEA) 2021). Moreover, flooding has been reported to significantly compromise public health (Guha-Sapir et al. 2015). At present, approximately 12% of the population in EU member states (about 53 million people) resides in regions that are vulnerable to flooding (European Environment Agency (EEA) 2021). Consequently, significant time and resources have been invested at the European scale to develop the EU Flood directive, which aims to “establish a framework for the assessment and management of flood risks, with the objective of reducing adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods” (European Parliament and Council of the European Union 2007). However, the transition from scientific risk assessment to decision-making and operational planning often remains incomplete. The need to incorporate hazard, exposure, and vulnerability information into flood risk assessment is imperative (Teng et al. 2017; Zeiger and Hubbart 2021; Costabile et al. 2021). However, implementing the Floods Directive in ungauged or data-scarce catchments remains challenging, as highlighted in previous studies (Yannopoulos et al. 2015).

Addressing this issue is a particularly challenging task, as disasters emerge due to the combined effect of various factors, such as topographical properties (e.g., slope and elevation), meteorological conditions (e.g., rainfall and evapotranspiration), soil properties (e.g., depth and texture), and land use patterns (Madsen et al. 2014; Sett et al. 2024). Developing sustainable flood mitigation strategies therefore requires a detailed understanding of the interactions among these processes. This can be achieved by integrating a plethora of data derived from technical evaluations, financial analyses, policy examinations, earth observation datasets, and model outputs, enabling decision-makers to devise well-informed policies (Chen et al. 2011). Modeling tools are employed to process these data and provide comprehensive insights into the mechanisms driving the dynamics of flood risk components, namely hazards, vulnerability, and exposure. These components are combined to produce flood risk maps and to assess the effectiveness of various mitigation measures. Such measures can be grouped into two distinct categories: structural and non-structural. The former includes levees, retention ponds, and enhancements to drainage systems, whereas the latter involves the integration of land use planning with flood forecasting and early warning systems.

Several methods and modeling systems are employed and combined to map the components of flood risk, such as hydrological (rainfall-runoff models simulating catchment response to precipitation) and hydraulic (simulating flow routing and flood inundation) models (Montanari and Koutsoyiannis 2012; Gori et al. 2019; Bai et al. 2019;

Abu-Abdullah et al. 2020; Mandal et al. 2016), remote sensing methods (Vaibhav Sharma et al. 1976; Muhadi et al. 2020; Sajjad et al. 2024), machine learning models (Abdellatif et al. 2015; Lu et al. 2018), and multiple-criteria decision analysis (Fekete and Fiedrich; Ganji et al. 2022; Panagiotou 2025; Panagiotou et al. 2025).

Hydrological and hydraulic models are basic parts of integrated flood modeling and management. In particular, hydraulic models emulate the evolution of water depths, water velocities, and consequently flood inundation extents. This information is crucial for designing flood protection measures and evaluating the potential impacts of extreme hydrometeorological events. The HEC-RAS (Hydrologic Engineering Centers River Analysis System) is a freely available software program widely used to conduct steady and unsteady hydraulic simulations (U.S. Army Corps of Engineers 2023a). It leverages the capabilities of geographic information systems (GIS) for spatial representation and analysis, enabling water planners and decision-makers to visualize the spatial extent of flood properties. Moreover, it can be integrated into decision-making frameworks that assess the relative significance of multiple factors influencing flooding (Costabile et al. 2021; Efraimidou and Spiliotis 2024; Panagiotou et al. 2025). On the other hand, hydrological models, such as SWAT (Arnold et al. 1998) and HEC-HMS (U.S. Army Corps of Engineers 2023b), simulate the spatiotemporal dynamics of rainfall-runoff processes. The resulting run off or discharge is then used as input to the hydraulic models to simulate downstream flood events (Abdessamed and Abderrazak 2019; Rajib et al. 2020; AL-Hussein et al. 2022; Peker et al. 2024). Such hydrological models can assess the response of a catchment under different scenarios by replicating the same initial conditions and system interactions. This capacity allows the objective comparison among these scenarios and enables policymakers to evaluate the efficiency of flood management strategies. Hydraulic models are essential for simulating the dynamic evolution of flows and sediments in river channels, floodplains, hydraulic pipeline networks, etc. (Tansar et al. 2020; Khattati et al. 2016; Fahad et al. 2020). Other studies (David and Schmalz 2020; Zeiger and Hubbart 2021) emphasized the strong dependence of HEC-RAS results on spatial resolution and the accuracy of the digital terrain model, underlining the need for proper calibration to ensure reliable results.

A plethora of recent studies (Zhang et al. 2022; Osman and Das 2023; Szopos et al. 2024; Azizi et al. 2025) have highlighted the necessity for including socioeconomic factors, such as population properties and land economic value, to conduct an integrated flood risk assessment. These factors are essential for modeling the spatial distribution of vulnerability and exposure, which can be subsequently combined with flood hazard to produce flood risk map. Recent studies have further demonstrated the benefits of integrating flood hazard with multi-criteria decision analysis (MCDA) to assess flood risk comprehensively (Costabile et al. 2021; Efraimidou and Spiliotis 2024; Panagiotou et al. 2025). Efraimidou and Spiliotis (2024) applied a decision-making technique (i.e., Decision Making Trial and Evaluation Laboratory (DEMATEL)) in conjunction with GIS to assess flood risk in the Kosynthos watershed basin (Thrace, Greece), enabling the incorporation of inter-criteria interdependence and providing good agreement with historical flood data. Zhran et al. (2024) developed a GIS-analytical hierarchical process (AHP) based framework for assessing flood risks in the Nile Basin, involving twelve thematic risks and six vulnerability levels. The results showed high agreement with ground-truth data, achieving a Receiver Operating Characteristic – Area Under the Curve (ROC–AUC) value of 0.741.

Despite these advances, most research studies focused on static risk mapping, neglecting the impact of real-world evacuation and civil protection frameworks (Lee et al. 2020; Musolino et al. 2022; Parajuli et al. 2023). Accurate and reliable information about these frameworks should be disseminated to first responders and the affected public (No et al. 2020) to minimize the adverse consequences during an emergency situation (Yang et al. 2020). This gap underscores the absence of methodologies that effectively translate scientific flood risk assessments into actionable evacuation and shelter planning. Existing studies often conclude at the stage of producing hazard maps, without progressing to the spatial analysis of safe assembly points or the identification of optimal evacuation routes. Lee et al. (2020) demonstrated that the coupling of evacuation planning and flood mapping can lead to safer routes, whereas Musolino et al. (2022) developed a model for optimizing evacuation routes based on pedestrian safety during flood events. Similarly, Alabbad et al. (2024) proposed an online decision support framework for routing and selecting emergency facilities during floods. Nevertheless, there are limited studies that report the integration of flood risk assessment, spatial analysis, and operational planning. One such study is the multiparameter flood risk assessment and management planning at high spatial resolution in the region of Attica, Greece (Tsouni et al. 2025), which was used as a basis for the present study and was accordingly adapted in order to be implemented in Cyprus, in the framework of the “EXCELSIOR” H2020 Widespread Teaming project (<https://excelsior2020.eu>).

The present study differs from the existing approaches as it is not limited to flood risk assessment, but also proceeds to its operational exploitation. Its innovation lies in coupling GIS-based hydraulic simulation with an ordinal, rule-based MCDA framework (using cross-tabulation based on 5×5 risk matrices), along with risk-aware evacuation route planning and shelter selection. Particularly, the proposed framework includes the following stages: (i) simulation of flood events with HEC-RAS 2D to produce hazard maps for different flood return periods; (ii) calculation of a flood risk indicator by integrating hazard, exposure, and vulnerability indicators via cross-tabulation based on 5×5 risk matrices; (iii) estimation of the spatial distribution of the flood risk indicator and its components, (iv) identification of optimal shelters through GIS analysis, considering safety, road capacity and accessibility, and building capacity; and (v) optimization of evacuation routes using risk-aware network analysis. Therefore, the proposed framework provides a reproducible and scalable pathway for flood risk-informed evacuation planning, aiming to bridge the gap between scientific modeling and operational crisis management (Teng et al. 2017; Lee et al. 2020; Zeiger and Hubbart 2021; Costabile et al. 2021; Musolino et al. 2022; Parajuli et al. 2023). The applicability of this methodology is demonstrated in the Garyllis River Basin, a highly urbanized area which is characterized by elevated flood vulnerability, as evidenced by historical flood records. The frequent occurrence of these events underscores the need to urgently strengthen infrastructure resilience and raise people’s awareness and preparedness for civil protection. To date, an integrated approach combining hydraulic simulation, decision-making, and evacuation planning has not been implemented in Cyprus within the same context. Moreover, the proposed methodology can be directly applied to flood-prone areas in other geographical regions, offering valuable insights for urban flood resilience and civil protection strategies.

2 Materials and Methods

2.1 Description of the Study Area

The Garyllis River catchment, covering approximately 104 km² in the southern and south-western parts of Cyprus, comprises river networks with a total length of 9.68 km (Fig. 1). Its northern part is characterized as hilly to semi-mountainous. The Garyllis River basin exhibits substantial variation in elevation, ranging from approximately 50 m to approximately 700 m in the northern hills. Low and high pressures are common in the Mediterranean climate, with large interannual variations in precipitation. Lower-elevation sites (altitudes ranging from 0 to 300 m.a.s.l.) receive approximately 300–350 mm of rainwater annually, whereas the highest-elevation sites (altitudes higher than 1600 m.a.s.l.) receive up to 1100 mm. The annual temperature ranges from 14 °C to 17 °C during the winter months, and from 30 °C to 35 °C during the summer months (Christou et al. 2017). According to the Urban Atlas Land Cover/Land Use 2018 (European Commission 2018), the northern part of the basin primarily includes arable land, herbaceous vegetation associations, and forests. In contrast, the southern part of the catchment is mainly covered by the urban fabric and various industrial, commercial, public, military, and private units.

According to the water authorities, the Garyllis River Basin is categorized as extremely prone to floods, particularly flash floods and urban flooding, with considerable damage according to historical flood records dating back to 1880. Especially, the flood events of November 1880 and 1894 were caused by overflow from the Garyllis River due to heavy rainfall. The 1894 flood event devastated more than 100 homes, including St. Anthony's

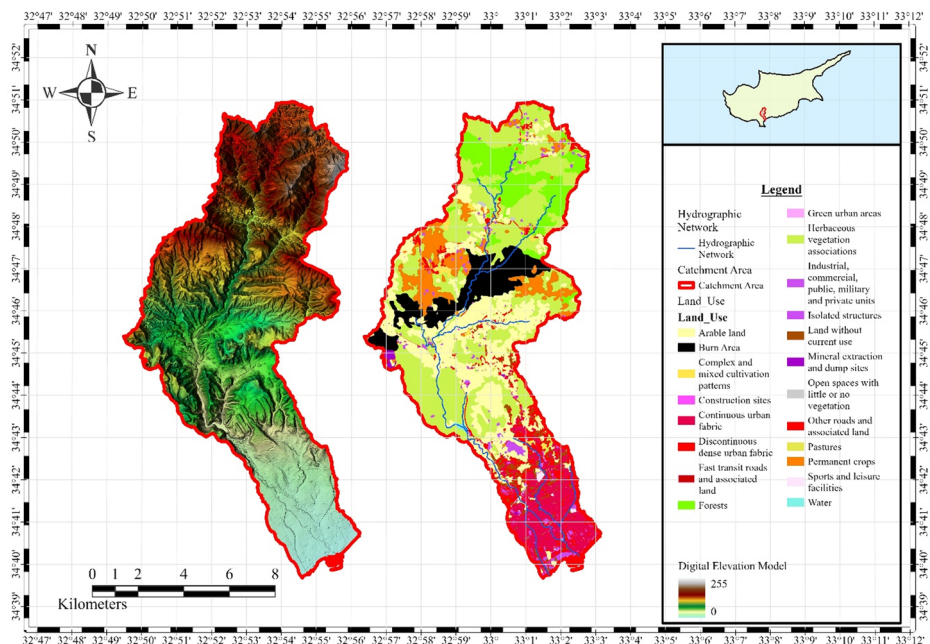


Fig. 1 Geographical location of the Garyllis River Basin, along with the spatial distribution of the river network, land use/land cover, and the topographical elevation

Church and a nearby mosque. This event resulted in more than 20 fatalities, including children, and the death of approximately 250 animals. Flooding events in 2019 and 2020 in the urban area of Limassol exceeded the scale of typical local disasters, triggered by intense rain and the full-capacity overflow of the Pólemidia dam, resulting in extensive damage to infrastructure and buildings. Local authorities and relevant agencies initiated preventive measures while recognizing the area's vulnerability to future flooding events. The hydrodynamic model incorporated the major river network which is available in the geoportal of the national water authorities, along with technical hydraulic structures. Moreover, the major branches of the network were refined based on on-site surveys, which were conducted in areas where structural information was either incomplete or not clearly visible in the available data. In particular, the geometric characteristics (i.e., dimensions and cross-sectional shapes) of artificial flow elements, such as culvert and bridges, were recorded during these surveys. These measurements were subsequently used to locally modify the topographic characteristics by excavating hydraulically equivalent open-channel sections. The same approach was applied at the single river diversion point, where the resulting modifications to the flow path were likewise represented by adjusting terrain elevation rather than explicitly incorporating artificial flow elements. In contrast, the Polemidia dam was explicitly represented in the hydrodynamic model to account for its effects on upstream storage and downstream flow conditions. The refined river network and DEM were then validated through flow direction and flow accumulation analyses, ensuring the hydraulic consistency of the model. Notably, flood management initiatives were undertaken following devastating floods in 1880 and 1894, which resulted in extensive destruction and loss of life, including diversion of the Garyllis River to alter its flow. Moreover, the construction of the Polemidia dam in 1965, with a storage volume close to 3.4 million cubic meters, contributed significantly to reducing flood damage in combination with the functionality of river diversification. The proximity of the river to residential and commercial areas, combined with the lack of designated flood protection areas, highlights the critical need to develop flood management planning in coordination with future land use activities, such as public gardens and parks.

2.2 Methodology

The proposed methodological framework integrates physical, hydraulic, and socioeconomic data to provide a complete view of flood risk and assist in designing evacuation strategies. This framework (Fig. 2) involves data collection from multiple sources (Step 1), compilation of hydraulic two-dimensional simulations under different return periods derived from the intensity-duration-frequency (IDF) curves (Step 2), and spatial decision-making analysis to compile flood risk maps by overlaying the three primary components of flood risk: hazard, vulnerability, and exposure (Step 3). The outcomes of this process are then used to propose mitigation actions in alignment with the EU Flood directive, particularly the design of optimal evacuation routes and the selection of suitable shelters in emergency situations (Step 4). Throughout all implementation steps, continuous interaction and communication with governmental authorities were maintained to obtain official datasets and to ensure that modeling assumptions, methodological choices, and proposed mitigation measures were consistent with local practices and regulatory requirements.

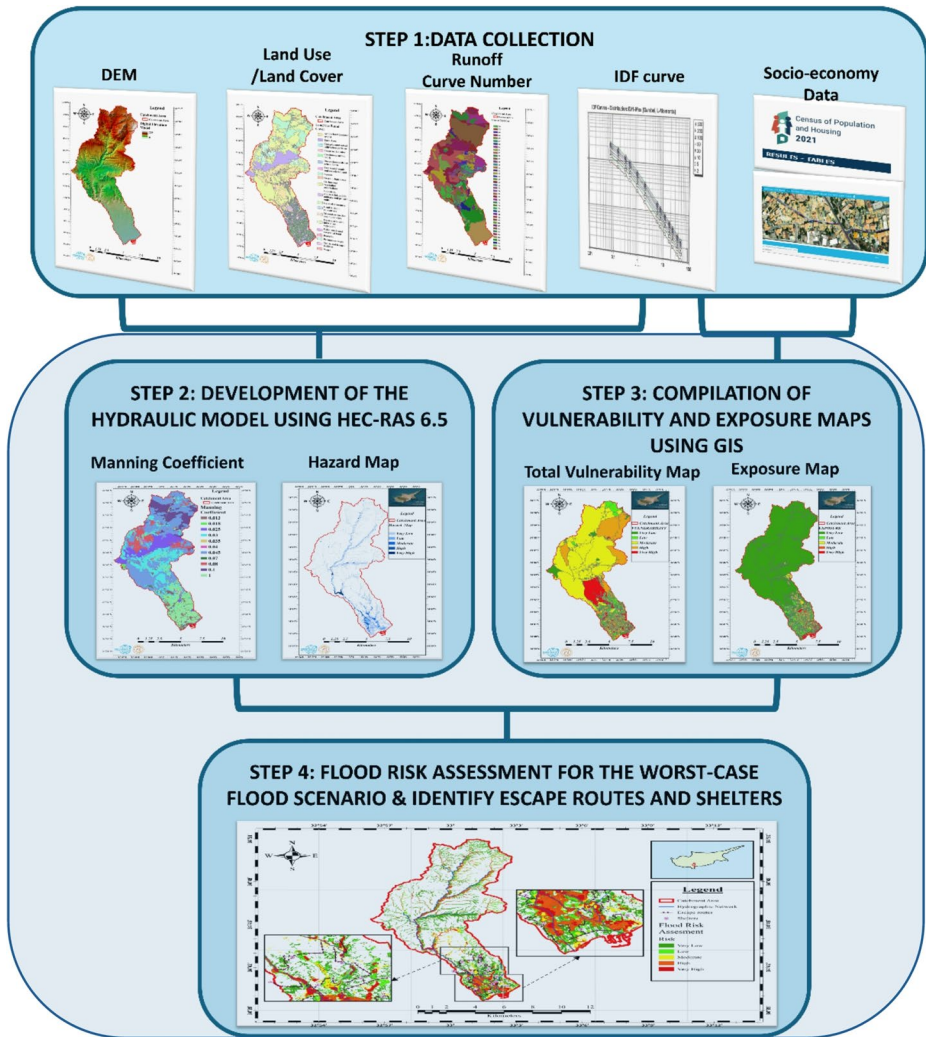


Fig. 2 Overview of the proposed methodology

2.2.1 Data Collection and Preparation

Table 1 presents a summary of the collected information from multiple data sources. In particular, the IDF curve corresponding to rainfall data collected from a nearby ground-based station located in Kalo Horio village was provided by the Department of Meteorology. Consequently, a synthetic hyetograph was constructed based on a single IDF curve and applied across the entire domain of the study area. This decision was imposed by the lack of additional rain gauges within and around the Garyllis basin. Consequently, rainfall patterns were generated to simulate storm events with three different return periods (50, 100, and 1000 years), which were used as inputs to the hydraulic model. The cumulative rainfall depth for each return period was obtained by multiplying the rainfall duration and the

Table 1 Summary of the information collected from different data sources

DATA	INFORMATION	RESOURCES
Digital elevation model (DEM)	5 m resolution	Department of Lands and Surveys Cyprus DLS Portal (moi.gov.cy)
Road Network	2016	Department of Lands and Surveys Cyprus DLS Portal (moi.gov.cy)
Intensity-Duration-Frequency (IDF) curve	Kalo Horio station, 2009	Meteorological Department of Cyprus Home Page Department of Meteorology (moa.gov.cy)
River network	-	Water Development Department of Cyprus Water Development Department Home Page (moa.gov.cy)
Land use/Land cover	2018	Copernicus Land Monitoring Service (CLMS), Urban Atlas Land Cover/Land Use 2018 (vector), Europe, 6-yearly — Copernicus Land Monitoring Service
Population (age and density)	2011	Statistical Service Στατιστική Υπηρεσία - Αρχική (cystat.gov.cy)
Land economic value	2021	Department of Lands and Surveys Cyprus DLS Portal (moi.gov.cy)
Runoff Curve Number (CN)	2009	Water Development Department of Cyprus Water Development Department Home Page (moa.gov.cy)

corresponding storm intensity. Rainfall time series with 10 min intervals (0.167 h) were then determined by calculating the differences between consecutive cumulative depths via Alternating Block Method. The IDF-generated synthetic hyetographs exhibited their highest intensities near the peak of a 24-hour design storm event. Therefore, the 24-hour storm event is derived from the single IDF curve due to the absence of high-resolution rainfall time series. This duration was selected to represent a full design rainfall event and to capture the catchment response over an entire day, thereby supporting emergency planning. Importantly, the maximum intensities occur within a few 10-min temporal blocks near the storm peak, while the remaining duration corresponds to lower intensities that progressively approach zero as one moves away from the peak. The Rain-on-Grid approach was then used to apply a spatially uniform rainfall time series over the 2D domain in the HEC-RAS solver. A digital elevation model (DEM) with 5-meter spatial resolution was provided by the Department of Lands and Survey and used to simulate the topographical characteristics of the watershed (i.e., terrain elevation, terrain slope, flow accumulation, flow direction, and river basin delineation). Even though this resolution might be considered rough for conducting a more detailed urban-scale analysis, it represents the most recent and finest available DEM at a national level. Supplementary geometric modifications were applied to mitigate the negative impact of DEM-related deficiencies, especially in urban regions. In particular, linear features (roads, levees, channels) are incorporated into the numerical grid as barriers

or flow guides, resulting in local modifications of the topography (i.e., resolution, smoothing) to ensure a more accurate and realistic flow path. With respect to the land use and land cover data, vector data (polygons) are extracted from the European Urban Atlas (2018) of the Copernicus Land Monitoring Service (European Commission 2018). Additional information was collected to simulate burned areas resulting from wildfires that occurred in September 2022 and August 2023, as reported by the European Forest Fire Information System (EFFIS) (European Commission 2025a, 2025b). These data were then used to modify the LULC layer, which was subsequently included in the hydraulic model. Curve Number (CN) data corresponding to year 2009 were collected from the Water Development Department (WDD) of Cyprus. Subsequently, the CN values were locally adjusted to account for the effects of wildfires that occurred after 2009. A CN value of 80 was assigned to the burned areas based on values reported in the literature (Cerrelli 2005; Natural Resources Conservation Service 2016) for post-fire hydrological conditions in comparable environments (Fig. 3). These modifications reflected the expected reduction in infiltration capacity and increase in surface runoff following wildfire events. Burned areas were introduced as distinct LULC polygons, and used to adjust hydrologic (CN) and hydraulic (roughness) properties according to post-fire conditions.

In addition, Manning's (n) roughness coefficients were also adjusted to account for vegetation loss and surface alterations. The impact of buildings was incorporated into the hydraulic model via the European Urban Atlas 2018 Land Cover data from the Copernicus Land Monitoring Service, which provides detailed polygon boundaries of urban areas, infrastructure, and built-up areas. These areas were associated with high values of the roughness coefficient (Manning) and reduced infiltration potential because of impermeable ground

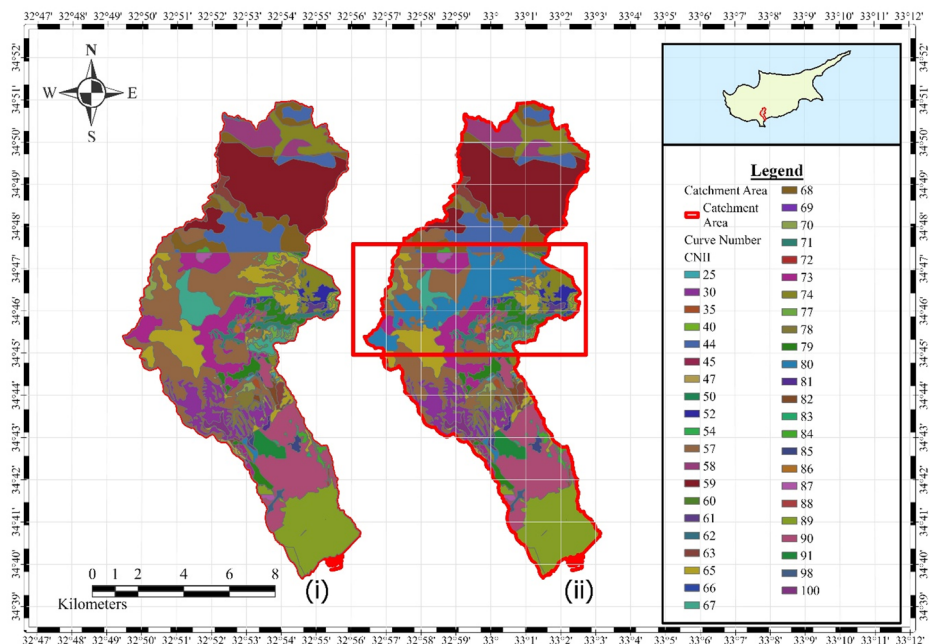


Fig. 3 The spatial distribution of Curve Number (CN) values (i) before and (ii) after the post-fire adjustment. Red box encloses= the areas where CN values were updated to represent post-fire conditions

surfaces. Finally, socioeconomic data (i.e., population age, population density, and land economic values) were collected from the Cypriot Statistical Service and the Department of Lands and Surveys, respectively.

2.2.2 Hydraulic Modeling and Hazard Map

HEC-RAS 6.5 software was employed to perform unsteady two-dimensional (2D) hydraulic simulations for mapping inundation depth during a 24-hour storm event for different return periods (i.e., 50, 100, and 1000 years). In particular, the full Saint-Venant (dynamic wave) equations are solved using an implicit finite difference numerical scheme, without applying the diffusion approximation (U.S. Army Corps of Engineers 2023a). A base time-step of 0.1 s is adopted, which is dynamically adjusted according to Courant criterion (De Moura and Kubrusly 2013) to guarantee numerical stability at each grid cell. In this study, the Courant number was set to range from 0.1 to 1.5. Simulations were initialized assuming unsaturated soil conditions, while the occurrence of wetting and drying grid cells was controlled within the HEC-RAS 2D solver settings to ensure consistent activation of flow paths during flood recession.

The DEM of the Garyllis River Basin was used to derive terrain properties, whereas the hydrographic network was enhanced with 2D break-lines (i.e., the boundaries of the grid cells along important linear topographical features), including ridges and artificial structures enabling flow motion within the numerical grid (U.S. Army Corps of Engineers 2023a). The geometry of the study area was created in ArcGIS. Additionally, the numerical grid was discretized on the basis of a variable cell size, mostly ranging between 10 and 20 m, to account for the local topographical features of the catchment area. Consequently, the spatial resolution was further refined in areas (a) where sharp topographic variations are present, and (b) that are very close to the hydrological network, ranging from 1 to 10 m.

As described in Sect. 2.2.1, a single IDF curve was used to develop synthetic hyetographs, while a spatially uniform rainfall field was applied across the entire study area due to limited precipitation data. A small base computational time step ($\Delta t_{\text{comp}} = 0.1$ s) was assigned to the HEC-RAS solver for transient simulations to accurately capture flow dynamics at the initial stages. This time step is dynamically adjusted according to the Courant criterion to ensure numerical stability (capturing changes at the pixel-level) and computational efficiency, avoiding excessively small timesteps that would slow the simulations. Following HEC-RAS documentation, the Courant number was allowed to vary between 0.1 (for high velocities) and 1.5 (for low velocities).

The Soil Conservation Service Curve Number (SCS-CN) method was used to model the rainfall losses and direct runoff, including the influence of burned areas that emerged after post-fire events. This method uses a CN polygon indicative of moderate antecedent soil moisture conditions. Standard formulations of the SCS method were applied, following established hydrological practice. According to U.S. Army Corps of Engineers (2023a), CN values typically range from 30 to 100, with lower values representing highly permeable surfaces and therefore low runoff potential. LULC data were extracted from the European Urban Atlas (European Commission 2018), along with burned areas (European Commission 2025a, 2025b), to assign Manning's roughness coefficients at each LULC class. Manning's roughness coefficients were assigned based on values reported in established hydraulic modeling references and previous flood modeling studies (Arcement and Schneider 1989;

Papaioannou et al. 2018). Table 2 summarizes the Manning coefficient values adopted for each LULC category. This coefficient strongly depends on land cover types and has significant impact on the predictions of the hydraulic model.

In addition, boundary conditions were imposed to represent physically realistic exchanges at the domain limits. A normal-depth boundary condition was applied at the downstream outlet of the 2D domain to allow water to exit without generating artificial backwater effects. The remaining outer boundaries were treated as closed (no-flow) boundaries, consistent with watershed divides. The normal depth was calculated using the energy slope derived from the downstream terrain gradient extracted from DEM, to ensure stable outflow conditions.

The resulting inundation depth maps were converted into multi-class hazard maps by adopting a conservative approach that prioritizes safety. This approach particularly considered the damage caused by historical flood events in urban areas located within the Garyllis River Basin (Civil Defence 2018), as well as the projected increase in flood severity under future climate change scenarios. Consequently, five hazard levels were defined as follows: “Very Low” (<0.3 m), “Low” (0.3–0.5 m), “Moderate” (0.5–1 m), “High” (1–2 m), and “Very High” (≥ 2 m). Each hazard level was assigned an integer score ranging from 1 (lowest) to 5 (highest) to facilitate the construction of the risk matrices. With respect to flood risk assessment, the occurrence of “High” and “Very High” classes should activate the first responders and local authorities to implement actions for preventing potential damages and health hazards, in alignment with the EU Flood Directive.

Table 2 Manning’s (n) coefficient values assigned to different land use/land cover classes (Arcement and Schneider 1989; Papaioannou et al. 2018)

Land Use/Land Cover (LULC) Category	Manning ‘s coefficient (n)
Continuous urban fabric	1.000
Discontinuous urban fabric	1.000
Isolated structures	1.000
Industrial - commercial, public, military and private units	0.013
Fast transit roads and associated land	0.013
Other roads and associated land	0.013
Railways and associated land	0.013
Port areas	0.013
Airports	0.013
Mineral extraction and dump sites	0.018
Construction sites	0.013
Land without current use	0.018
Green urban areas	0.025
Sports and leisure facilities	0.025
Arable land (annual crops)	0.030
Permanent crops (vineyards, fruit trees and olive groves)	0.080
Pastures	0.035
Complex and mixed cultivation patterns	0.040
Forests	0.100
Burn area	0.030

2.2.3 Vulnerability, Exposure, and Flood Risk Assessment

The total vulnerability map was developed by analysing demographic data, particularly population density and population age. The population density index is expressed by the number of inhabitants per unit area (inhabitants/km²). Initially, the total human population was distributed among the individual buildings based on their proximity to the corresponding road segments, as population data were provided by the authorities at the street level. Subsequently, the human population inside each building was aggregated within its corresponding building block, allowing the calculation of the total population per block. Finally, population density was derived by dividing the total population of each building block by its area. The population age indicator (P_a) equals the proportion of the most vulnerable age groups (children (P_{child}) and elderly (P_{eld})) relative to the total population (P_{tot}) at the street level:

$$P_a = \frac{(P_{child} + P_{eld})}{P_{tot}}. \quad (1)$$

The human population was proportionally distributed from the street-level data to individual buildings and subsequently aggregated at the building-block level, as described previously. The same procedure was applied for each age group, with the number of young and elderly inhabitants proportionally distributed from the street-level data to individual buildings based on their proximity to each road segment, and then aggregated at the building-block level. All values were normalized between 0 and 1 to allow a uniform classification. A high population density indicates high vulnerability to extreme precipitation events. With respect to population age, high vulnerability is associated with children and elderly people. Both datasets were classified into five classes - Very Low (1), Low (2), Moderate (3), High (4) And Very High (5) using equal interval classification (Table 3).

Consequently, an MCDA framework was adopted to integrate these indicators by employing an ordinary decision-rule method (cross-tabulation matrix) to consolidate the reclassified criteria into one unified vulnerability index (Table 4). Similar to the hazard case, the vulnerability index was organized into five categories (i.e., “Very Low”, “Low”, “Moderate”, “High”, and “Very High”).

Next, exposure levels were estimated by quantifying the economic risks associated with flooding. In particular, the economic risk was estimated based on the land’s economic value for each land parcel, as provided by the Department of Land Registry. The land’s economic values were classified by facility use type (residential, commercial, industrial). This approach enabled the spatial mapping of economic risk, hence the identification of areas with an increased probability of economic losses in the event of a flood. Similar to the other

Table 3 Classification of vulnerability levels based on the population density and population age

Vulnerability level	Population density indicator	Population age indicator
Very Low	[0.000000–0.004485]	[0.000000–0.155556]
Low	[0.004486–0.010832]	[0.155557–0.280271]
Moderate	[0.010883–0.026700]	[0.280272–0.391232]
High	[0.026701–0.057403]	[0.391233–0.583378]
Very High	[0.057404–0.138484]	[0.583379–1.000000]

Table 4 Cross-tabulation of population density and population age

		Vulnerability based on population density				
		VL	L	M	H	VH
Vulnerability based on population age	VL	1	2	3	4	5
	L	2	2	3	4	5
	M	3	3	4	4	5
	H	4	4	4	5	5
	V	5	5	5	5	5
	H	5	5	5	5	5

VL: Very Low, L: Low, M: Moderate, H: High, VH: Very High

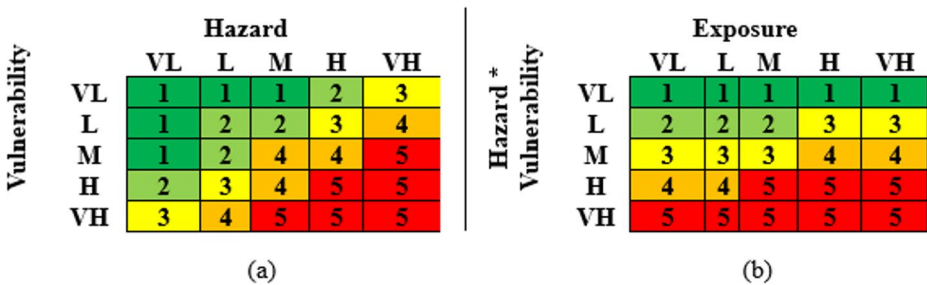


Fig. 4 Risk matrix for determining (a) the intermediate flood risk levels on the basis of hazard and vulnerability scores, and (b) the final risk index by combining the exposure index and the intermediate risk values (VL: Very Low, L: Low, M: Moderate, H: High, VH: Very High)

flood risk components, the levels of exposure were classified into five distinct classes: “Very Low”, “Low”, “Moderate”, “High”, and “Very High”.

The flood risk indicator was then calculated by integrating the hazard, vulnerability and exposure indicators via ordinal 5×5 risk matrices to establish both intermediate and final flood risk classes. In particular, an intermediate risk value is calculated by relating the hazard and vulnerability scores (Fig. 4a) via a 5-by-5 risk matrix. The matrix elements are assigned discrete risk levels which range from 1 (“Very Low”) to 5 (“Very High”). As shown in Fig. 4b, the final risk value is calculated by combining the exposure scores, ranging from 1 to 5, with the intermediate risk values. This two-phase strategy ensures comprehensive and spatially detailed flood risk investigations to pinpoint high-risk areas and suggest feasible flood risk mitigation measures shelters.

2.2.4 Mitigation Measures

The flood risk map was subsequently used to develop an emergency planning framework in the emergence of the most catastrophic scenario (i.e., 1000-year return period). This framework facilitates the transition from compiling flood risk maps to proposing practical actions for civil protection and municipal authorities. Specifically, the framework focuses on selecting appropriate safe shelter sites and identifying evacuation routes that comply with established safety rules, in accordance with the EU Floods Directive (Directive 2007/60/EC)

which mandates the creation of flood hazard and flood risk maps, as well as the construction of Flood Risk Management Plans. This information is particularly important for Cypriot authorities, as there are currently no designated safe shelters or escape routes for flooding in Cyprus. Existing shelters are designed to withstand military attacks and are all underground, making them unsuitable as flood shelters. A criteria-based methodology was employed to identify potential shelters and establish safe evacuation routes using clear, replicable guidelines. Candidate shelters were initially identified based on local knowledge and field observations and were subsequently verified using Google Maps and on-site visits. Moreover, only publicly accessible buildings were considered.

The areas associated with “Zero”, “Very Low” and “Low” risk levels served as the starting point for designing the evacuation route. The escape route was chosen according to the following set of rules to ensure a direct and safe connection between residential areas and the designated shelter: (i) follow the main and shortest road of the existing road network, (ii) comply with the traffic flow direction, and (iii) avoid passing through high-risk regions and riverbeds. Riverbeds were prevented based on visual inspection of the map and local/field knowledge. When multiple routes satisfied the selected rules, the preferred route was chosen as the one with the shortest total distance along the road network.

Several conditions were considered to select the most appropriate shelters. The selected shelters should satisfy strict accessibility, safety and structural standards. The selected shelters should be: (i) public buildings (ii) accessible to people with disabilities and/or mobility limitations, (iii) covered and adequately resilient to extreme weather conditions, and (iv) equipped with essential facilities and materials, such as toilets, drinking water, and first aid kit. These features ensure that people can remain safely accommodated during an emergency situation. With respect to the escape routes, they should be carefully designed to guarantee safe passage avoiding high-risk areas. These shelters should be located in “Zero”, “Very Low” or “Low” risk regions. Shelters located within “Moderate”, “High” or “Very High” risk zones were excluded due to their increased likelihood of inaccessibility or inundation under the design event. These criteria were utilized as a series of binary exclusion filters (“Pass”/ “Fail”), rather than using a weighted multi-criteria scoring system. Finally, the outputs of this research (i.e., maps, evacuation routes) were integrated into a WebGIS platform to ensure user-friendly access for all relevant stakeholders. In particular, the WebGIS platform enables interactive visualization of risk and hazard levels, retrieval of shelter information, and rapid identification of recommended evacuation routes, supporting operational use by municipalities and first responders during flood emergencies. The workflow was designed to be adaptable and can be applied to different catchments, provided that a flood risk map and fundamental spatial layers (such as settlements and the road network) are available, along with local validation of shelter suitability.

3 Results

Figure 5 illustrates the 24-hour synthetic rainfall hyetographs for three return periods, particularly 50, 100, and 1000 years. For all scenarios, the hyetograph is assumed to follow a symmetric distribution, with rainfall intensities progressively increasing while approaching the 12-hour peak value. Both the peak intensity value and the cumulative rainfall are increased while increasing return period. Particularly, the total rainfall amounts are

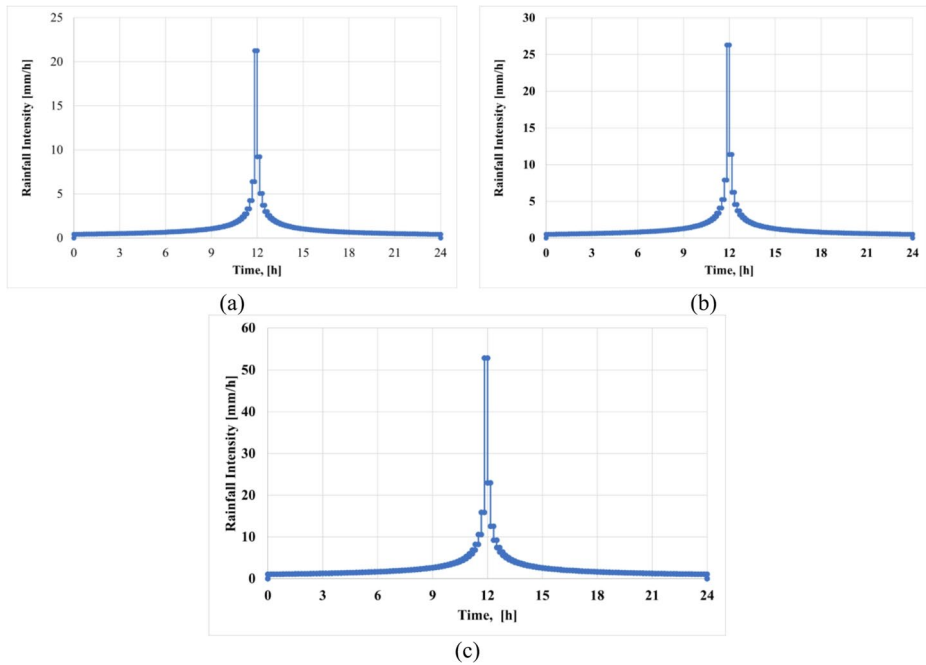


Fig. 5 Synthetic hyetographs for (a) 50-year, (b) 100-year, and (c) 1000-year return periods

21.2 mm, 26.3 mm, and 52.9 mm for the 50-year, 100-year, and 1000-year return periods, respectively.

In this study, both flood and flow velocity maps were generated for the three return periods. A water depth threshold of 0.2 m was adopted, below which inundation was not deemed significant for flood mapping purposes. Consequently, these areas were excluded from the risk analysis. With respect to water velocity, regions associated with water speed below 0.005 m/s were assigned to the negligible category, which reflects stagnant water conditions, and was excluded from subsequent analyses. Table 5 shows the distribution of flow-velocity classes for each return period.

For the 50- and 100-year return periods, over 99% of the study area was covered by practically stationary flow (<0.005 m/s). Consequently, these areas were excluded from the hazard classification process. The remaining flooded areas were characterized mostly by very low speeds (<1 m/s). With respect to the 1000-year case, “Very Low” [0.05–1 m/s]

Table 5 Percentage distribution of flow speed among velocity classes for each return period (RP)

Flow Velocity Class	Flow Speed (m/s)	50-year RP (%)	100-year RP (%)	1000-year RP (%)
Negligible	0–0.005	99.42	99.36	57.25
Very Low	0.05–1	0.53	0.58	22.27
Low	1–3	0.041	0.05	14.82
Moderate	3–6	0.008	0.009	4.71
High	6–9	0.001	0.001	0.86
Very High	9–20	–	–	0.09

and” Low” [1–3 m/s] velocity classes covered approximately 22% and 15% of the entire study area, respectively, whereas “Moderate” [3–6 m/s] and “High” speed classes [>6 m/s] accounted for less than 6% of the total study area. These findings indicated that the study area is mostly covered by low flow velocities. Eventually, flood depth was chosen for classifying flood hazards in this study, since it is more representative, relevant and reliable parameter, also offering smoother profile compared to the flow velocity which is highly sensitive to local channel geometry and pathways, roughness, and uncertainties/errors in topographical properties.

Figure 6 shows the flood hazard maps for a 24-h storm duration under the three return periods. The hazard maps for the 50-year and 100-year return periods (Fig. 6a–b) exhibit very similar spatial patterns, with flood-prone areas mainly located along the main river channel and in the lower part of the catchment. The spatial extent of high hazard zones remains almost unchanged between the two scenarios, rising slightly from 0.08 km² to 0.13 km², and covering only small parts of the catchment area. As expected, the maximum water depth (5.3 m) is located within the densely urbanized coastal zone, whereas the minimum water depth (0.3 m) is located in the upstream areas. The areas which are characterized as “Very Low” hazard zones cover most of the mountainous, northern part of the catchment, mainly because of the presence of steep topography, dense vegetation, and low population density. “Low” hazard zones mainly occur 50–150 m away from the hydrological network, covering mostly mid- and low-elevation areas characterized with gentle terrain slopes. Although the hydrological network extends to the northern mountainous region, the most pronounced low-hazard passages are observed along the central and southern reaches of the catchment, where wider floodplains and lower gradients favor water accumulation.

Moderate-hazard areas occurred mainly in the lower parts of the basin, specifically within urban and semi-urban areas. These areas exhibited local terrain depressions and land cover changes that affect flood accumulation. Moreover, the results revealed the absence of either “High” or “Very High” hazard zones for 50- and 100-year return periods.

With respect to the worst-case scenario (1000-year period, Fig. 6c), the simulated hazard levels are shown to be substantially increased in terms of both spatial extent and intensity, covering approximately 8.2 km² of land area. The maximum water depth is 6.2 m, whereas the highest values are clustered in low-altitude urban regions. These high-risk areas are mostly covered by extensive presence of asphalt roads, buildings, and paved surfaces that prevent natural infiltration, favor surface runoff during extreme precipitation events. As expected, “Very Low” and “Low” hazard levels are predicted in the mountainous regions because of the presence of steep terrain slopes, dense vegetation, and forests.

Figures 7a–b show the geographical distribution of the population density and age groups (children, adults, elder). A composite vulnerability index was created by combining these population aspects. Higher scores are assigning to areas with dense population and higher proportions of the most vulnerable human groups (i.e., children and elderly people) to flood impacts. Like in hazard case, vulnerability index is classified into five distinct levels: “Very Low”, “Low”, “Moderate”, “High”, and “Very High”. The geographical distribution of the flood vulnerability component is shown in Fig. 7c.

In addition to demographic-based flood vulnerability, the geographical distribution of flood exposure was also assessed using land economic value as an indicator of economic risk. Figure 8 shows the spatial distribution of exposure within the basin. The southern part

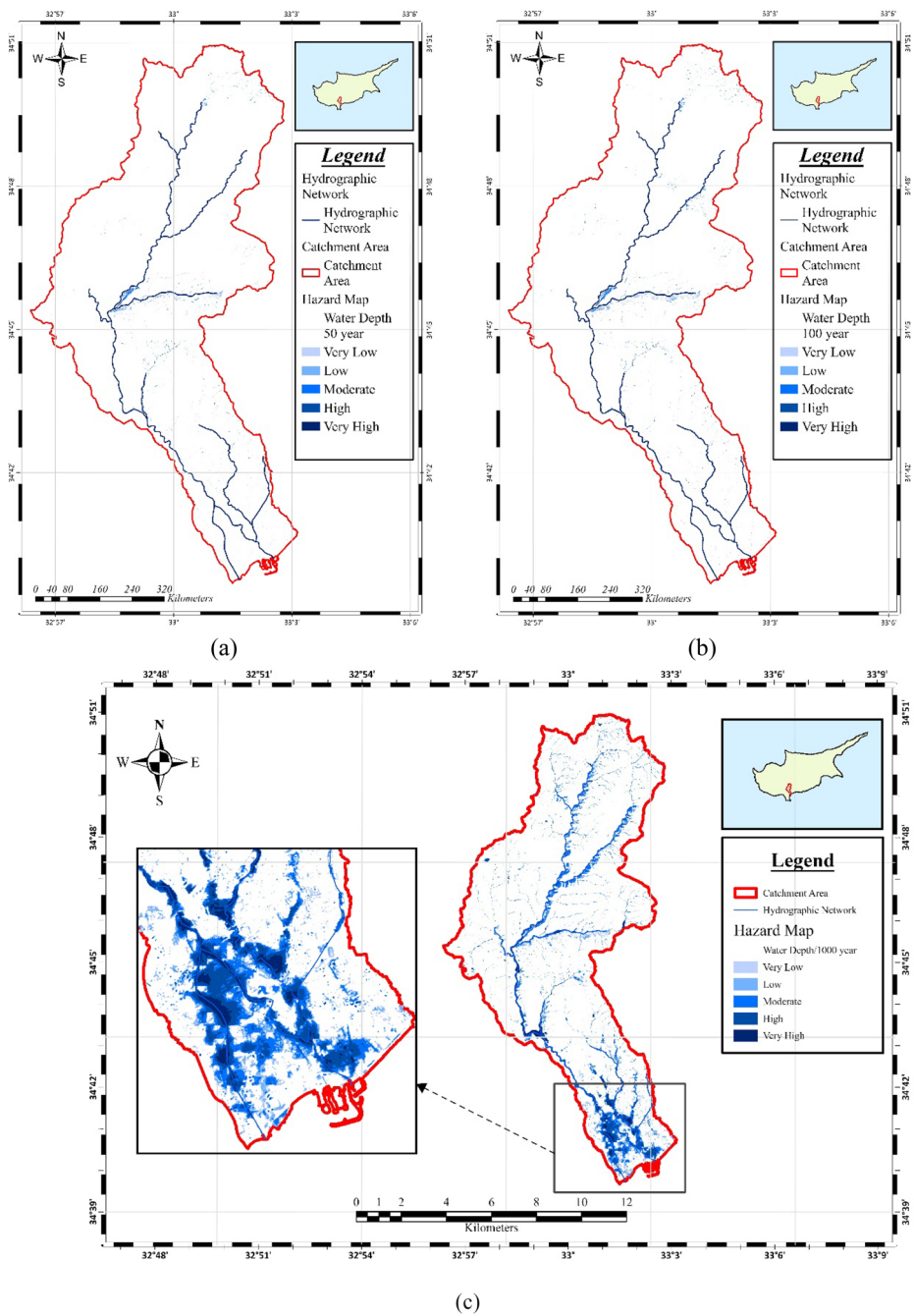


Fig. 6 Hazard maps for three different scenarios: (a) 50-year (b) 100-year (c) 1000-year return periods

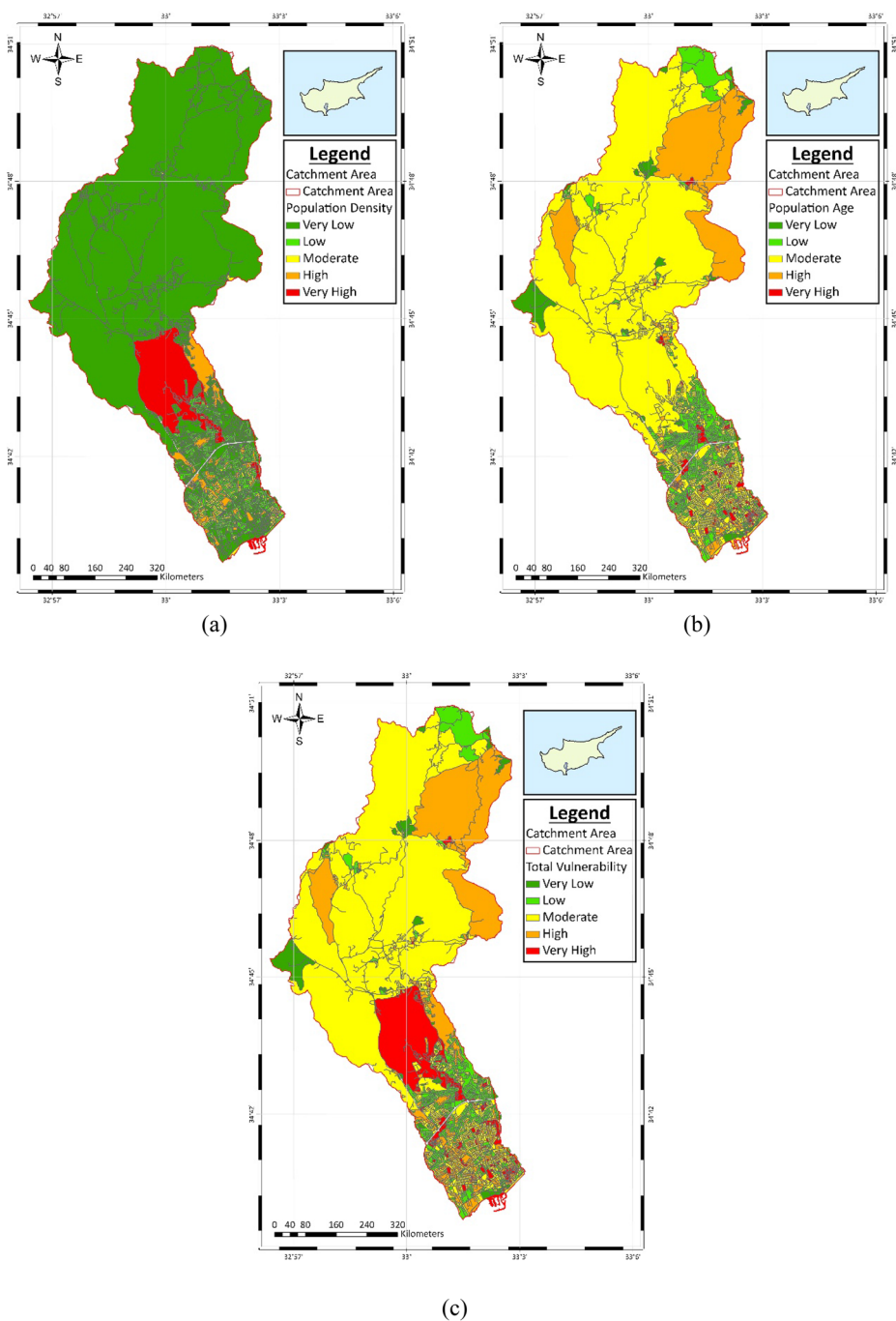
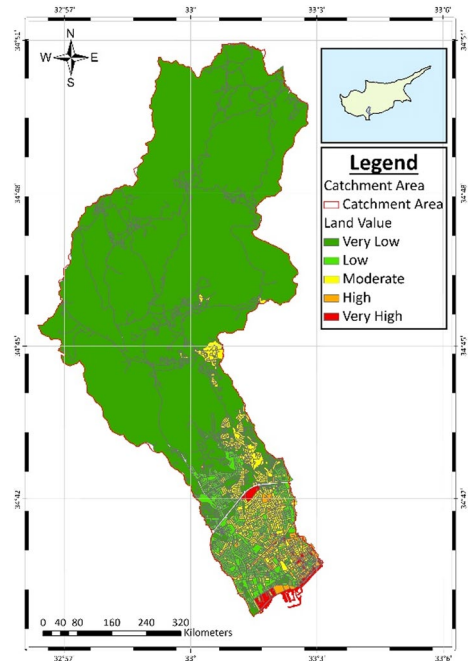


Fig. 7 Spatial distribution of the flood vulnerability components, particularly (a) population density, (b) age disruption, and (c) total vulnerability, categorized into five levels: Very Low, Low, Moderate, High, and Very High

Fig. 8 Flood exposure map of the study area

of the basin, especially the coastal and urbanized areas, exhibit “High” and “Very High” exposure due to the concentration of residential, commercial, and industrial facilities with high economic values. In contrast, the northern and northwestern mountainous regions are characterized by low exposure levels, reflecting the sparse population and limited economic activity. Nevertheless, ongoing urban expansions and population growth in semi-urban areas are expected to increase exposure levels in the near future.

Figure 9 shows the geographical representation of flood risk across the catchment under the 1000-year return period scenario. As expected, the high-risk areas are clustered in the southern, highly urbanized part of the basin. These areas are highly-prone to flooding because they possess favorable topographical characteristics, such as low terrain elevation and gentle terrain slopes, and flood-inducing anthropogenic factors, such as rapid urbanization, dense population, strong presence of flood-vulnerable population groups, and expensive land and building properties. As expected, the results indicated the presence of the highest risks in Limassol city. These results are consistent with the characterization of this area by the water authorities as one of the most flood-prone regions at a national scale.

These zones often coincide with transitional land-use areas located between rural/agricultural and urban environments, where rapid land-use change and insufficient drainage infrastructure increase flood susceptibility. The current urban drainage system in Limassol operates at return periods between 2 and 10 years, which follows standard practices for urban flood management. The 1000-year return period analysis in this study functioned to assess long-term flood resilience instead of evaluating the present drainage system performance. This approach helps to identify areas where the current drainage system is likely to be overwhelmed under extreme events. The results, therefore, highlight potential zones of

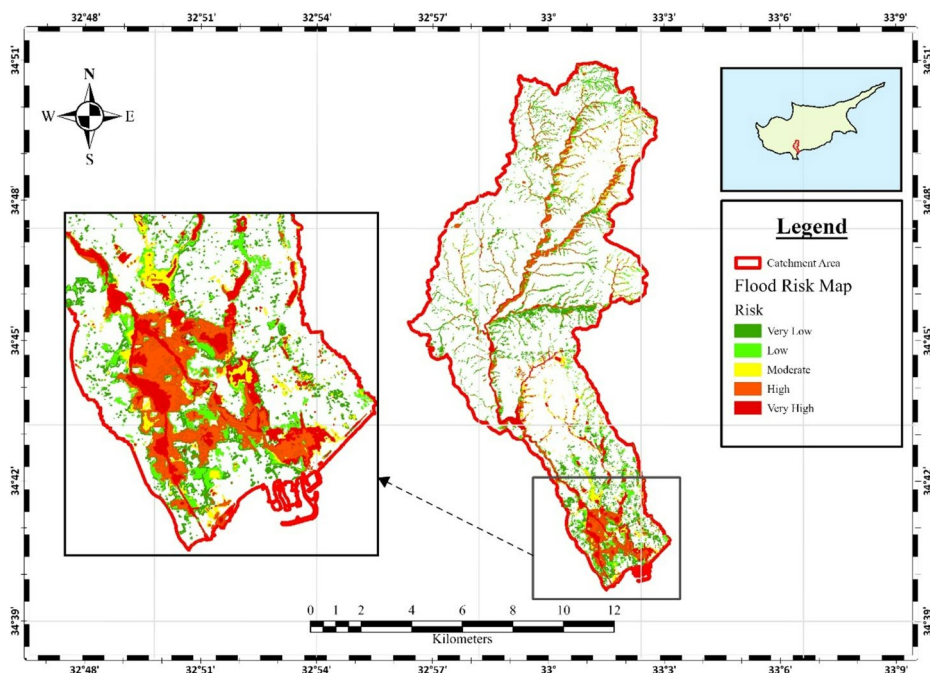


Fig. 9 Flood risk mapping of the Garyllis River Basin

extreme exposure, providing valuable insight for strategic urban planning and future infrastructure upgrades.

On the other hand, the northern, mountainous areas of the catchment are mainly characterized as “Moderate” to “Low” risk zones because of the dominant presence of steep terrain slopes, sparse population density, and limited urban and infrastructure development.

Figure 10 shows the optimal escape routes for reaching appropriate shelters according to the traffic flow direction, in alignment with the relevant articles of the EU Flood directive. The map shows how the escape routes pass through no or very low-risk regions while (i) following the primary road network, and (ii) bypassing river intersections and hazardous flood zones. Public schools are ranked as the most appropriate shelters because of their accessibility and capacity to house people, followed by public buildings, such as municipal centers and community offices. As expected, the selected shelters are located in areas with no or very low-to-low flood risk levels. A large number of shelters is considered throughout the urban area to provide quick and safe access for residents who live in flood-prone districts. The zoomed windows in Fig. 10 shows a detailed view of the southern region to offer better visualization of the evacuation paths and the spatial arrangement of the shelter positions. The overall structure indicates that the evacuation strategy attains equitable accessibility between the northern and southern sections of the city. The preferred evacuation route was selected as the one with the shortest travel distance to the selected shelter while satisfying all rules, ensuring the highest geographical proximity and safety.

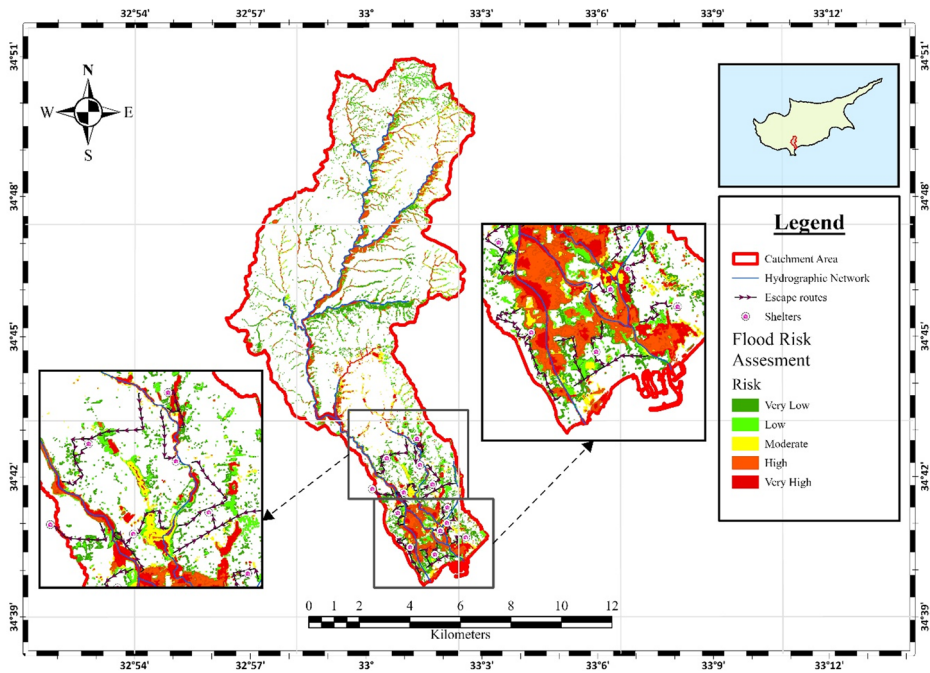


Fig. 10 Flood risk assessment for Garyllis River Basin in Limassol: selected shelters and evacuation routes based on geographical proximity and safety

4 Discussion

This study presented an integrated, comprehensive framework that combined hydraulic simulations, decision-making, and multiple data sources to quantify risk levels, identify high-risk areas, and proposed optimal escape routes and shelters in line with the requirements of the EU Flood Directive. Consequently, the outcomes of this study can contribute to future flood management plans and future research.

4.1 Relevance with Previous Studies in the Mediterranean Basin

The risk map revealed that approximately 18% of the Garyllis basin is highly prone to flooding, whereas approximately 2.7% is associated with either moderate or very high flood risk levels. The “High” and “Very High” risk regions are located primarily in the southern, densely populated urban areas (Limassol city), where impermeable surfaces and the dense presence of high-value infrastructure increased the likelihood of flooding. The dense presence of population groups with mobility limitations (i.e., children, elder) in these areas resulted in high values of the vulnerability index, highlighting the need for selecting optimal and safe escape routes. The economic data showed that commercial and industrial areas are the most economically vulnerable, as they occupy the largest portion of the urban area. The findings of the proposed approach highlighted the need for integrating both physical and socio-economic information to assess flooding. The high spatial variability of the risk levels, especially in the southern urban areas, illustrated the combined effect of topographi-

cal, LULC, and human-induced activities on flood mechanisms. These findings are consistent with those of similar studies conducted in the Mediterranean basin. Recent studies in Mediterranean urban catchments have identified similar spatial patterns and drivers of flood hazard and risk. Hotspots are most frequently found in low-elevation, densely developed areas with extensive impervious surfaces and insufficient drainage capacity. For example, Rodopoulos et al. (2025) applied GIS-based AHP to evaluate flood susceptibility across three ungauged catchments in Volos, Greece. The authors highlighted that uncontrolled urban growth, extensive impervious surfaces, and inadequate drainage systems can lead to an increase in the flood risk in low-altitude areas. A similar study was conducted by Mazarakis et al. (2025), who incorporated several criteria, such as terrain slope, elevation, distance from rivers, LULC, and geology, into an analytical hierarchical process to identify high-risk regions in the central part of the island of Evia (Greece). Moragues et al. (2025) integrated fuzzy logic into a GIS-based framework, together with Principal Component Analysis (PCA), to assess social vulnerability due to flooding. Their results revealed that the simultaneous presence of densely built areas over floodplains, limited open spaces, and high population density significantly increased both physical and social vulnerability. Moreover, Varra et al. (2025) applied the HEC-RAS 2D Rain-on-Grid approach to simulate rainfall-induced flooding in Southern Italy, showing that integrating direct rainfall and detailed surface processes improves flood hazard estimation in urban and low-elevation areas. Collectively, these studies validated the identification of risk hotspots in the Garyllis area, although their primary focus was on mapping susceptibility, hazard, and vulnerability. In contrast, the present study extends these works by applying the derived risk map to operational decision-making, specifically for identifying safe shelters and planning risk-aware escape routes. In this context, Tsouni et al. (2025) established a comprehensive framework for flood risk assessment at the building-block level; however, the present study exhibits several notable discrepancies. Specifically, the present study assessed the geographical distribution of population exposure using street-level data, which were subsequently aggregated to the building block level. Additionally, the vulnerability assessment excluded building type and construction material due to limitations in data availability. To address these constraints (population information, spatiotemporal resolution, building properties), additional assumptions were applied, making the current methodology adaptable to other data-scarce environments. Furthermore, an alternative hydrological modeling methodology was employed: unlike Tsouni et al. (2025), who used a district hydrological model (HEC-HMS) for rainfall-runoff transformation, this study implements a rain-on-grid methodology within the HEC-RAS framework, allowing direct simulation of rainfall-runoff processes. Finally, stricter classification thresholds for inundation depth were applied to reflect historical flood events and to support a more precautionary risk assessment approach. As the intensity and frequency of extreme weather events is progressively increasing throughout the years, it is essential to incorporate climate projections into the hydrological aspects (i.e., rainfall intensity, duration, IDF curves) in future flood risk assessments. This inclusion will assist policymakers in designing urban flood management strategies which are adaptable to climate change.

4.2 Flood Mitigation Measures

The southern areas of Limassol city require both structural and non-structural flood control systems because of their dense urban development and high population, being more

vulnerable to flooding. The resulting risk maps for the worst-case scenario (1000-year return period) can be used to improve the drainage system through the implementation of flood protection works. Nature-based solutions for reducing flow speed and depth, such as the construction of retention basins, check dams, and culverts, are primarily recommended in the upstream rural/mountainous part of the catchment to attenuate runoff and reduce peak flow before reaching the downstream urban areas. Upstream rural areas are the most suitable for NbS due to greater land availability and fewer urban constraints, allowing measures that enhance storage and infiltration and ultimately reduce downstream flood peaks. Moreover, monitoring systems should be installed at specific sections of the river network to allow early warning of the first responders, as well as Sustainable Urban Drainage Systems (SUDS), including rain gardens, green roofs, and permeable pavements can reduce runoff generation and improve infiltration in highly impervious urban areas. The combined effect of steep mountainous landscapes and intense rainfall in the northern part of the study area generated surface runoff, making urban-coastal areas more susceptible to flooding due to their low elevation, impermeable soil, and rapid urban development. Consequently, a key contribution of this study is the recommendation of evacuation routes and shelters in the urban units to mitigate the negative impacts in the affected areas. This operational focus is aligned with recent literature highlighting evacuation planning (routes and shelters) as a key non-structural flood mitigation measure in urban environments (Thapa et al. 2022; Li et al. 2025). The proposed framework serves as a ready-to-use planning resource that can be delivered directly to the responsible authorities, enabling more effective planning and coordination during flood events. Furthermore, these maps can be incorporated into municipal emergency plans to guide preparedness activities and improve public safety strategies (Crenganis et al. 2025). Similarly, Tsouni et al. (2025) proposed combined mitigation measures in Attica (Greece), including both structural interventions (i.e., drainage and water retention projects) and non-structural actions, such as evacuation plans and public awareness. The adoption of such practices can further enhance the effectiveness of the risk management framework developed for the Garillis basin, promoting a more integrated approach to prevention and preparedness.

4.3 Operational Framework and Management Implications

This research aims at contributing towards the development of a holistic decision support system for assessing flood risk which can be adopted by the first responders (e.g., civil protection, fire brigade), and local water authorities. The integration of decision-making method into the proposed approach allows the adaptation of indicator weights according to local priorities and expert feedback, and operationalizes core principles of vulnerability assessment — notably exposure, sensitivity and adaptive capacity — as supported by recent reviews of the IPCC vulnerability framework (e.g., (Estoque et al. 2023) and empirical applications in spatial contexts (Yu et al. 2021). It also aligns with the objectives of the EU Floods Directive (2007/60/EC) by linking risk assessment directly with response measures (i.e., design of escape routes and identification of safe shelters) for optimal emergency planning directly.

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4.4 Limitations

While the framework provides a robust and holistic foundation for flood risk assessment and management, several limitations affect the precision and scalability of the results. For example, population data were collected from the official reports at the street level. Next, these data were subjected to multiple transformations and assumptions, and finally reprojected at building block level to build the vulnerability map. Inevitably, several sources of uncertainty were propagated from the source data to the final vulnerability map. Moreover, additional factors are influencing the vulnerability assessment, such as construction materials, number of floors, and construction age. These factors are especially important in the central areas of the city of Limassol, where there is a dense presence of old buildings and high, modern buildings. A single IDF curve was used to develop the synthetic hyetographs based on data collected in 2009, neglecting the recent climatic patterns that strongly affect the rainfall intensity and duration. Additional uncertainties are inherited from the geographical and thematic inaccuracies of the input datasets, such as land use and soil properties. Moreover, this study didn't include other dynamic factors, such as the operational capacity of the sewerage network, the condition and coverage of pipes or sewers, or any human-made changes to in-streams and drainage channels, which can significantly impact the actual distribution of flood risk. Lastly, the hydraulic model was based on a limited number of rainfall scenarios and did not account for uncertainties in hydrological, topographical, and hydraulic data. Consequently, the results inherently contain both aleatory and epistemic uncertainties. Aleatory uncertainty arises from the natural spatiotemporal variability of rainfall and storm patterns, which cannot be fully captured when applying a spatially uniform design storm. Epistemic uncertainty refers to structural model limitations (i.e., simplifications in the representation of physical processes and flow paths, mesh resolution, breaklines, and omission of drainage network effects, as well as parameter uncertainty (e.g., Manning's n , curve number/infiltration losses, DEM-derived terrain representation, and

boundary condition choices), all of which may influence inundation estimates. Addressing these limitations through improved data collection, higher-resolution of the inputs, more detailed on-site inspections, and updated climate conditions and projections, can further enhance the reliability and applicability of future flood risk assessments.

5 Conclusion

This paper presents a comprehensive flood risk assessment of the Garyllis River Basin in Limassol, Cyprus, based on an integrated, cross-disciplinary approach that integrated flood risk mapping (2D hydraulic simulations, exposure and vulnerability analysis) and emergency planning. The results indicated that the southern part of the basin, especially the southern urban areas, is highly exposed to flooding, whereas two-dimensional hydraulic simulations revealed that the water depths can exceed 6 m under the worst-case scenario (1000-year return period). These findings demonstrated that flood-risk levels are strongly influenced not only by hydrological factors, but also by demographic factors, especially in dense-populated areas.

This study makes a significant contribution by proposing an integrated flood risk assessment and mitigation methodology that supports the planning and the operations of the civil protection authorities. It improves disaster resilience by proposing a series of optimum evacuation routes to reach safe shelters in zero-to-low-risk areas, ensuring that all citizens, including those with mobility limitations, can reach the closest shelter without passing through high-risk regions. By translating modeling outcomes into actual infrastructure development (e.g., enhancement of the road network to further improve the evacuation pathways, renovate public buildings in optimal locations), the study contributes to the community resilience and demonstrates best practices in risk-informed development. Consequently, these results can be valuable for policy-makers, urban planners and emergency services. They align with flood risk management objectives for managing flood risks and adhere to international frameworks such as the EU Floods Directive 2007/60/EC. The developed approach is also transferable to other flood prone sites, particularly where flash floods and urban runoff are of serious concern in diverse surroundings, and has already been successfully implemented in the Madra River Basin in Attica, Greece. It emphasizes the importance of proactive adaptation measures, such as infrastructure upgrades, public education, and integrated spatial planning to develop long-term resilience against future hydrological extremes.

Author Contributions All the authors contributed to the study's conception and design. JK is involved in the following tasks: writing original draft; writing, review and editing; software; methodology; investigation; data curation; and conceptualization. SS and VP were involved in the following tasks: writing, review and editing; software; methodology; investigation; data curation; and conceptualization. AT is involved in the following tasks: investigation, conceptualization, methodology, and writing - review & editing. CK and DH were involved in the following tasks: writing, review & editing; funding resources. CFP was involved in the following tasks: writing original draft; writing, review and editing; data curation; investigation. All the authors read and approved the manuscript.

Funding This work was supported by the "EXCELSIOR": ERATOSTHENES: Excellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment H2020 Widespread Teaming project (www.excelior2020.eu, accessed on 13 March 2023). The "EXCELSIOR" project has received funding from the European Union's Horizon 2020 Research and Innovation (Grant Agreement No 857510).

Data Availability Data are provided within the manuscript.

Declarations

Clinical trial number Not applicable.

Competing interests The authors declare no competing interests.

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