Holistic multicriteria framework to assess flood risk in Garyllis river basin, Cyprus

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ABSTRACT

The high occurrence and intensity of flood events at the European scale has urged the policymakers and water planners to invest time and funds for the design and implementation of effective flood management strategies that address major stages of disaster risk reduction, namely preparedness, response, recovery and mitigation. The optimal incorporation of these stages in the management plans is especially important in hydrographic networks that intersect urban units since these cities are highly vulnerable to flash floods. A holistic multicriteria framework is presented that estimates the spatiotemporal distribution of flood risk levels in the Garyllis River basin, which is located in the southern part of the island of Cyprus. A plethora of relevant information has been collected from multiple data sources, including satellite services, governmental portals, in-situ measurements, and historical records, at different spatiotemporal resolutions. For instance, a digital elevation model (DEM) with a 5 m spatial resolution was provided by the Department of Land and Surveys of Cyprus to model the topographical characteristics of the case site, the most recent land use/land cover map (2018) was extracted from Copernicus Land Monitoring Services, whereas daily precipitation data from nearby ground-based rainfall stations were provided by the Department of Meteorology. The collected data have been further verified and improved via field visits and discussions with relevant actors, harmonized in terms of spatial and temporal resolution and resampled into a common numerical grid to conduct two-dimensional hydraulic simulations (HEC-RAS) for estimating the evolution of flood hazard on the basis of water depths for different scenarios (i.e., three different return periods). The vulnerability levels of the study area are estimated by multiplying the weights and standardized scores of population age and population density, according to the most recent official governmental reports. In addition, the flood exposure was estimated on the basis of the land value. For each flood risk component, all factors are assigned equal weighting coefficients. Consequently, the flood risk indicator is estimated at each location by integrating the hazard, vulnerability and exposure indicators. The validity of the proposed methodology is tested by comparing the critical points that were identified during the on-site visits with the estimations of the flood risk levels. Consequently, escape routes and refuge regions were recommended for the worst-case scenario according to specific constraints. The results of this study have been discussed and approved by the national water authorities and will contribute to their ongoing efforts to further align with the EU priorities and strategies, particularly Floods Directive 2007/60/EC. Additionally, the outcomes of this study are expected to support social awareness regarding the actions that need to be taken.

Keywords: Flood risk; hydraulic modelling; multi-criteria decision analysis; escape routes; refuge areas.

1. INTRODUCTION

Floods is one of the most disastrous natural phenomena, caused by a combination of climatic and anthropogenic factors, such us heavy precipitation, urban expansion, deforestation, and insufficient drainage infrastructure[1], negatively affecting people's health, cultural and socioeconomic development [2]. Since 2000, floods have impacted over 1.8 billion

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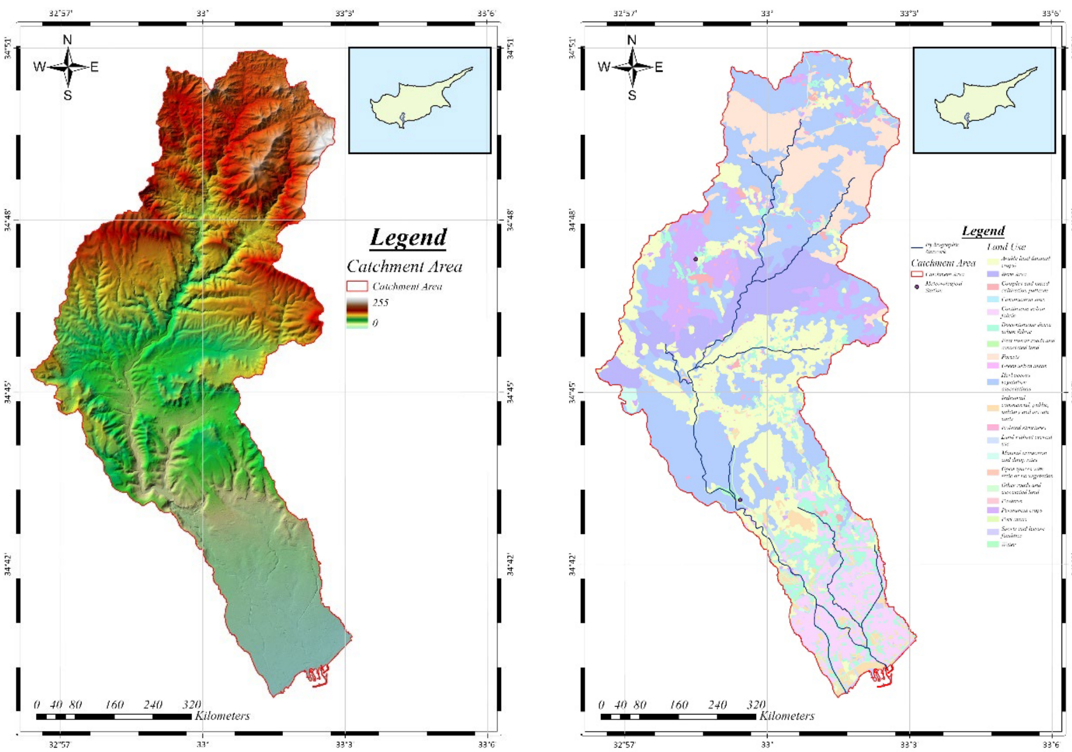
people worldwide[3]. In 2023 alone, 164 flood events occurred globally, resulting in 7.763 fatalities affecting approximately 32.4 million individuals, and causing economic losses estimated at USD 20.4 billion[4]. Recent studies reported a rising trend in flood frequency and severity linked closely to rapid climatic changes and intensified land-use [5–7] forcing the European authorities to introduce a systematic framework (i.e., the Flood Directive 2007/60/EC) for effective flood risk assessment and management. This directive focuses on the development of effective strategies for damage mitigation, identification of vulnerable areas, ideal emergency responses and infrastructure planning [8]. Given the complexity of flood phenomena, a holistic risk assessment is required that incorporates multiple data sources and methodologies, such as multicriteria decision analysis, machine learning, multivariate statistical methods, physical-based simulations, etc [9–16]. The combination of such diverse yet extensive datasets provide an unprecedented spatiotemporal characterization of floods, and could potentially aid authorities in establishing effective flood mitigation, preparedness, response, and forecasting strategies[17]. Hydraulic modelling coupled with Geographic Information Systems (GIS) can provide insights to the impact of several factors on flooding, such as urbanization, deforestation notes, wildfires, and weather-related drivers such as rainfall intensity[18–21]. As a result, precise estimates of flood extent, water depth, and water velocity can be obtained from comprehensive hydraulic models. These analyses are used by government officials and policymakers to create accurate plans that lower the risk of flooding and promote community resilience [22,23]. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is commonly used to conduct hydraulic modelling and analysis of river system[24]. It estimates the evolution of water surface profiles under both steady and unsteady flow conditions, while modeling the impact of artificial barriers such as bridges, weirs, and culverts [25]. The integration of HEC-RAS with GIS software, has been successfully applied in numerous global studies.For example, Khalil and Khan examined flood depth along Pakistan's Indus River[26], while Khattak et al.(2016) evaluated flood risks in Africa's Medjerda Basin, aiding local authorities in planning targeted flood mitigation policies[27].Similar to this , Salajegheh et al. created floodplain maps of the in Iran's Polasjan River Basin, regularly updating them frequently to account for shifting hydrological conditions[28]. The Teesta River Basin in Bangladesh was assessed for flood susceptibility by Islam et al. (2022) , who also produced vital spatial hazard maps that aid in local emergency response planning[29]. Additionally, Rahmati et al (2016) estimated flood scenarios in the Iranian Dez River Basin using HEC-RAS with ArcGIS. In order to make sure that the most vulnerable areas were given priority by the authorities when putting together preventive measures, the authors outlined flood hazard zones and provided insights on how floodwaters change in extreme situations like severe weather and dam failures. Both emergency response plans and infrastructure development projects were significantly influenced by flood hazard maps that were produced as a result[30].The National Observatory of Athens accompanied a similar study following following the catastrophic floods in the Mandra river basin, located in the southwest part of the Attica Region in central Greece. The authors developed a holistic approach for flood risk assessment which involved the integration of several data sources, such as remote sensing, geo-spatial data, in-situ observations, and hydraulic simulations [31]. This study aims at mapping the flood risk within the Garyllis River basin (Limassol) to identify vulnerable areas and propose suitable shelters and evacuation routes within the study area.

2. STUDY AREA AND DATA

The Garyllis River basin in occupying approximately 103.50 square km at the south and the south-west of Cyprus, with a river network lengthening about 9.68 kilometers (see Figure 1). The north is known for hilly to semi-mountainous land. Based upon urban atlas use data[32], this northern part of the city is mainly covered with arable land, herbaceous vegetation and forest, whereas the southern part is substantially occupied by sprawling urban sprawl because of the presence of different industrial, commercial,public, military and private activities. According to the implementation plan of the EU Floods Directive (Directive 2007/60/EC) national authorities have classified the Garyllis river basin as possibly highly vulnerable to flash floods and urban floods. Past historic data, starting in 1880, demonstrates the vulnerability of the basin with disastrous flood events in 1880 and 1894 causing extensive damage. The 1894 flood was highly devastating, causing widespread property destruction and loss of life, Reports indicate that more than 20 people, including children, lost their lives, and approximately 250 animals drowned. In the light of such catastrophic recurrence, the authorities responded to the diversion of the river in an attempt to reduce the future risk of flooding. Although river diversion has helped reduce the impact of floods, the urban nature of the basin, the unavailability of areas reserved for protection and the changes in land use contribute to keeping the flood risk high[33]. More recently, in 2019 and 2020, major floods events occurred that resulted in significant damages in the central part of Limassol due to the combined effect of heavy rain and the bursting of the Polemidia Dam (capacity of about 3.4 million m^3)[34,35].



(a) (b)

Figure 1: Overview of the Garyllis River Basin showing topography (a) and Land Use with stream network and meteorological stations (b).

The study entailed the acquisition of datasets from several sources (Table 1) to carry out the hydraulic analysis of the Garyllis River Basin. The datasets include geospatial, hydrometeorological, land use, and socioeconomic information. A 5 m spatial resolution digital elevation model (DEM) with an estimated vertical accuracy than ± 1 meters, was obtained from the Department of Lands and Surveys of Cyprus in order to derive topographical variables such as slope, flow direction and watersheds. Land use and land cover (LULC) data were derived from the Copernicus Urban Atlas 2018, which offers vector data with a minimum mapping resolution equivalent to approximately 50 x 50 meters. [32] and further modified to include wildfire-affected areas in 2022 and 2023, as reported by the European Forest Fire Information System (EFFIS)[36]. Rainfall time series from 2011 to 2023 are provided by the Meteorological Department of Cyprus, whereas discharge/water level daily records throughout 1980–2023 are provided from the Water Development Department. The most updated intensity-Duration-Frequency (IDF) curve of the meteorological station of Kalo Horio, located in the upstream part of the basin, was also provided by the water authorities to establish synthetic hyetographs for extreme rain events. , Curve Number (CN) values, which are used to calculate the rainfall-runoff conversion as a function of soil and land cover characteristics are also collected and used as inputs in the hydraulic simulations. Manning's roughness values were assigned to each LULC to reflect the flow resistance over the channel surfaces in the hydraulic model. The most recent population data (2011) were obtained from the Statistical Service of Cyprus to assess the vulnerability of the exposed communities, together with subjective land values from the Department of Lands and Surveys to quantify the economic exposure.

Table 1: Information and data collected about the Garyllis river basin

Data	Information	Resources
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)
Rainfall Timeseries	2011-2023	Meteorological Department Of Cyprus Home Page | Department Of Meteorology (Moa.Gov.Cy)
Intensity-Duration-Frequency (Idf) Curve	Kalo-Horio Station	Meteorological Department Of Cyprus Home Page | Department Of Meteorology (Moa.Gov.Cy)
Discharge And Water Level Timeseris	1980-2023	Water Development Department Of Cyprus Water Development Department | Home Page (Moa.Gov.Cy)
Hydrological 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	2011	Statistical Service Στατιστική Υπηρεσία - Αρχική (Cystat.Gov.Cy)
Runoff Curve Number (Cn)	2009	Water Development Department Of Cyprus Water Development Department | Home Page (Moa.Gov.Cy)
Land Value	2021	Department Of Lands And Surveys Cyprus Dls Portal (Moi.Gov.Cy)

3. METHODOLOGY

The methodology includes hydraulic modelling to compile hazard maps for different return periods (50, 100, and 1000 years) combined with flood vulnerability and exposure assessments in order to map the flood risk associated to an extreme rainfall event (1000-year return period) via multicriteria decision analysis. Figure 2 shows an overview of the research methodology which is adopted to generate flood risk assessment. The study area's geometry was developed in ArcGIS based on a 5-m resolution Digital Elevation Model (DEM), while hydrographic network were integrated as 2D breaklines to constrain and direct flow paths within the basin. A numerical grid with variable spatial resolution was generated to reasonably capture the small-scale characteristics of the urban and topographic features. The basic grid analysis was set at 20x20 meters, resulting in an average cell size of approximately 158 m^2. In the configuration of break lines a denser grid was applied near the river in order to better capture the hydraulic behavior and geometric complexity of the channel and adjacent areas. Specifically, breaklines near the river were enforced with near-spacing value of 5 meters, enabling increased resolution in critical flow regions. The artificial hyetograph (Sees Figure 3) obtained from the IDF curve of Kalo Horio was assigned as the hyetograph of the two-dimensional model. Hydrological loss were estimated via the Soil Conservation Service Curve Number (SCS-CN) technique, whereas the CN values were spatially distributed as a function of land use and soil properties. Land cover classifications were also used to assign Manning's roughness to floodplain and channel entities. The outputs of the hydraulic model were the water depth and velocity of surface water at each grid cell, which are used to classify inundated areas into five hazard classes: very low (<1 m), low (1–2 m), moderate (2–3 m), high (3–5 m), and very high (>5 m). Flood vulnerability was assessed based on population density and age distribution while flood exposure was evaluated using land value. A multi criteria analysis was applied to integrate hazard, vulnerability, and exposure into a single flood risk map. Finally, flood risk mitigation options based on the findings of the risk assessment were prepared to address areas with high or very high risk from flooding including proposals of site-specific measures and possible protection measures such as safe refuge areas and escape routes for safe evacuation.

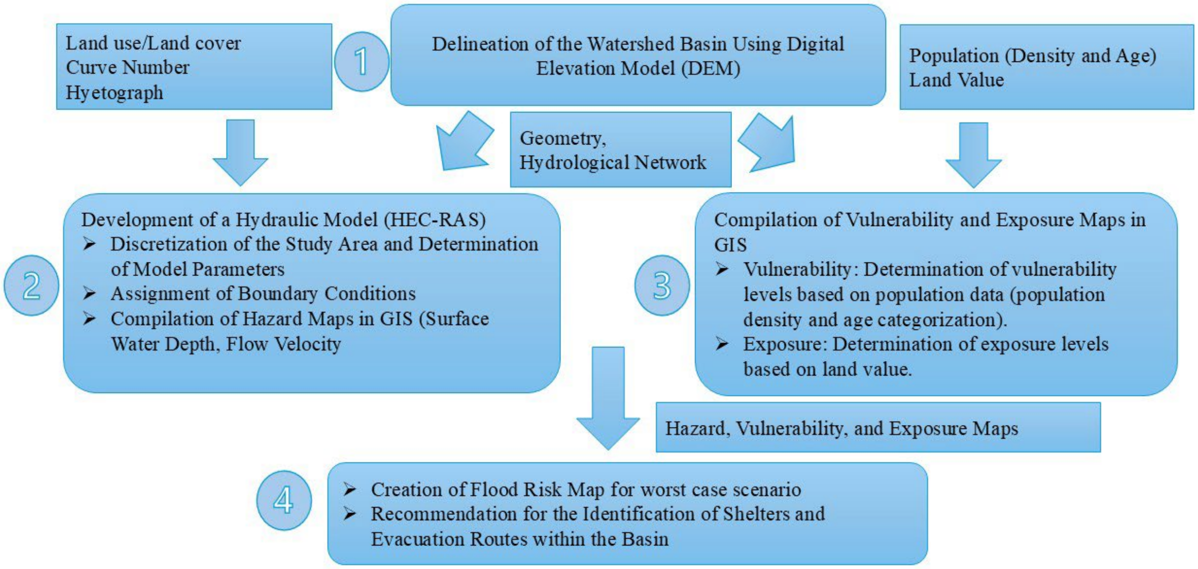


Figure 2: Schematic overview of methodological framework

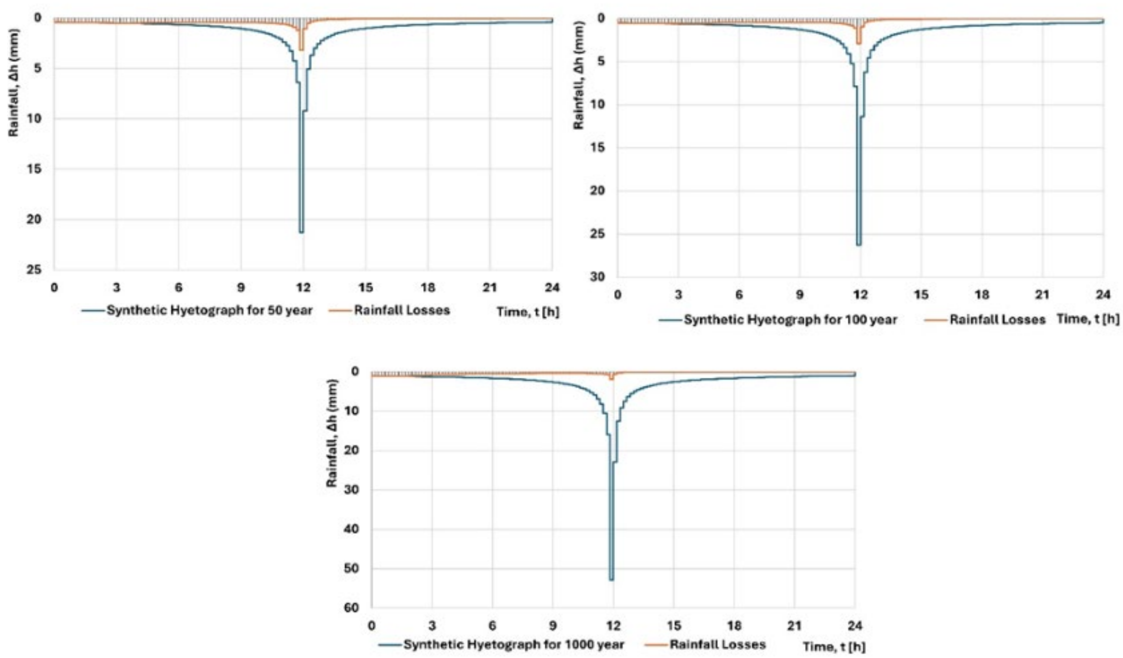


Figure 3: Synthetic hyetographs generated for return periods of 50,100, and 1000 year based on the IDF curve from the Kalo Horio Meteorological station

4. PRELIMINARY RESULT AND DISCUSSION

The hydraulic simulation generated regionally dispersed results of flood water depth and velocity throughout the Garyllis river basin for the 1000-year return periods scenario. The result of the water depth map are shown in Figure 4, which is separated into five hazard levels: very low (<1 m), low (1–2 m), moderate (2–3 m), high (3–5 m), and very high (>5 m). The southern, urbanized portions of the basin, have the highest inundation zones especially in low elevation and poorly-drained areas. The finding reflects the core output of hydraulic model and serves as the basis for subsequent risk assessment. The flood risk assessment was developed from water depth map using a multi-criteria decision analysis that included three essential elements: flood hazard (water depth), vulnerability (age distribution, density), and exposure (Land value). Figure 5 presents the conclusive flood risk map, which additionally features planned emergency shelters and evacuation routes. High and Very High-risk areas are found mainly in the southern part of the catchment, specifically in the urbanized coastal area in Limassol. The high-risk areas are all built-up areas, involving critical urban infrastructure which are vulnerable when there is an extreme rainfall. The combined effect of imperviousness and the vicinity to the river network are the main reasons for high vulnerability to floods. The need for the specialized mitigation measures is highlighted by the fact that areas designated as Very High risk for both the eastern and western insects are concentrated inside residential zones and along major roads.Emegercy shelters and evacuation routes have been suggested to aid in evacuation planning in these keys areas. In order to provide a comprehensive assessment of flood risk, this study combined physical and socioeconomic data analyze flood hazard, vulnerabilities, and exposure at the building-block level in the Garyllis watershed. The suggested methodology seeks to provide mitigation strategies in a way that both technologically sound and supported by science.Several simulations were performed with different mesh resolutions to ensure the convergence of the hydraulic outcomes. The assessment of vulnerability and exposure was subjected to inherent limitations due to the presence of missing data, which were tackled using a tailored multicriteria method that combined photo analysis with logical deductions. Additional challenges arose when designating safe zones and escape routes. To address these challenges, emergency shelters were selected among enclosed public buildings capable of covering basic needs during a crisis. In order to ensure adequate coverage across the whole river basin, these shelters were purposefully positioned. In similar vein, the evacuation routes were chosen from low-risk areas and planned to avoid the river, which lowers the possibility of flooding and guarantees continuous access in the event of an emergency.

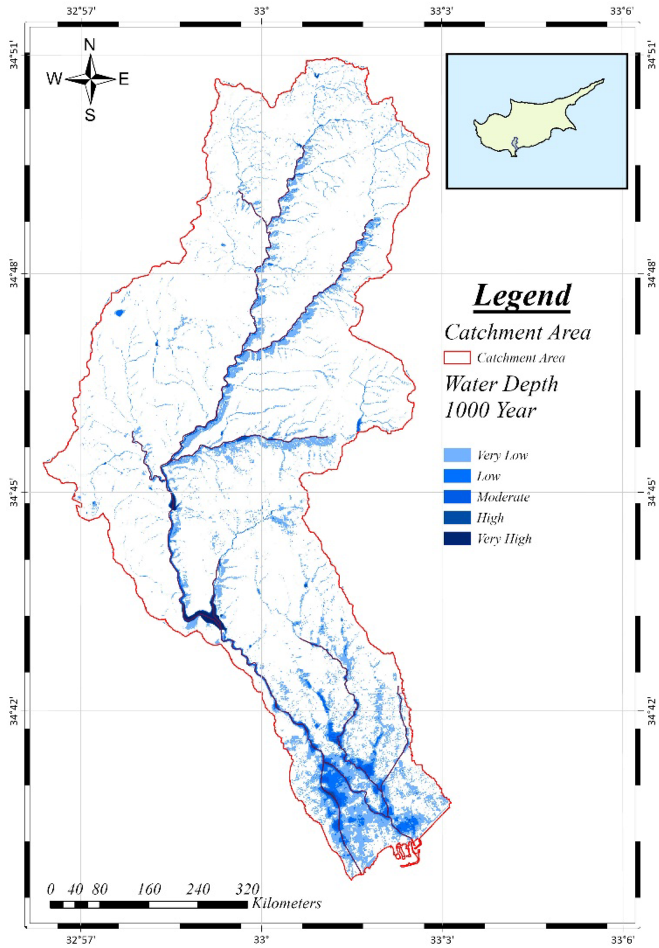


Figure 4: Simulated flood water depth for the 1000 year return period in the Garyllis river basin. water depth map, divided into five hazard levels: very low (<1 m), low (1–2 m), moderate (2–3 m), high (3–5 m), and very high (>5 m).

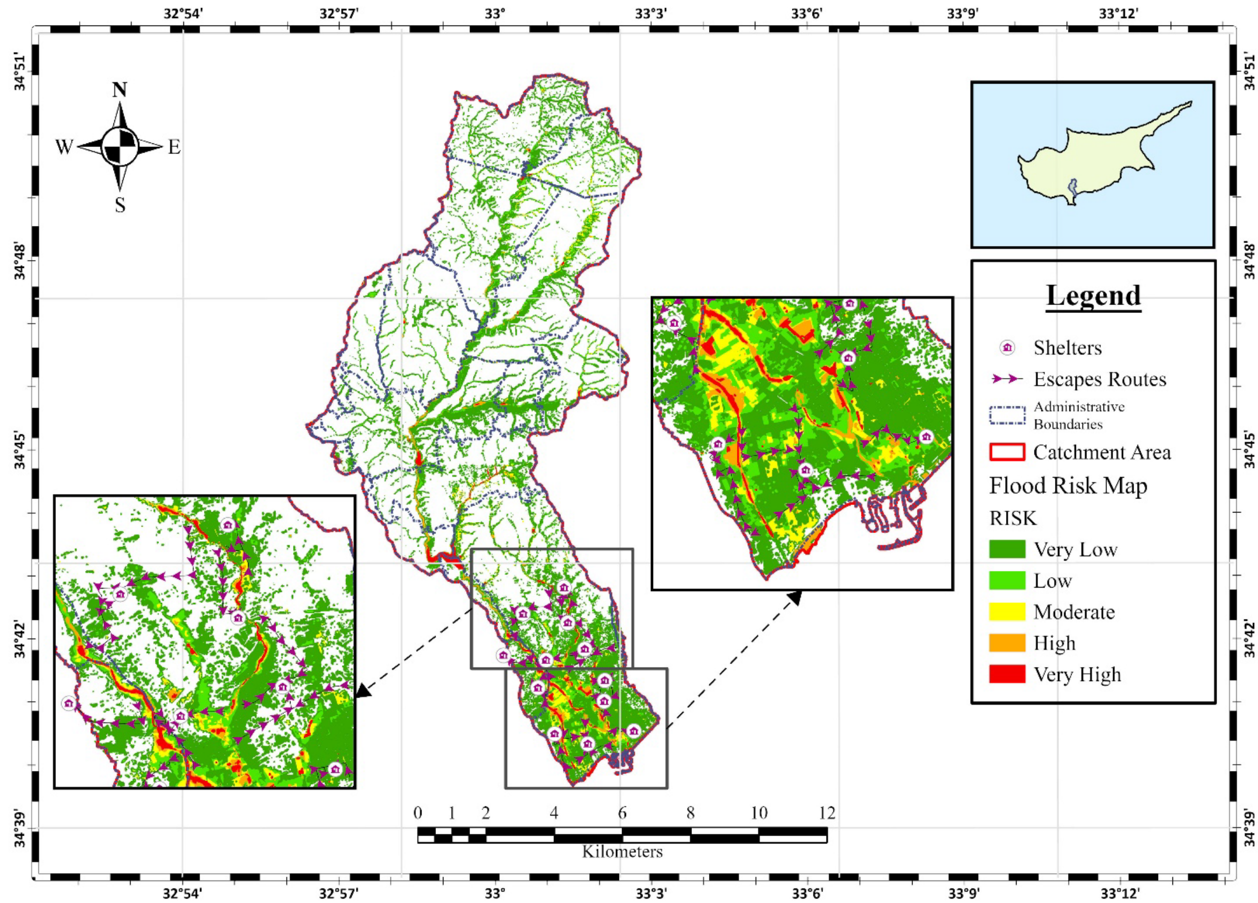


Figure 5: Map of flood risk assessment in Garyllis river basin for return period 1000 years, shelters and escape routes

5. CONCLUSION

The paper introduced an integrated flood risk assessment model for the analyzing the Garyllis River basin, Cyprus, combining hydraulic modeling, geospatial mapping and multicriteria evaluation of vulnerability and exposure. With high resolution physical and socioeconomic data integrated, the method allowed a fine-grained area-based flood-prone area detection in building-block scale, which is crucial for emergency preparedness. Despite the difficulties of model instability and lack of available data, the strategy worked well in yielding good and reliable flood risk predictions. The suggested site-specific mitigation strategies such as escape routes and shelters also emphasize the applied utility of the study on preparedness and resilience in urban catchments. The outcomes are anticipated to assist the national and local levels to harmonize with EU mechanisms for flood management as well to promote evidence-based initiatives in other urbanized river basins.

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