NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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Development and implementation of methodological framework towards flood risk management in ungauged basins

Aimilia-Panagiota Theochari
Ph.D. Thesis

Athens, September 2024

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The advisory committee has approved this dissertation:

Prof. E. Baltas, NTUA, Greece, Supervisor

Emer. Prof. A. Stamou, NTUA, Greece, Member of the Advisory Committee

Prof. V. Tsihrintzis NTUA, Greece, Member of the Advisory Committee

Member of the Advisory Committee Members of the Ph.D. Examination Committee:

Prof. E. Baltas
National Technical University of Athens (NTUA), Greece

Emer. Prof. A. Stamou
National Technical University of Athens (NTUA), Greece

Prof. V. Tsihrintzis
National Technical University of Athens (NTUA), Greece

Prof. G. Karatzas
Technical University of Crete

Asst. Prof. H. Vangelis
National Technical University of Athens (NTUA), Greece

Prof. D. Hadjimitsis
Cyprus University of Technology

Prof. C. Laspidou
University of Thessaly

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Dedicated to my family

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Abstract

The main scope of this PhD dissertation is to pioneer an integrated approach to flood risk management (FRM) using advanced technologies, hydrological modelling, and Nature-Based Solutions (NBS). The increasing frequency and severity of flooding due to climate change and urban expansion highlight the urgent need for improved FRM strategies. This research develops and implements a comprehensive framework to enhance FRM, focusing on vulnerable regions like the Sarantapotamos River basin in West Attica. By addressing critical aspects of FRM, it aims to mitigate recurrent flooding and its threats to public safety, infrastructure, and the environment. This approach is divided into three main sections.

The first section introduces an innovative methodology for identifying optimal sites for hydrometric and hydrometeorological stations using GIS-based multicriteria decision-making (MCDM) analysis. This methodology is applied to a case study in the Sarantapotamos River basin, a region highly prone to flooding, especially in areas like Mandra. The region requires a comprehensive streamflow data collection system and a network of hydrometeorological stations to provide timely flood warnings essential for public safety and socioeconomic stability. The aim is to build a robust database for water resource management and ecosystem protection. Key objectives include employing a GIS-based MCDM approach to design the hydrometric-hydrometeorological network and evaluate site suitability. Two different weighting calculation methods and various criteria for hydrometric station placement are explored, highlighting the approach's adaptability. Additionally, it examines how these criteria and weighting methods impact the selection of suitable locations for station installation. Emphasising a GIS-based strategy for site assessment addresses a significant gap in flood management research, where monitoring site selection often needs a systematic, data-driven methodology.

After setting up these monitoring stations, the next phase builds upon the data collected from these strategically located stations, concentrating on creating a Geomorphological Unit Hydrograph (GUH) customised for ungauged basins. The second section introduces an innovative hydrological modelling approach for Greece by developing GUHs tailored for ungauged basins. This method uses geomorphological metrics to create precise relationships for hydrological assessments in data-sparse regions. It addresses the challenges of limited data availability by combining the time-area diagram method with validation regression analysis, providing a deep understanding of hydrograph features and their correlation with geomorphological parameters. Improving the applicability and accessibility of GUHs, especially in areas with scarce hydrological data, offers significant potential for flood management and hydrological predictions.

The third section focuses on implementing two Nature-Based Solutions (NBS), specifically land cover change and construction of retention ponds, in the Sarantapotamos River basin upstream of the Magoula settlement. It evaluates NBS effectiveness by analysing flood hydrographs at the basin outlet under present and future climate scenarios. This analysis is crucial for assessing NBS performance, efficiency, resilience, and adaptability under different climate conditions. The hydrological analysis for this phase depends on data obtained from both the hydrometeorological stations and the improved GUHs. Converting rainfall data into runoff models produces flood hydrographs that are crucial for comprehending and mitigating flood risks. By comparing pre- and post-NBS conditions, the section provides insights into their efficacy in enhancing flood resilience and mitigating hazards to local populations and environments. The findings aim to guide decision-makers in selecting and implementing suitable NBS measures to reduce future flood impacts. Additionally, the section explores land cover change as an NBS in areas affected by the catastrophic fire in North Evia in August 2021, examining alterations across five watersheds. By investigating land cover modifications and NBS deployment in Northern Evia post-fire, this case study contributes to hydrological modelling and environmental stewardship, offering practical strategies for addressing hydrological changes induced by wildfires.

The proposed methodological framework introduces a scalable and efficient approach for FRM, addressing challenges in vulnerable areas like the Sarantapotamos River basin. It integrates technological innovations, hydrological modelling, and sustainable environmental strategies to tackle climate change impacts and limited data availability. This comprehensive approach emphasises the seamless integration of data collection, hydrological modelling, and sustainable flood mitigation strategies. Leveraging data from monitoring stations and refined GUHs, the framework generates flood hydrographs essential for understanding and managing flood risks. The research aims to bridge the gap between traditional flood management practices and innovative solutions for climate change adaptation. The holistic framework can be scaled and customised to suit the needs of different regions, contributing to more effective and resilient flood risk management worldwide.

Keywords: Floods; Flood risk management (FRM); Nature-Based Solutions (NBS); climate change; GIS; Multicriteria decision making (MCDM) analysis; Hydrometric stations; Hydrometeorological stations; Geomorphological Unit Hydrograph (GUH); ungauged basins; geomorphological metrics; time-area diagram method; validation regression analysis; Land cover change; Construction of retention ponds; West Attica; Sarantapotamos; Magoula; North Evia

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Selected Publications

Theochari, A. P., Feloni, E., Bournas, A., Karpouzos, D., & Baltas, E. (2019). Multi-criteria decision making and GIS techniques in the design of a stream gauging network. *World Review of Science, Technology and Sustainable Development*, *15*(4), 358-377. https://doi.org/10.1504/WRSTSD.2019.104097

Theochari, A. P., Feloni, E., Bournas, A., & Baltas, E. (2021). Hydrometeorological-hydrometric station network design using multicriteria decision analysis and GIS techniques. *Environmental Processes*, *8*, 1099-1119. https://doi.org/10.1007/s40710-021-00527-x

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Abbreviations

CN	Curve Number
FRMPs	Flood Risk Management Plans
HEC-GeoHMS	Geospatial Hydrologic Modeling Extension
HEC-HMS	Hydrologic Modeling System
MCDM	Multi-criteria decision-making
NTUA	National Technical University of Athens
R^2	Coefficient of Determination
RMSE	Root mean square error
US UH	User-Specified Unit Hydrograph
AHP	Analytic Hierarchy Process
Cc	Compactness coefficient
CCA	Climate change adaptation
CLC	CORINE Land Cover
CR	Consistency ratio
CRDEMO	Combined regionalization and dual entropy-multiobjective optimization
CRES	Center for Renewable Energy Sources and Saving
DD	Drainage density
DEM	Digital Elevation Model
DG RTD	Directorate-General for Research and Innovation of the European Union
DRR	disaster risk reduction
DSS	Decision support system
EAGME	Hellenic Geological Survey
EEA	European Environment Agency
ESI	European Structural and Investment Funds
EU	European Union
FAHP	Fuzzy Analytic Hierarchy Process
FF	Form factor
FRM	Flood Risk Management
FS	Stream frequency
GCF	Green Climate Fund
GCMs	General Circulation Models
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GIUH	Geomorphological Instantaneous Unit Hydrograph
GUH	Geomorphological Unit Hydrograph
HELMAS	Hellenic Center for Meteorological Applications and Remote Sensing
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
IUH	Instantaneous Unit Hydrographs
JWD	Joss-Walvogel RD-69 disdrometer
MAE	Mean Absolute Error
MCA	Multicriteria analysis

MMU	Minimum mapping unit
NARI	Network analysis for regional information
NBS	Nature-Based Solutions
NFM	Natural flood management
NHMDB	National Hydrological and Meteorological Data Bank
NMS	National Meteorological Service
NOA	National Observatory of Athens
NSE	Nash-Sutcliffe Efficiency
NWRM	Natural Water Retention Measures
OCR	Optical character recognition
OSM	OpenStreetMap
PAWP	Paris Agreement Work Program
PPC	Public Power Corporation
PUB	Predictions in Ungauged Basins
Rc	Circularity Ratio
RCMs	Regional Climate Models
RCPs	Representative Concentration Pathways
RDPs	Rural Development Programme
Re	Elongation ratio
RMSEz	Root mean square error
SCS	Soil Conservation Service
SDGs	Sustainable Development Goals
SRES	Special Report on Emissions Scenarios
SUDS	Sustainable urban drainage systems
SUH	Synthetic Unit Hydrograph
T	Drainage texture
TFN	Triangular fuzzy numbers
UH	Unit Hydrograph
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WFD	Water Framework Directive
WFIUH-1par	Width Function Instantaneous UH with one parameter
WLC	Weighted linear combination
WMO	World Meteorological Organization

Extended Abstract

Introduction

Floods are recognised as one of the most severe natural disasters globally, particularly affecting regions like the Mediterranean due to unique geographical and climatic conditions. These events, exacerbated by climate change and urban expansion, pose significant risks to life, infrastructure, and economies. Historical data and recent catastrophic events, such as the floods in Mandra in 2017 and the broader Greek territory like the 2020 Ianos flooding, illustrate such disasters' escalating frequency and intensity. The economic impact is profound, with floods in Europe between 1980 and 2017 costing approximately 166 billion euros (Ciabatti et al. 2018).

Following severe floods in Central Europe and southern France in 2002, the European Union (EU) enacted Directive 2007/60/EC, known as the Floods Directive. This directive aims to assess and manage flood risks across the EU to protect human health, economic activities, the environment, and cultural heritage. It requires the identification of high-risk areas and the development of collaborative Flood Risk Management Plans (FRMPs) for river basins and coastal regions.

In 2020, floods emerged as the predominant form of disaster on a global scale, comprising 62% of all reported incidents (Peng et al. 2024). The complexity of flood origins—from intense rainfall and rapid snowmelt to infrastructural failures—necessitates innovative approaches in flood risk management (FRM), transitioning from traditional strategies to more advanced hydrological models. Recent studies and reports indicate that floods are becoming the predominant form of global disaster, with climate change as a key driver in increasing both the frequency and severity of these events. The Intergovernmental Panel on Climate Change (IPCC) predicts this trend will continue, with significant implications for weather patterns and flood risk across Europe (Allegri et al. 2024). The multifaceted origins of floods—including intense rainfall, rapid snowmelt, and the failure of artificial structures—demand a robust and multidisciplinary approach to FRM that addresses immediate risks and builds long-term resilience. FRM integrates technical, strategic, and administrative measures at various scales to mitigate flood impacts and enhance societal resilience, aligning with European legislation. This approach emphasises comprehensive planning, risk assessment, and Nature-Based Solutions (NBS), as well as promoting community engagement, early warning systems, and sustainable land use to boost flood resilience.

The effective and equitable management of water resources, as well as the protection from flood-related challenges, are heavily reliant on meticulously designed hydrometeorological and hydrometric networks. These networks are not just tools, but the backbone of our work, collecting reliable and detailed data fundamental to hydrological models and river flow simulations, which are essential for water resource management (Theochari et al. 2021). Since the 1970s, there has been a significant interest in developing precise hydrometeorological networks that integrate both types of stations to support diverse management objectives (Mishra and Coulibaly 2009). A variety of techniques have been developed over the years to optimise these networks according to specific goals (Rodda et al. 1969; Fujioka 1986; Sestak 1989; Moss and Tasker 1991; Shepherd et al. 2004; Barca et al. 2008; Baltas and Mimikou 2009; Hong et al. 2016; Kemeridis et al. 2017; Feloni et al. 2018; Theochari et al. 2019; Nguyen et al. 2021; Theochari et al. 2021; Mazi et al 2023; Liu et al 2023; Brunet and Milbrandt 2023; Singhal et al. 2024; Suri and Azad 2024). The World Meteorological Organization (WMO) has extensively studied the advancement and application of technologies for these purposes (WMO 2008b; 2010). Geographic Information Systems (GIS) are vital in optimizing network design, managing spatial data, analysing it, adding thematic layers, and mapping river basins and stream networks efficiently (Baltas and Mimikou 2009; Maidment 2002).

Advancing the need for innovative methodologies, the development of the Geomorphological Unit Hydrograph (GUH) has not just improved but revolutionized the capability to predict and manage floods, particularly in ungauged basins where conventional data might be sparse. GUHs, by utilizing geomorphological metrics to establish relationships between the physical characteristics of a basin and its hydrological response, enable precise predictions of flood events in regions lacking extensive hydrological data. This methodology is not just a tool, but a game-changer, capitalising on the integration of geomorphological and hydrological data to enhance the accuracy and reliability of flood forecasting models. By employing techniques that consider basin shape, relief ratios, and other geomorphological parameters, GUHs provide a valuable tool for understanding and managing hydrological processes in diverse geographical settings (Theochari et al. 2021). Such models are not just crucial, but a necessity for regions like Greece, where varying climatic and topographical conditions across different hydrological basins necessitate tailored approaches to water resource management and flood risk mitigation. The integration of GUH models into FRM practices signifies not just a change, but a significant transformation towards a more resilient and proactive approach to addressing natural hazards in ungauged basins.

The application of NBS in FRM represents a significant shift towards sustainable and environmentally friendly approaches to mitigating the impacts of floods. NBS helps manage flood risks, enhances biodiversity, and provides additional ecological benefits. These solutions are increasingly recognised for their effectiveness in reducing flood risks and contributing to the resilience of ecosystems and communities against climate change impacts (Directive 2007/60/EC). Integrating NBS with traditional engineering solutions can achieve a more holistic and sustainable approach to flood management. This is particularly relevant in the context of European legislation and international environmental policies that promote green infrastructure and sustainable land use practices to combat flooding.

Acknowledging the importance of NBS in water management, the European Water Association has highlighted their critical role in tackling climate change challenges throughout Europe (Beceiro et al., 2022). The global importance of NBS is increasingly recognised, with numerous European initiatives exploring NBS for climate change adaptation and disaster risk reduction under programs like Horizon 2020. NBS are also integral to several European Commission policies, including the Water Framework and Floods Directives, which focus on climate change mitigation and adaptation. In December 2014, Greece initiated a national adaptation strategy to align with EU climate priorities. This evolved into Law 4936/2022, enacted in May 2022, which outlines Greece's transition to climate neutrality by 2050, setting interim targets for 2030 and 2040 and establishing a carbon budget mechanism to reduce emissions in key sectors like energy, construction, and transport.

The main goal of this PhD dissertation is to develop and implement a comprehensive methodological framework to enhance FRM strategies, mainly focusing on the Sarantapotamos River basin in West Attica. This region, known for its vulnerability to recurring flooding events, requires innovative approaches to mitigate risks and protect public safety, infrastructure, and the environment. The research questions this dissertation aims to answer are structured into three main sections. The first concern: *Can optimal hydrometric-hydrometeorological station network design through GIS techniques be achieved without on-site evaluation?* The second question concerns the following: *What is the significance of establishing empirical relationships between geomorphological metrics and GIUH attributes in enhancing the applicability of hydrological models for FRM in ungauged basins?* The third question concerns: *What role does NBS play in mitigating flood risks, and how can its effectiveness be quantitatively assessed within an integrated FRM strategy?* To effectively answer these research questions, the research encompasses various phases, each addressing critical aspects of FRM through the integration of innovative methodologies and advanced hydrological models.

The dissertation is organised into five main chapters to explore and address these issues thoroughly. Chapter 1 sets the stage with an introduction and literature review of FRM, discussing the design of hydrometric-hydrometeorological networks, the development of GUHs, and the implementation of NBS. Chapter 2 details the study area's geomorphological and hydrometeorological conditions, focusing on the data used for the research. Chapter 3 outlines the methodological framework employed, describing the design of the station network, the development of GUHs, and the analysis of NBS implementation. Chapter 4 presents the results and discussions derived from the methodologies applied, providing insights into the effectiveness of the proposed FRM strategies. Finally, Chapter 5 concludes the thesis by summarising the findings, addressing the research questions, and suggesting directions for future research.

Study Area and Data Used

This dissertation explores the Sarantapotamos river basin in West Attica, contrasting its natural and industrial environments with the urban intensity of Central Athens. Spanning 341 km^2, including Mandra-Eidyllia, Elefsina, and Tanagra, it is a crucial hydrological catchment—the Sarantapotamos River, enhanced by tributaries like Saint Vlassis, Ksirorema, and Grant Katerini. The basin supports urban areas housing 70000 residents and contrasting rural upstream areas with scattered villages. The research also focuses on a 226 km^2 subbasin upstream of the Magoula settlement, outlined in Figure 1, which shows the boundaries and location of the basins within Greece. Despite urbanisation in parts, 89.4 % of West Attica's terrain remains natural, featuring agricultural fields, grasslands, and forests, contrasting with Athens' urban sprawl.

The Sarantapotamos basin includes urban and industrial areas, covering about 28.15 km^2 combined, with essential infrastructure such as roads and railways emphasising its role as a hub of activity. However, the basin primarily showcases vast agricultural and forested areas, highlighting its rural character and biodiversity. These regions support a variety of crops and traditional farming, which is vital for maintaining ecological balance and wildlife. The Sarantapotamos river basin, including its upstream subbasin near Magoula, showcases the environmental dynamics of West Attica under a Mediterranean climate. With mild winters and hot summers, rainfall varies from 350 mm in low areas to 1000 mm in the mountains, influencing local water patterns and occasionally causing summer flooding. The basin and its subbasin, surrounded by mountains like Mount Pateras and Mount Parnitha, support diverse ecosystems, from forests to shrublands, with typical temperatures between 17 to 19 °C (Baltas 2008). The Sarantapotamos River and its tributaries, like Saint Vlassis, play a crucial role in the area’s hydrology and ecological diversity (Theochari and Baltas, 2024). Western Attica has faced numerous catastrophic floods, which prompted a review of environmental management strategies and underscored the need for improved infrastructure to prevent future disasters. Although the Sarantapotamos River basin initially lacked a uniform monitoring network, significant flooding led to the installation of a telemetric system with three hydrometeorological stations by NOAA's FloodHub service (Beyond-centre 2021). This development is crucial for enhancing regional environmental management and disaster preparedness.

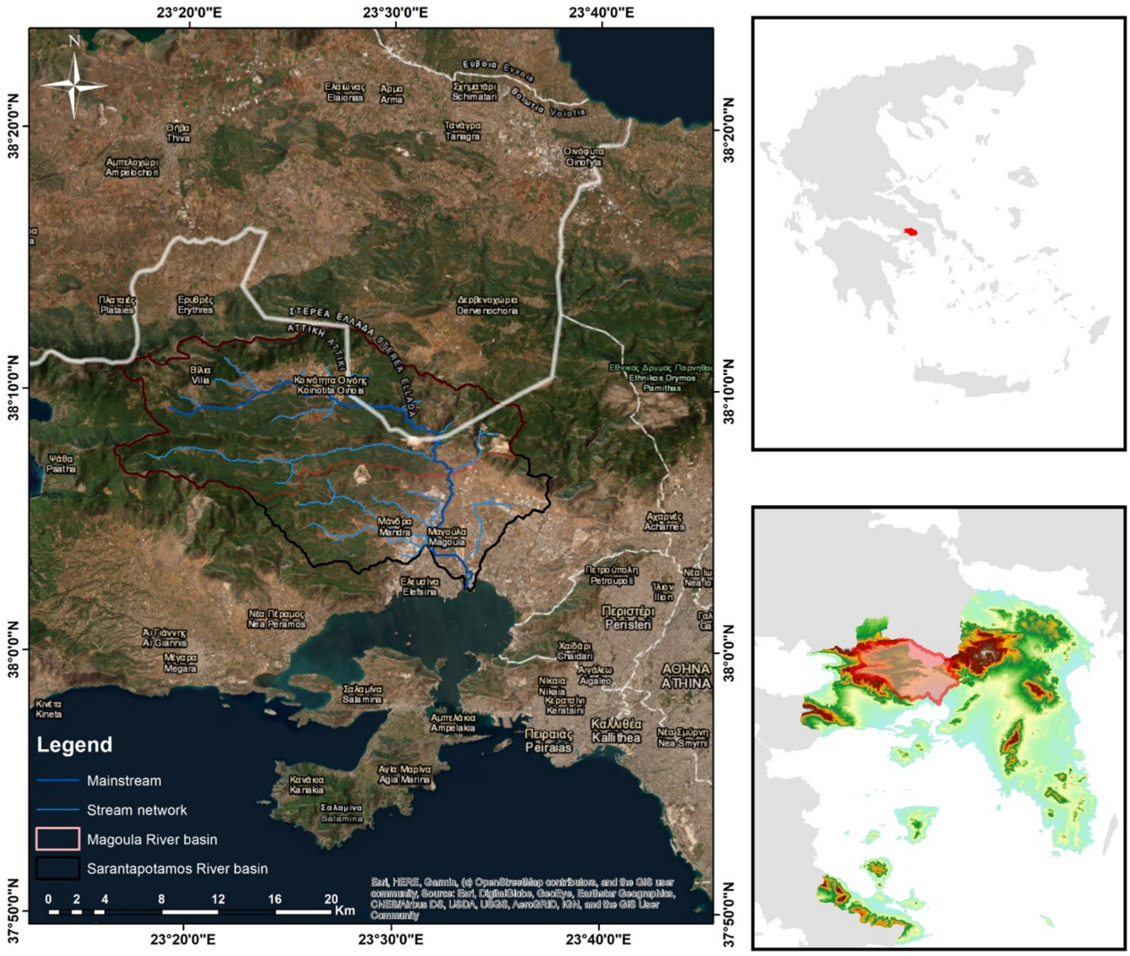


Figure 1: The Study area.

The primary datasets utilised in this research are outlined below:

- Unit Hydrographs (UH) and drainage basin boundaries: This research utilises a dataset of 14 UHs provided by the Public Power Corporation (PPC) of Greece, covering various durations like half-hour, one-hour, and two-hour intervals. These UHs are essential for studying hydrological behaviours in ungauged basins within Greece. Using GIS technology, watershed boundaries were georeferenced and digitised to ensure accurate representation in digital format. Eight of the original 14 hydrographs, standardised based on basin size, were deemed complete and suitable for developing the GUH model.
- Roughness Coefficient Data: The research focuses on the roughness coefficient, the key for accurately calculating water velocities in hydrological models. This coefficient integrates velocities across landscapes, considering factors like land cover, slope, and stream order. Values were sourced from established literature, specifically, Haan et al. 1994 and McCuen 1997, aiding in precise overland flow velocity assessments. This detailed data handling enhances the GUH accuracy.

- Rain Gauge Datasets: This research employs rain gauge datasets from the Mandra hydrometeorological station, utilising the Alternating Block Method to compute design precipitation hyetographs based on standard Intensity-Duration-Frequency (IDF) curves. For future climate scenarios—mean, upper, and lower—with a consistent 100-year return period, revised IDF curves from Kourtis et al. 2023 are applied to enhance modelling accuracy. These updates are critical for predicting future flood hydrographs and evaluating NBS under different climate conditions. The IDF data used in this research comes from the FRMPs for Greece, provided by the Ministry of Environment, Energy and Climate Change. Table 1 presents the specific parameters for the station and the calculated accumulative rainfall height, H, rainfall intensity, i, time of concentration, tc, through Giandotti's formula, for the selected duration for each scenario and return of period 100 years.
- Digital Elevation Model (DEM): The cornerstone of all spatial analyses, this high-resolution DEM obtained from the National Cadastre & Mapping Agency S.A. served as the base layer, featuring a spatial resolution of 5 m x 5 m.
- CORINE Land Cover (CLC, 2018): The URBAN Atlas 2018 dataset provides an inventory of land cover for Europe and specifically selected urban areas.
- Road Network Data: This dataset includes detailed road network information from the OpenStreetMap (OSM) project, obtained via the Geofabrik website. It was essential for designing the hydrometric-hydrometeorological network.
- Borehole Data Layer: This layer maps borehole locations and characteristics across the study area using data obtained from the National Register of Water Intake Points on the Greek Ministry of Environment, Energy and Climate Change website.
- Historical Flood Events Records: Compiled from the Greek Ministry of Environment and Energy's website, this archive documents significant historical flooding events in Greece, providing a spatial record of past floods.
- Flood Vulnerable Areas: Information from a GIS-based Multi-Criteria Decision Making (MCDM) analysis by Feloni et al. 2020 identifies flood-prone zones in the Attica region, particularly the Sarantapotamos basin, aiding in strategic monitoring station placements for flood risk management.
- Municipal Boundaries: Derived from open-access GIS resources, such as geodata.gov.gr, these administrative boundaries enable a focused analysis of flood risks and management within specific municipalities.
- Geological Information: Obtained from the Hellenic Geological Survey (EAGME) website, this comprehensive dataset includes maps and data on regional geological features crucial for studying soil composition and structural geology.

- IDF Stations: This inventory includes IDF stations with their corresponding parameters, developed by the Ministry of Environment, Energy, and Climate Change for the FRMPs for Greece and available in shapefile format.

Table 1: IDF parameters of Mandra station and calculated rainfall characteristics

Station	Mandra			
ID	292			
Elevation	258			
IDF Parameters	η		0.622	
	κ		0.125	
	λ		213.4	
	ψ		0.641	
	θ		0.124	
Scenario	**Current**	**Mean**	**Upper**	**Lower**
$t_c(h)$	6.5	6.5	6.5	6.5
$d(h)$	24	24	24	24
$T(y)$	100	100	100	100
$i(mm/h)$	9.15	13.54	40.09	6.43
H *(mm)*	219.53	325.02	962.27	154.23

Methodological Framework

This dissertation presents a methodological framework for FRM in the Sarantapotamos River basin, as shown in Figure 2. It begins with the 1) strategic placement of hydrometric-hydrometeorological stations based on GIS-multicriteria decision analysis, focusing on factors like flood susceptibility and environmental significance. This setup supports 2) the development of GUH for ungauged basins, utilising geomorphological metrics to link rainfall and runoff accurately. The framework concludes with 3) implementing NBS, such as land cover changes and retention ponds, using data-driven hydrographs to manage flood risks effectively. This integrated approach ensures a robust, scalable strategy for enhancing flood resilience in vulnerable regions.

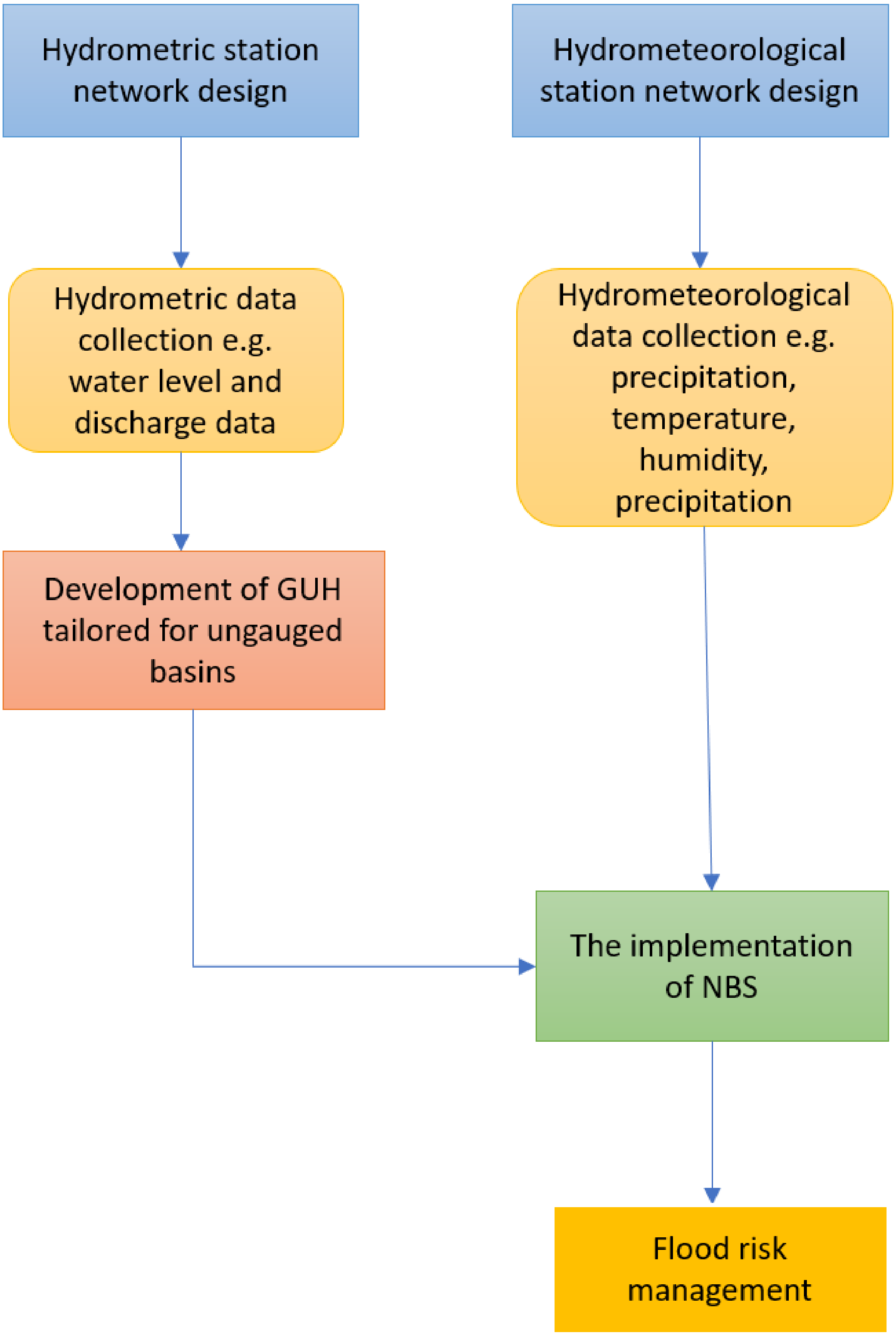


Figure 2: Flowchart of the methodological framework towards FRM.

1. Hydrometric-Hydrometeorological station network design using GIS techniques: This phase introduces a GIS-based MCDM methodology to identify potential sites for hydrometric and hydrometeorological stations within the Sarantapotamos River basin.

These stations are integral to water resources management and flood warning systems, addressing the critical needs for accurate data collection and timely flood response. Based on Theochari et al. 2019, 2021, the methodology employs predefined sets of geomorphological, technical, and spatial criteria to evaluate site suitability. The main steps of the analysis include selecting criteria for network design, normalising their values through standardisation and classification, formulating the criteria in a GIS environment and determining the weights for each criterion. Hydrometeorological stations use a simplified approach where all criteria are assigned equal weights. For hydrometric stations, the criteria weights are defined using the Analytic Hierarchy Process (AHP) proposed by Saaty 1977, and the Fuzzy AHP (FAHP) method. This part of the methodology allows for a detailed analysis of each site's suitability based on specific hydrological and geographical requirements. The design criteria are formulated within the GIS framework outlined in Theochari et al. 2019, 2021. GIS is essential for handling spatial data from various sources and facilitating spatial decision-making processes. The criteria are integrated and analysed using the Weighted Linear Combination (WLC) technique to produce detailed suitability maps. The GIS-based MCDM process pinpoints several ideal locations, selecting those with the highest final scores (FS) for establishing the network.

2. Development of GUH: The methodological framework aims to advance hydrological modelling in Greece by developing GUHs for ungauged basins. This phase leverages geomorphological features to establish accurate hydrological assessments in data-sparse areas. The approach includes statistical validation of UHs calculated via the time-area diagram method, implemented using ArcPy in GIS environments. Recent advancements in GIS tools and DEMs facilitate precise geomorphological and hydrological metric calculations, enhancing model accuracy. The process involves integrating empirical hydrological data from Greece's PPC and optimising channel velocity ranges to fit observed UHs effectively. The time-area diagram method analyses hydrograph characteristics in 70 drainage basins within the study area, totalling 100 basins. The main goal is to calculate the UH for each basin. This method examines different hydrograph features alongside corresponding geomorphological measurements for each basin. These associations help establish connections between hydrograph features and morphometric measurements, which are crucial for defining the GUH for each basin through regression analysis. Equations expressing each hydrograph feature about the associated morphometric parameter are then formulated based on these connections. Validation regression analysis across 30 basins confirms the model's robustness, offering a reliable tool for understanding hydrological behaviours in diverse watersheds. This

innovative GUH approach addresses the challenge of limited data and improving flood management and hydrological predictions in Greece.

3. NBS analysis: This phase focuses on implementing and analysing NBS, specifically land cover change, construction of retention ponds, and their combinations in the Sarantapotamos river basin upstream of the Magoula settlement in Greece. The effectiveness of these NBS is assessed by examining flood hydrographs to determine changes in peak discharge, volume, and flow timing under current and projected future climate scenarios. The analysis uses IDF curves adapted from Kourtis et al. 2023 for future climate projections. It employs the User-Specified UH method with Hydrologic Modeling System (HEC-HMS) software for hydrological modelling. This analysis evaluates how NBS can enhance flood resilience and adapt to varying climatic conditions, providing critical insights into sustainable water management and flood risk reduction. The chosen study area's significant flood history and vulnerability underscore the importance of this innovative approach to FRM, offering valuable guidance for environmental agencies, policymakers, and communities. During the implementation phase, focusing on NBS for FRM, the research also investigates the utilisation of land cover changes as an NBS in regions impacted by the severe wildfire in Northern Evia in August 2021. It concludes alterations in land cover across five watershed areas. By analysing changes in land cover and the adoption of NBS in Northern Evia post-fire, this case study contributes to advancing hydrological modelling and environmental conservation efforts, offering a pragmatic strategy for mitigating the hydrological impacts triggered by wildfires.

Results and Discussion

Optimal hydrometric-hydrometeorological station network design

Optimal hydrometric station network design

The hydrometric station network design uses the AHP method to assign weights to criteria, as illustrated in Table 2(a), through pairwise comparison matrices based on Saaty's 1977 scale. To address the potential subjectivity of these comparisons, an alternative scenario using the FAHP method is shown in Table 2(b), leading to different scenario labels: “3a” for AHP and “3b” for FAHP. FAHP includes fuzzy numbers in comparisons and suggests zero weights for significantly less important criteria, unlike AHP, where weights are near zero but not absolute (Özdağoğlu and Özdağoğlu 2007). Although FAHP reduces subjectivity with linguistic values, it may not be ideal for stream-gauging network design due to impractical increases in suggested locations requiring extensive fieldwork. In all scenarios, the significance of topographic slopes (W_{C1}) underscores terrain's critical role in influencing water movement and hydrological data accuracy, emphasising the importance of understanding diverse water flow dynamics.

In Scenario 1, topographical slopes (W_{C1}) are prioritised, reflecting their critical role in measuring runoff, where steep slopes increase flood risk and gentle ones slow the flow, impacting network design and hydrological data accuracy. In Scenario 2, focused on flood protection, the importance of slopes (W_{C1}) slightly decreases but remains critical. The emphasis shifts to the distance from flood-prone areas (W_{C5}), reflecting its crucial role in flood mitigation and strategic station placement to improve flood management and predictive capabilities. Scenario 3a shows that the weight for slopes (C1) aligns closely with Scenario 1, emphasising topographic factors in a balanced approach. However, the weight for distance from settlements (C4) decreases from the initial 0.060, suggesting a lesser priority for proximity to settlements under the AHP approach compared to the initial technical scenario. This shift indicates a change in assessment priorities. Scenario 3b, utilising FAHP, maintains a high weight for topographic slopes (W_{C1}) but assigns zero weight to distances from road networks (W_{C2}), confluences (W_{C3}), and settlements (W_{C4}), emphasising natural hydrological features and flood risk (W_{C5}) in decision-making. Comparative analysis reveals that while topographic slopes consistently have the highest weight, the emphasis on the distance from settlements varies across scenarios. This highlights methodological differences in prioritising human-related factors and underscores the complexity of balancing diverse objectives in station network design. Table 3 delineates the calculated criteria weights across different scenarios for the optimal placement of hydrometric stations.

Table 2: Pairwise comparison matrix for each scenario as cited in Theochari et al. 2019

a)	*Scenario 1*					*Scenario 2*					*Scenario 3 (3a)*				
	C1	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**	**C3**	**C4**	**C5**
C1	**1**	5	9	7	5	**1**	7	9	5	3	**1**	5	7	9	3
C2	1/5	**1**	3	3	3	1/7	**1**	1	1/7	1/9	1/5	**1**	3	5	1/5
C3	1/9	1/3	**1**	3	3	1/9	1	**1**	1/7	1/9	1/7	1/3	**1**	3	1/7
C4	1/7	1/3	1/3	**1**	1	1/5	7	7	**1**	1/3	1/9	1/5	1/3	**1**	1/9
C5	1/5	1/3	1/3	1	**1**	1/3	9	9	3	**1**	1/3	5	7	9	**1**

b)	*Scenario 3 (3b)*														
	C1			**C2**			**C3**			**C4**			**C5**		
C1	1	**1**	1	4	5	6	6	7	8	9	9	9	2	3	4
C2	1/6	1/5	1/4	1	**1**	1	2	3	4	4	5	6	1/6	1/5	1/4
C3	1/8	1/7	1/6	1/4	1/3	1/2	1	**1**	1	2	3	4	1/8	1/7	1/6
C4	1/9	1/9	1/9	1/6	1/5	1/4	1/4	1/3	1/2	1	**1**	1	1/9	1/9	1/9
C5	1/4	1/3	1/2	4	5	6	6	7	8	9	9	9	1	**1**	1

Table 3: Criteria weights for each scenario as cited in Theochari et al. 2019

	Scenario 1	*Scenario 2*	*Scenario 3a*	*Scenario 3b*
W_{C1}	0.566	0.474	0.476	0.565
W_{C2}	0.183	0.039	0.118	0.000
W_{C3}	0.124	0.036	0.061	0.000
W_{C4}	0.060	0.166	0.032	0.000
W_{C5}	0.067	0.284	0.312	0.435

The hydrometric station network design utilises the WLC method, integrating weights from AHP and FAHP to produce a single suitability score. This ensures that station placement aligns with scenario-specific needs. Using GIS and Map Algebra, criteria are standardised and synthesised, focusing on station placement along the Sarantapotamos basin's mainstream. FS ranges from 0 to 1 and helps identify optimal locations using thresholds. According to Theochari et al. 2019, locations are classified into two categories: those with FS below 0.90 or 0.95 and those with FS above these thresholds. This method visually and quantitatively distinguishes more suitable from less suitable sites. The number of suitable locations varies with FS thresholds; for example, one scenario identifies only four highly suitable sites. The FAHP approach yields more potential sites using less restrictive selection criteria.

In the Theochari et al. 2021 study, FS values are categorised into two clusters: those with FS below 0.90 and those with FS above this threshold. The "slopes" criterion is most critical across scenarios, while "distance from settlements" varies in importance, being least significant in the first and third scenarios. Conversely, "distance from the confluence with another stream" is the least important in the second scenario, except in flood warning systems where "distance from settlements" is crucial. All scenarios suggest the same high-potential sites for FS values over 90%, primarily in the river's southern part. Scenario 3a (AHP) identifies 59 high FS sites, whereas Scenario 3b (FAHP) identifies 437 due to fewer criteria. Most suitable locations are in the southern lowlands near settlements and flood-prone areas, except the first scenario, which favours sites along the entire river, emphasising low slopes and proximity to roads while avoiding stream junctions. The variation in recommended sites across scenarios highlights the impact of different datasets and criteria on the GIS-based hydrometric station network design, underscoring the critical role of dataset selection in influencing decision-making.

Optimal hydrometeorological station network design

The criteria for the hydrometeorological station network in the Sarantapotamos basin strictly define suitable and unsuitable locations for station placement. This method ensures that only locations meeting all criteria are considered, optimising the network's effectiveness. Formulating criteria as Boolean constraints directs the WLC process, producing a detailed suitability map shown in Figure 3. The map divides the FS into five equal classes from "0" to "1": "0", "0.25", "0.50", "0.75", and "1.00". The distribution across the river basin shows 34% at FS = 0, indicating zones where station placement is prohibited; 39% at FS = 0.25; 16% at FS = 0.50; 7% at FS = 0.75; and 4% at the highest score of FS = 1.0, marked in dark green to highlight optimal locations. This classification facilitates decision-making and reflects the complexity of site identification in a dynamic river basin, emphasising the importance of meticulous criteria selection and spatial analysis in establishing an efficient and reliable station network.

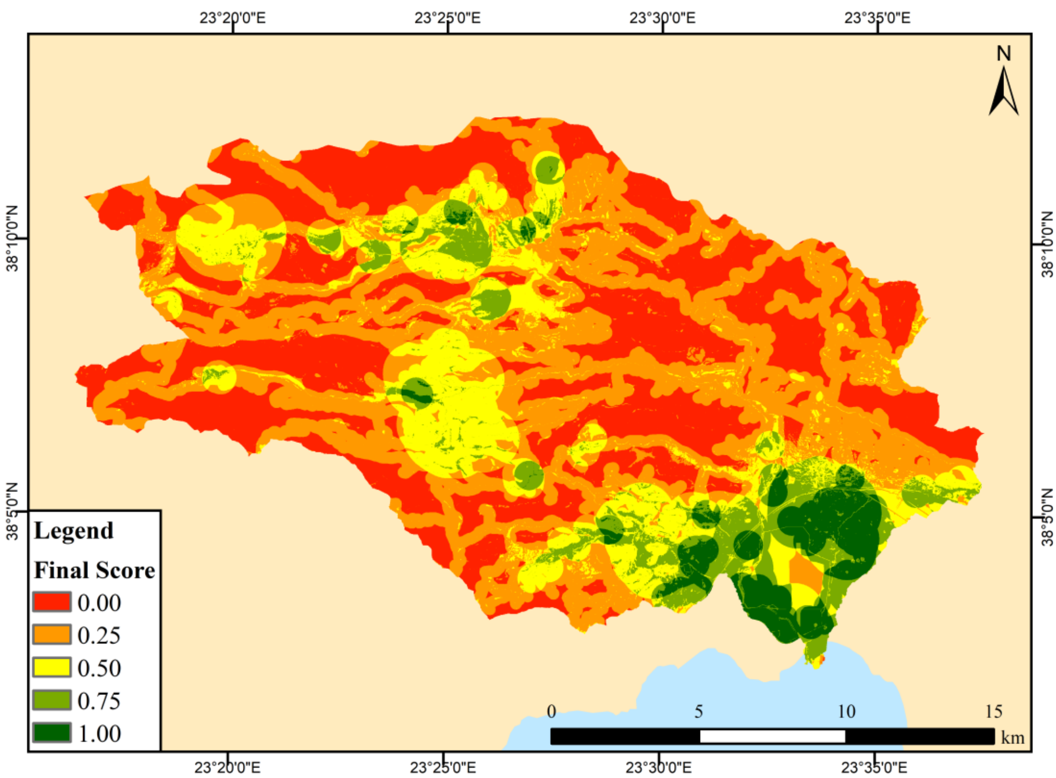


Figure 3: WLC among criteria for hydrometeorological station network design. Source: (Theochari et al. 2021)

The placement of hydrometeorological stations within the Sarantapotamos basin assesses station distribution by elevation to ensure the network is scientifically valid and cost-effective. This process involves using a density criterion connected to elevation to calculate the minimum necessary number of stations for effective monitoring in each elevation zone. Based on the station density criterion related to elevation, three stations are optimally determined for the Sarantapotamos basin. This decision integrates suitability assessments, Boolean constraints, and elevation considerations. Areas needing more station coverage due to elevation are minimal, justifying the limited number of stations.

The location of optimal hydrometric-hydrometeorological stations

Figure 4 illustrates the distribution of hydrometeorological and hydrometric stations across the Sarantapotamos basin. The proposed network includes three hydrometeorological stations and two strategically placed hydrometric stations, ensuring detailed coverage of the basin's hydrology. Hydrometeorological stations are positioned based on criteria to achieve optimal density and spatial distribution across the basin, capturing a diverse range of meteorological data essential for precise weather forecasting and climate analysis. Meanwhile, hydrometric stations are selected for their technical precision and relevance to the basin's flood management needs. For example, the northern station, situated along the Oinois-Panaktou provincial road bridge, is chosen for its ability to capture flow data unaffected by backwater effects, enhancing the quality of hydrological measurements. The southern station, near Oinoi-Magoula road and close to Mandra and Magoula, is consistently recognised across scenarios as a high-suitability site (FS > 0.9), strategically crucial for enhancing flood protection efforts and acting as an early warning point for the surrounding communities. This placement strategy integrates technical accuracy with practical needs, ensuring the network provides comprehensive data for effective management and mitigation strategies. The approach reflects a balance between precision and flexibility, which is necessary for adapting to dynamic environmental conditions and effectively managing water resources.

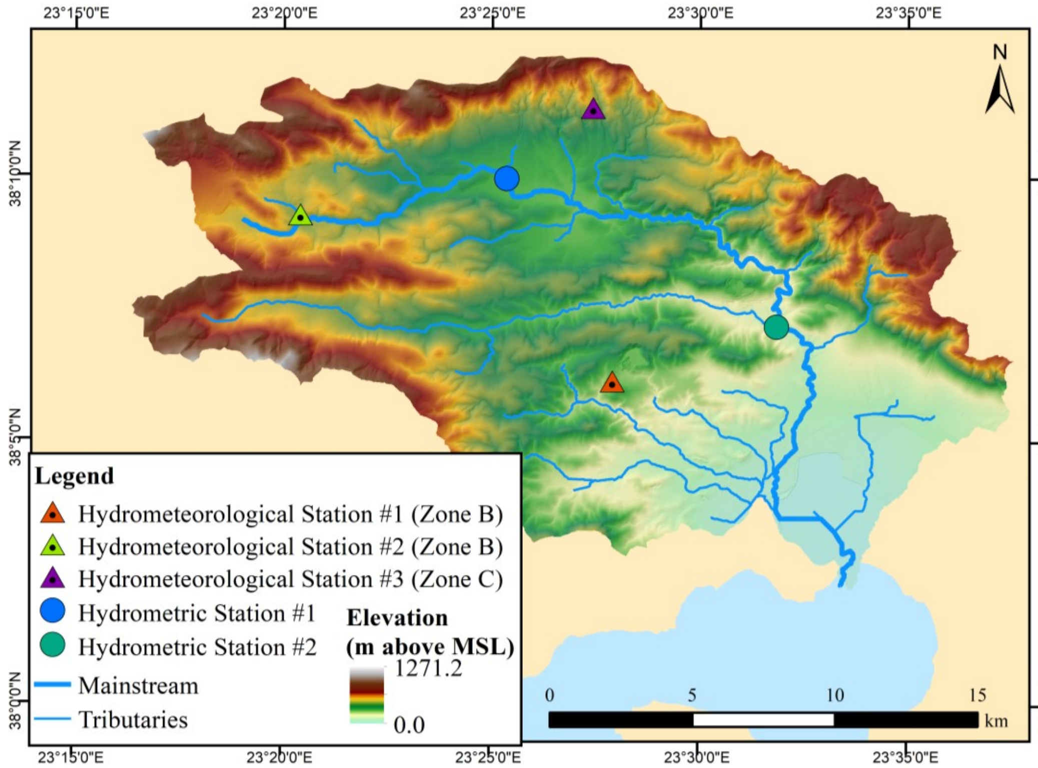


Figure 4: Hydrometeorological and hydrometric station network site selection. Source: (Theochari et al. 2021)

Development of Geomorphological Unit Hydrograph (GUH)

System Analysis of channel velocity

The system analysis delves into the influence of channel velocity on the UH using the time-area diagram method, which produces eight distinct hydrographs to gauge model accuracy at different velocities. The Nash-Sutcliffe Efficiency (NSE) metric, a crucial tool for assessing model performance, is used. A line graph in Figure 5 showcases NSE values across various velocities, playing a pivotal role in pinpointing the ideal velocity range for precise hydrological predictions.

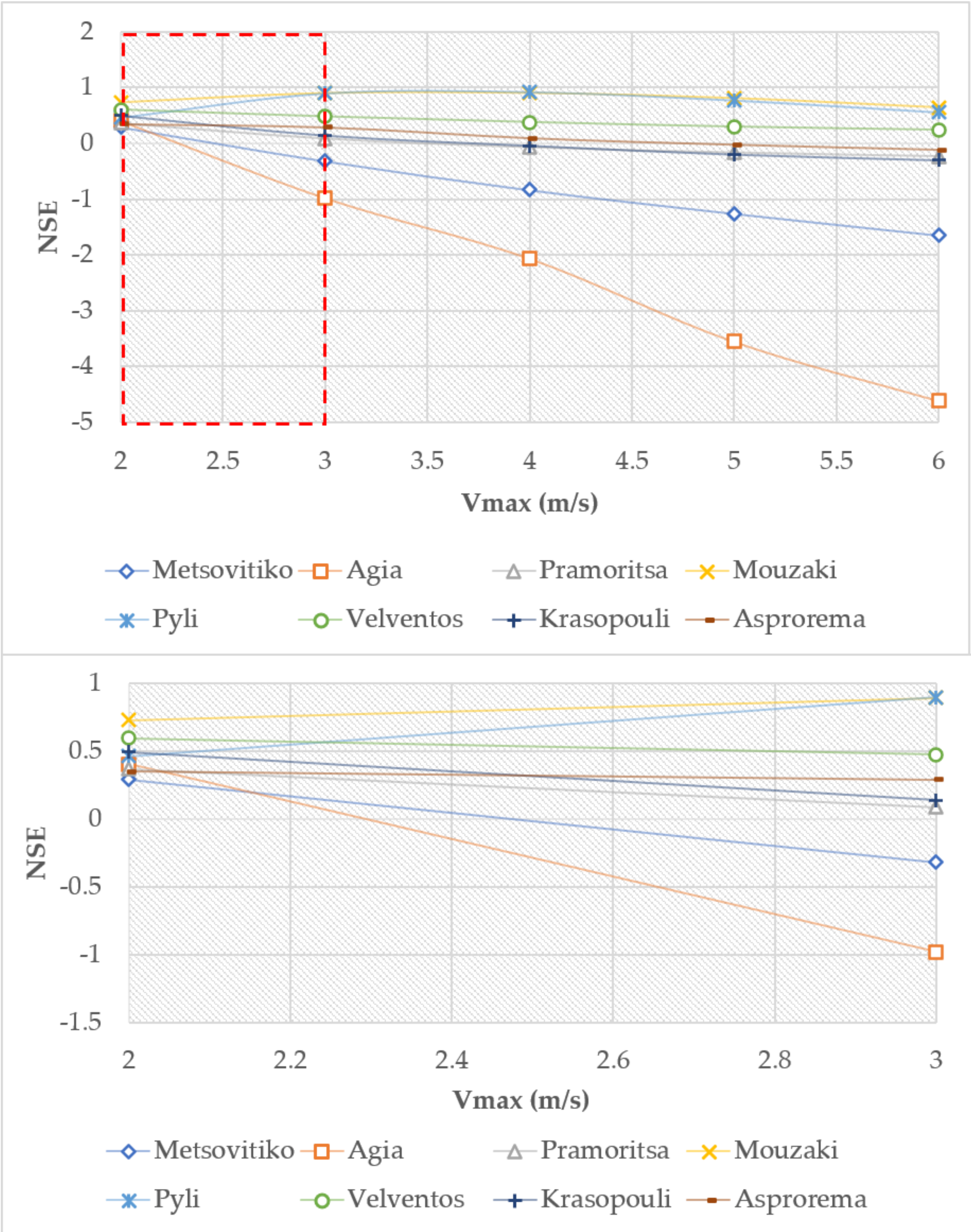


Figure 5: Analysis of Nash-Sutcliffe Efficiency (NSE) comparison across different velocity ranges.

In the Metsovitiko basin, NSE values range from 0.293 to -1.647, indicating varied model performance. The highest NSE, 0.293, occurs at a Vmax of 2 m/s, suggesting that velocities within 0.1-2 m/s yield more accurate predictions. Similarly, in the Pramoritsa basin, NSE values vary between 0.37 and -0.234, with the best performance being 0.37, also in the 0.1-2.0 m/s range. In the Mouzaki basin, the model shows consistent accuracy with NSE values between 0.73 and 0.641, optimal at 0.1-4.0 m/s, though 0.1-2.0 m/s is also effective. The Velventos basin displays a good fit with NSE values from 0.599 to 0.243, and in the Pyli basin, NSE values between 0.465 and 0.561 suggest a consistently good fit at 0.1-4.0 m/s, with positive outcomes even in the 0.1-2.0 m/s range. In the Krasopouli basin, NSE ranges from 0.496 to -0.301, showing more favourable results at lower velocities, particularly within 0.1-2.0 m/s. The Asprorema basin's NSE varies from 0.35 to -0.117, favouring lower velocities for better model performance. Lastly, in the Agia basin, NSE values range from 0.405 to -4.614, with the highest at 0.405 for 0.1-2.0 m/s, indicating reasonable model accuracy at lower velocities. However, NSE values decline sharply with higher velocities up to -4.614, suggesting significant deterioration in model performance at faster flows. This analysis confirms that lower velocities generally correspond to higher and more reliable NSE values across these basins, suggesting that a velocity range of 0.1-2.0 m/s is optimal for achieving the most accurate hydrological predictions.

Regression analysis

The investigation into 70 out of 100 drainage basins has significantly advanced our understanding of the interplay between geomorphological metrics and hydrograph attributes. Utilising the time-area diagram method, the UH for each basin is calculated to explore the hydrological processes across varied terrains. Histograms summarise the relationships between the basins' geomorphological characteristics and the features of their hydrographs. These histograms provide insights into how different geomorphological metrics influence hydrograph characteristics, revealing patterns and potential correlations within the data. For instance, examining the peak discharge (Q_{max}) about geomorphological metrics like Rc and FF indicates varying degrees of correlation. While Rc and FF show dispersed histogram bars suggesting weak correlations, other metrics display more concentrated distributions, indicating moderate correlations. This pattern varies as the analysis extends to variables like t_{Qmax}, t_b, t_{Q50L}, and t_{Q50R}, consistently showing that variables like Cc and Re tend to have tighter clusters, suggesting stronger correlations. Further statistical analysis, including regression, quantifies these relationships, providing predictive equations summarising the interactions between hydrograph attributes and geomorphological metrics. These findings enhance the understanding of hydrological processes, aiding in water resource management and flood risk assessment by establishing a quantitative basis for predicting hydrograph behaviour from geomorphological characteristics.

Validation regression analysis

The validation regression analysis is crucial, focusing on the remaining 30 basins from 100 to determine the most appropriate regression equations for predicting hydrograph attributes based on geomorphological metrics. This phase employs statistical measures such as Coefficient of Determination (R^2), Mean Absolute Error (MAE), and Root Mean Square Error (RMSE) to evaluate the performance and reliability of each equation, ensuring accurate predictions across various basin characteristics. Here is a concise summary of the results for each regression equation derived from the analysis, focusing on the performance metrics and the derived equations for predicting various hydrograph attributes:

T-Polynomial Model for Q_{max}

Equation: $y = 8.6049x^2 + 78.275x + 6.3238$ (1)

where:

y= Q_{max} represents the peak discharge of the UH (m^3/s)

x= T is the geomorphological parameter associated with the drainage texture

Performance: This model has the lowest MAE and RMSE, indicating superior predictive accuracy and minimal errors for peak discharge.

Cc-Linear Model for t_{Q50L}

Equation: $y = 0.6835x$ (2)

where:

y= t_{Q50L} represents the time to 50% of the rising limb of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Performance: Offers a strong balance of high R^2 and low error metrics, effectively predicting the time to 50% of the rising limb of the hydrograph.

Cc-Linear Model for t_{Q50R}

Equation: $y = 2.4892x$ (3)

where:

y= t_{Q50R} represents the time to 50% of the falling limb of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Performance: Distinguished by the lowest RMSE and MAE, suggesting excellent accuracy for predicting the time to 50% of the falling limb.

Cc-Linear Model for t_{Q75R}

Equation: $y = 2.0333x$ (4)

where:

y= t_{Q75R} represents the time to 75% of the falling limb of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Performance: Exhibits a high R^2 and the lowest RMSE and MAE, indicating predictive solid performance for the time to 75% of the falling limb.

Cc-Linear Model for t_{Q75L}

Equation: $y = 0.9958x$ (5)

where:

y= t_{Q75L} represents the time to 75% of the rising limb of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Performance: The best fit with the highest R^2 and the lowest error values, effectively predicting the time to 75% of the rising limb.

Cc-Linear Model for t_b (base time)

Equation: $y = 9.0156x$ (6)

where:

y= t_b represents the base time of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Performance: Achieves the highest R^2 value and the lowest errors among the models, making it the most robust predictor for the base time of the hydrograph.

Cc-Linear Model for t_{Qmax} (time to peak)

Equation: $y = 1.4738x$ (7)

where:

y= t_{Qmax} represents the time to peak of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Performance: Despite a high R^2, this model maintains low MAE and RMSE, indicating reliable predictions for the time to peak of the hydrograph.

These models are selected based on their ability to provide the most dependable predictions across various datasets. The regression analysis shows a significant dependence on the Cc in determining effective regression equations for various hydrograph attributes, underscoring its crucial role in enhancing model accuracy.

The validation regression analysis emphasises the significance of residuals in evaluating the goodness of fit for regression equations. Residuals, representing the variance between observed and predicted values, provide crucial insights into model precision and reliability. According to residuals analysis, for Q_{max}, there is a reasonable agreement between observed and predicted values, with some variations. Residuals suggest predictive capability but with discrepancies. Regarding t_{Q50R}, good agreement is observed, with slight under-prediction for higher values. For t_{Q50L}, a positive linear relationship is observed, with prediction variability. For t_{Q75L}, a positive linear trend is evident, with some outliers indicating areas for improvement. For t_{Qmax}, there is a positive correlation but with some variance. For t_{Q75R}, the model captures the trend with slight overestimation. Lastly, for t_b, there is a positive relationship, but predictions deviate more as t_b increases. The thorough analysis of model evaluation metrics leads to selecting accurate regression equations, enhancing hydrograph attribute prediction.

Analysis of Nature-based solutions (NBS)

The comparative analysis showcases the impact of NBS on flood mitigation in the Sarantapotamos River basin, Greece. Initial findings reveal a peak discharge of 535.7 m^3/s under current climate conditions. Implementing land cover changes reduces peak discharge to 465.8 m^3/s, with a peak time delay of 20 h and a notable decrease in flood volume. Construction of retention ponds further decreases peak discharge to 383.3 m^3/s, with a peak time accelerated to 15 h and a significant reduction in flood volume. Combining both NBS results in a peak discharge of 318.5 m^3/s, indicating a 41 % reduction compared to the pre-NBS scenario. Flood volume decreases to 99.7 hm^3, corresponding to a 15.3 % reduction compared to the baseline scenario. Notably, achieving these results requires constructing 250 retention ponds. Figure 6 visually depicts the effects of NBS on flood hydrographs, highlighting the potential of nature-aligned measures in flood risk reduction.

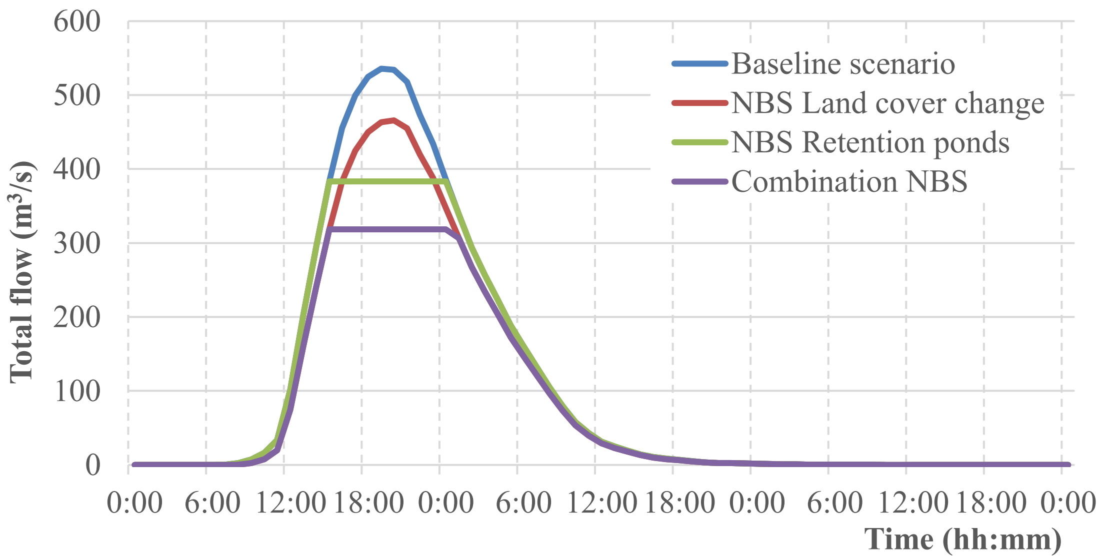


Figure 6: Flood hydrographs before and after NBS for current climate conditions

Initially, the design storm features a peak rainfall of 61.6 mm, with a cumulative depth of 219.5 mm and an intensity of 9.1 mm/h. Under the upper scenario, these figures increase, complicating flood management, while the lower scenario shows reductions, offering a more manageable outlook. The mean scenario reveals a peak discharge and flood volume rise, stressing the need for NBS and climate adaptation strategies. Specifically, the upper scenario shows a peak discharge of 4075 m3/s, a 600% increase in flood volume. The mean scenario sees a peak discharge of 1107.4 m3/s, a 79.2% rise. The lower scenario, however, presents decreases in both measures. Visual comparisons in Figure 7 emphasise the value of NBS in managing varying climate impacts on flooding. Hydrological analysis selects the upper and mean scenarios to test NBS efficacy, exploring land cover changes and retention ponds separately and combined. Changes in land cover reduce the peak discharge to 3945.5 m3/s, a 3.7% drop, with the peak discharge time maintained at 18 hours.

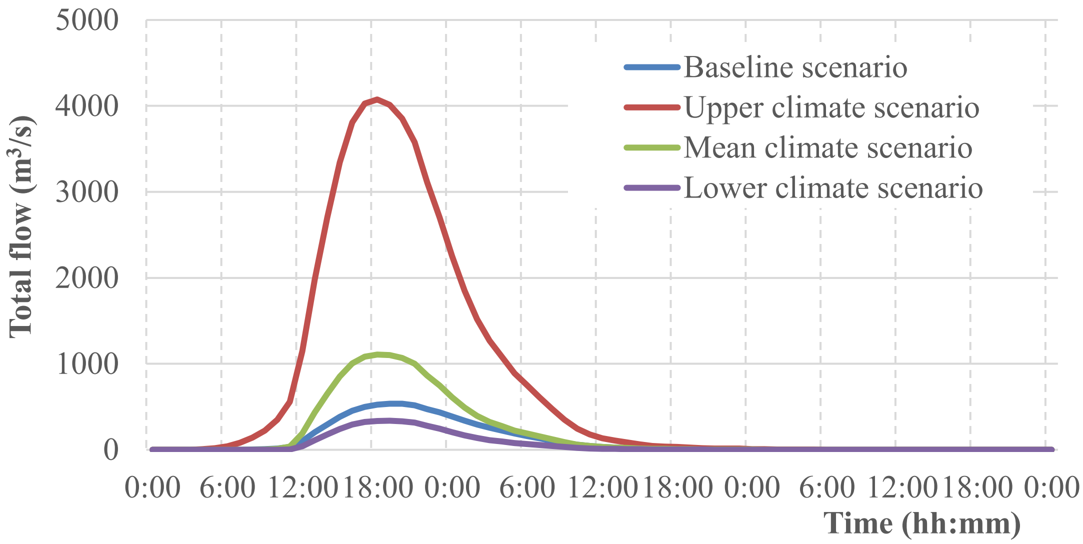


Figure 7: Flood hydrographs for future climate conditions

Retention ponds as a NBS significantly reduce flood risks. Implementing them cuts peak discharge to 2702.9 m^3/s and shortens peak time to 14 hours, with a 75% reduction from the initial peak. The intervention stores 29.4 hm^3 of water, and the overall flood volume reduces to 797.4 hm^3. To meet flood mitigation targets, 2198 retention ponds are necessary. Combined NBS strategies further reduce peak discharge to 2567.4 m^3/s. Standalone retention ponds optimise water storage to 30.2 hm^3, decreasing total flood volume by 7.2% to 767.55 hm^3. Approximately 2258 ponds are needed, highlighting planning challenges in flood management. In the mean climate scenario, peak discharge decreases to 999.8 m^3/s, showing a 9.73% reduction from 1107.4 m^3/s due to effective land cover management. The time to peak remains at 18 hours, while total flood volume drops by 9.25% to 192.1 hm^3. Implementing retention ponds reduces peak discharge to 851.7 m^3/s, with time to peak shortened to 15 hours. These ponds decrease the magnitude and speed of peak flow, storing 4.6 hm^3 of water. After pond implementation, the final total flood volume adjusts to 207.1 hm3, which necessitates 340 ponds for optimal mitigation. A combined approach further lowers peak discharge to 755.9 m^3/s with a consistent peak time of 15 hours and a storage capacity of 4.4 hm^3, resulting in a total flood volume of 207.3 hm^3. About 327 retention ponds are projected to meet flood mitigation goals.

The assessment of NBS reveals that combining land cover management with retention pond construction significantly reduces flood peak flow rates and volumes. Optimal NBS should consider specific catchment characteristics like morphology and land use. Effective planning and implementation of NBS require integrating scientific insights, stakeholder engagement, and ecological awareness, enhancing flood resilience.

Land Cover Changes as NBS under Changing Conditions (Fire)

This case study evaluates NBS in mitigating post-fire land changes in Northern Evia, which experienced severe wildfires in August 2021. The fires burned over 507950 acres, impacting ecosystems, communities, and the economy. The study focuses on the Xiropotamos and Kireas river basins in Northern Evia (Figure 8) and examines how NBS can address increased flood risks following wildfires. Given the area's Mediterranean climate, which features hot summers and cold winters and an average annual rainfall of 1200 mm, the research highlights the role of NBS in enhancing resilience against environmental extremes.

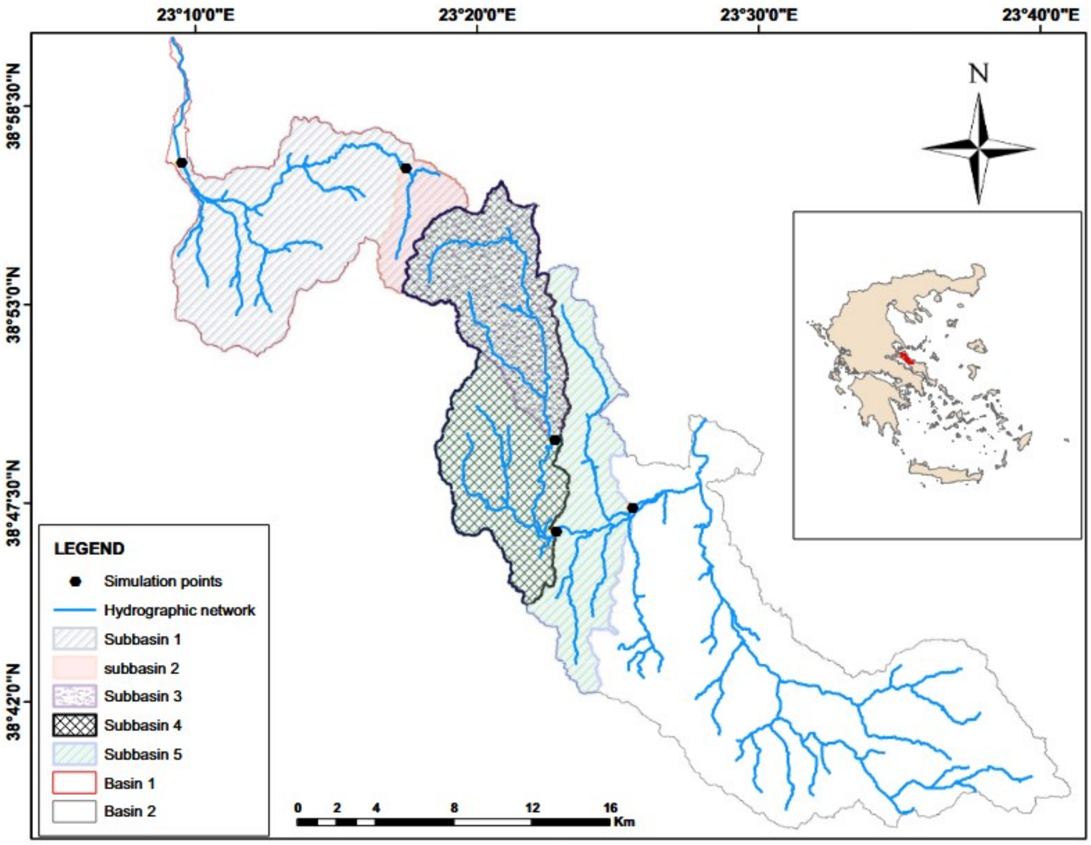


Figure 8: The study area. Source: (Theochari and Baltas 2024 a)

Theochari and Baltas 2022 utilise MCDM and GIS to identify flood-prone zones in two river basins, focusing on increased runoff risks in upper areas. They set up five simulation points (Figure 8) to analyse the impact of forest fires on flooding and assess NBS effectiveness in managing floods through land cover changes in burnt areas. The study also includes comparisons of hydrological responses using HEC-HMS software to model flood hydrographs before and after wildfires. This software models rainfall-runoff processes using basin and meteorological models and applies the Soil Conservation Service (SCS) CN method to calculate precipitation losses affected by changes in land use and soil type post-fire. It integrates total runoff with the UH to estimate runoff. The analysis shows that wildfires significantly alter flood hydrographs in each subbasin, increasing peak discharge and reducing peak times due to greater land imperviousness. Post-fire CN values rise, intensifying the flood hydrographs in HEC-HMS simulations. Notably, peak discharges in subbasins 2, 3, 4, and 5 are three to four times higher than pre-fire levels, with the time to peak halved in subbasins 2, 3, and 4. The study demonstrates the importance of NBS, like reforestation, in mitigating increased flood risks due to wildfires. In Northern Evia, under the implementation of land cover areas as NBS, areas in these subbasins affected by the fire are replanted with "Coniferous" and "Broad-leaved" forests to restore ecosystems and reduce runoff. Hydrological analyses across five subbasins evaluate the effectiveness of reforesting 3.26 km² to 60.52 km² to improve water infiltration and runoff management. Details of each subbasin's characteristics pre- and post-fire are listed in Table 4.

Table 4: The geomorphological and hydrological characteristics of each subbasin

Subbasin		1	2	3	4	5
Area (km^2)		103	14	55	104	160
Burnt area (km^2)		76	14	55	103	155
CN	**Pre-fire**	80	80	75	75	75
	Pro-fire	88	90	85	85	84
	NBS pro-fire	83	80	75	75	74
Peak discharge (m^3/s)	**UH pre-fire**	10	3	9.6	11	17
	UH pro-fire	29.5	10	21	28	47
	Flood hydrograph pre-fire	192	31	84	180	261
	Flood hydrograph pro-fire	505	118	247	446	709
	NBS Flood hydrograph pro-fire	478	97	210	414	598
Time to peak (hr)	**UH pre-fire**	14	6.5	8.5	20	14
	UH pro-fire	12	4	3.5	9	10
	Flood hydrograph pre-fire	25	9	14	31	25
	Flood hydrograph pro-fire	23	6.5	11.5	21	21
	NBS Flood hydrograph pro-fire	23	6.5	10.5	22	21

The analysis introduces new flood hydrographs for post-fire land cover changes as NBS, illustrating how these can alter hydrological responses. Adjusted CN values simulate conditions closer to a restored ecological state, showing improved infiltration and reduced runoff potential post-NBS. Results demonstrate significant decreases in peak discharge due to NBS, with reductions ranging from 5.3% in Subbasin 1 to 17.8% in Subbasin 2. NBS also positively affects the time to peak, a critical factor in flood risk management, indicating an overall improved hydrological response.

Conclusions and Future Research

This section briefly synthesises the dissertation's core findings concerning FRM strategies. It encompasses optimising hydrometric and hydrometeorological station networks, developing a GUH for ungauged basins, and implementing and evaluating NBS for flood management. The summary outlines each aspect's data, methodologies, outcomes, and critical conclusions.

Concerning the optimal hydrometric-hydrometeorological- station network design, the research highlights the impact of criteria and GIS integration on designing optimal hydrometric-hydrometeorological station networks, emphasising the importance of accurate geospatial data. The WMO determines the recommended stations, allowing flexible placements in flood-prone areas. While fuzzy logic reduces subjectivity, it may not be as efficient as the AHP in scenarios with increased site options. However, it can be effective in complex situations. Overall, the methodology is cost-efficient and effective for identifying suitable station locations in large watersheds, underlining the value of GIS tools in flood management.

Concerning the development of GUHs for Ungauged Basins, it is evident that channel velocities between 0.1-2.0 consistently yield positive NSE values across various basins, indicating accurate simulations compared to observed hydrographs. This velocity range is preferred for further research. The study also explores the time-area diagram method across 70 basins, revealing connections between hydrograph characteristics and geomorphological metrics, with visual aids like histograms enhancing understanding of these relationships. This groundwork facilitates regression analysis to predict hydrograph features based on geomorphological metrics, notably the metric Cc, which significantly influences the accuracy of these predictions. The research prioritises minimising prediction errors (MAE and RMSE) and maximising R^2 values in regression analysis to ensure robust and reliable predictions. Models like the T-Polynomial for Q_{max} and Cc-Linear for various hydrograph timings show strong predictive abilities, with residual analysis confirming their validity through scatter plots and residual plots displaying data alignment and random distribution around zero. This indicates the models' reliable predictive power for hydrograph attributes.

The effectiveness of NBS in reducing peak discharge is demonstrated. Under current climate conditions, land cover changes result in a 9.3% reduction from the baseline, while retention ponds achieve a more significant 28% decrease. Combining NBS leads to the most substantial reduction, approximately 40.5%. Similarly, total flood volumes see notable decreases across all NBS scenarios, with 12.3%, 15.3%, and 15.7% reductions for land cover change, retention ponds, and combined NBS, respectively. Climate change scenarios further highlight the impact of NBS, with intensified precipitation in the upper scenario increasing peak discharge and flood volume, while the lower scenario shows reductions. Overall, combining NBS provides the most effective means to reduce peak discharge under various climate conditions. The case study in Northern Evia examines the effects of post-wildfire land cover changes on flood dynamics and the effectiveness of NBS in mitigating these impacts. Significant post-fire increases in peak discharge across all subbasins are linked to higher CN values from extensive burn areas. Simulations show that NBS can reduce peak discharge and quicken response times to rainfall. The findings highlight NBS's role in enhancing resilience against hydrological extremes in wildfire-prone regions.

Future research recommendations stemming from the limitations of this research include exploring advanced factor weighting methods and implementing the hydrometric-hydrometeorological station network design methodology across various spatial scales. Additionally, integrating alternative hydrological data, potentially sourced from satellite observations, could supplement the limited data provided by the PPC of Greece for the development of GUH. Regarding the effectiveness of NBS, determining design criteria for retention ponds requires future efforts to concentrate on establishing a standardised framework that considers regional topography, slope gradients, and river network density. Furthermore, exploring the impact of soil erosion on retention ponds' effectiveness is essential for comprehensive understanding and improvement.

Εκτενής Περίληψη

Εισαγωγή

Οι πλημμύρες είναι μία από τις πιο σοβαρές φυσικές καταστροφές παγκοσμίως, επηρεάζοντας ιδιαίτερα περιοχές όπως τη Μεσόγειο λόγω των γεωγραφικών και κλιματικών συνθηκών. Τα πλημμυρικά γεγονότα, που επιδεινώνονται από την κλιματική αλλαγή και την αστική επέκταση, συνιστούν σημαντικούς κινδύνους για τη ζωή, τις υποδομές και την οικονομία. Ιστορικά δεδομένα και πρόσφατα καταστροφικά γεγονότα, όπως οι πλημμύρες στη Μάνδρα το 2017 και σε ευρύτερες περιοχές της Ελλάδας όπως αυτή του Ιανού το 2020, τονίζουν την αυξανόμενη συχνότητα και ένταση αυτών των φαινομένων. Ο οικονομικός αντίκτυπος είναι μεγάλος, με τις πλημμύρες στην Ευρώπη από το 1980 έως το 2017 να κοστίζουν περίπου 166 δισεκατομμύρια ευρώ (Ciabatti et al. 2018).

Μετά από σοβαρές πλημμύρες στην Κεντρική Ευρώπη και τη νότια Γαλλία το 2002, η Ευρωπαϊκή Ένωση (ΕΕ) υιοθέτησε την Οδηγία 2007/60/ΕΚ, γνωστή ως Οδηγία για τις Πλημμύρες. Αυτή στοχεύει στην αξιολόγηση και διαχείριση των κινδύνων πλημμύρας σε όλη την ΕΕ για την προστασία της ανθρώπινης υγείας, των οικονομικών δραστηριοτήτων, του περιβάλλοντος και της πολιτιστικής κληρονομιάς. Απαιτεί τον εντοπισμό των περιοχών υψηλού κινδύνου και την ανάπτυξη συνεργατικών Σχεδίων Διαχείρισης Κινδύνου Πλημμύρας (FRMPs) για τις λεκάνες απορροής ποταμών και τις παράκτιες περιοχές.

Το 2020, οι πλημμύρες αναδείχθηκαν ως η κυρίαρχη μορφή καταστροφών σε παγκόσμιο επίπεδο, αποτελώντας το 62% όλων των καταγεγραμένων περιστατικών (Peng et al. 2024). Η πολυπλοκότητα των αιτίων των πλημμυρών - από τις έντονες βροχοπτώσεις και το ταχύ λιώσιμο του χιονιού έως τις στοχίες των υποδομών - απαιτεί καινοτόμες προσεγγίσεις στη διαχείριση πλημμυρικού κινδύνου (FRM), μεταβαίνοντας από τις παραδοσιακές στρατηγικές σε πιο εξελιγμένα υδρολογικά μοντέλα. Πρόσφατες μελέτες και αναφορές δείχνουν ότι οι πλημμύρες γίνονται η κυρίαρχη μορφή καταστροφής παγκοσμίως, με την κλιματική αλλαγή να λειτουργεί ως κύριος παράγοντας στην αύξηση τόσο της συχνότητας όσο και της σοβαρότητας αυτών των γεγονότων. Η Διακυβερνητική Επιτροπή για τις Κλιματικές Αλλαγές (IPCC) προβλέπει τη συνέχιση αυτής της τάσης, με σημαντικές επιπτώσεις στα καιρικά μοτίβα και τον κίνδυνο πλημμύρας σε όλη την Ευρώπη (Allegri et al. 2024). Οι πολυδιάστατες αιτίες των πλημμυρών - συμπεριλαμβανομένων των έντονων βροχοπτώσεων, του γρήγορου λιώσιμο του χιονιού και της στοχίας των ανθρώπινων κατασκευών - απαιτούν μια ισχυρή και διεπιστημονική προσέγγιση στην FRM που να μην αντιμετωπίζει μόνο τους άμεσους κινδύνους αλλά και να χτίζει μακροπρόθεσμη ανθεκτικότητα. Η FRM ενσωματώνει τεχνικά, στρατηγικά και διοικητικά μέτρα σε διάφορες κλίμακες για να μετριάσει τις επιπτώσεις των πλημμυρών και να ενισχύσει την κοινωνική ανθεκτικότητα, ευθυγραμμιζόμενη με την ευρωπαϊκή νομοθεσία. Αυτή η προσέγγιση δίνει έμφαση στον ολοκληρωμένο προγραμματισμό, την αξιολόγηση κινδύνων και τις λύσεις βασισμένες στη φύση (NBS), καθώς και την προώθηση της συμμετοχής της κοινότητας, των συστημάτων έγκυρης προειδοποίησης και της βιώσιμης χρήσης γης για την ενίσχυση της ανθεκτικότητας στις πλημμύρες.

Η αποτελεσματική διαχείριση των υδατικών πόρων και η προστασία από τις πλημμυρικές προκλήσεις απαιτούν σωστά σχεδιασμένα δίκτυα υδρομετεωρολογικών και υδρομετρικών σταθμών. Αυτά τα δίκτυα είναι κρίσιμα για τη συλλογή αξιόπιστων και λεπτομερών δεδομένων που είναι θεμελιώδη για τα υδρολογικά μοντέλα και τις προσομοιώσεις ροής ποταμών, απαραίτητα για τη διαχείριση των υδάτινων πόρων (Theochari et al. 2021). Από τη δεκαετία του 1970, υπάρχει έντονο ενδιαφέρον για το σχεδιασμό υδρομετεωρολογικών δικτύων που ενσωματώνουν και τα δύο είδη σταθμών για την υποστήριξη διαφόρων διαχειριστικών στόχων (Mishra και Coulibaly 2009). Ποικιλία τεχνικών έχει αναπτυχθεί κατά την πάροδο των χρόνων για τη βελτιστοποίηση αυτών των δικτύων σύμφωνα με συγκεκριμένους στόχους (Rodda et al. 1969; Fujioka 1986; Sestak 1989; Moss και Tasker 1991; Shepherd et al. 2004; Barca et al. 2008; Baltas και Mimikou 2009; Hong et al. 2016; Kemeridis et al. 2017; Feloni et al. 2018; Theochari et al. 2019; Nguyen et al. 2021; Theochari et al. 2021; Mazi et al 2023; Liu et al 2023; Brunet και Milbrandt 2023; Singhal et al. 2024; Suri και Azad 2024). Ο Παγκόσμιος Μετεωρολογικός Οργανισμός (WMO) έχει μελετήσει εκτενώς την προώθηση και εφαρμογή τεχνολογιών για αυτούς τους σκοπούς (WMO 2008b; 2010). Τα Γεωγραφικά Συστήματα Πληροφοριών (GIS) διαδραματίζουν σημαντικό ρόλο στη βελτιστοποίηση του σχεδιασμού των δικτύων, στη διαχείριση χωρικών δεδομένων, στην ανάλυσή τους, στην προσθήκη θεματικών επιπέδων και στην αποτελεσματική χαρτογράφηση λεκανών απορροής ποταμών και υδρογραφικών δικτύων (Baltas και Mimikou 2009; Maidment 2002).

Με βάση την ανάγκη για προηγμένες μεθοδολογίες, η ανάπτυξη του Γεωμορφολογικού Μοναδιαίου Υδρογραφήματος (GUH) έχει βελτιώσει σημαντικά την ικανότητα πρόβλεψης και διαχείρισης πλημμυρών, ιδιαίτερα σε λεκάνες χωρίς μετρήσεις όπου τα συμβατικά δεδομένα μπορεί να είναι σπάνια. Τα GUH χρησιμοποιούν γεωμορφολογικούς δείκτες για να καθορίσουν σχέσεις μεταξύ των φυσικών χαρακτηριστικών μιας λεκάνης και της υδρολογικής της απόκρισης, επιτρέποντας την ακριβή πρόβλεψη πλημμυρικών εκδηλώσεων σε περιοχές που στερούνται εκτεταμένων υδρολογικών δεδομένων. Αυτή η μεθοδολογία αξιοποιεί την ένταξη γεωμορφολογικών και υδρολογικών δεδομένων για να ενισχύσει την ακρίβεια και την αξιοπιστία των μοντέλων πρόβλεψης πλημμυρών. Με την εφαρμογή τεχνικών που λαμβάνουν υπόψη το σχήμα της λεκάνης, το ανάγλυφο και άλλες γεωμορφολογικές παραμέτρους, τα GUH παρέχουν ένα πολύτιμο εργαλείο για την κατανόηση και διαχείριση των υδρολογικών διεργασιών σε διαφορετικά γεωγραφικά πλαίσια (Theochari et al. 2021). Τέτοια μοντέλα είναι σημαντικά για περιοχές όπως η Ελλάδα, όπου οι διαφορετικές κλιματικές και τοπογραφικές συνθήκες σε διάφορες υδρολογικές λεκάνες απαιτούν προσαρμοσμένες προσεγγίσεις στη διαχείριση των υδατικών πόρων και στη μετρίαση του πλημμυρικού κινδύνου. Η ένταξη των μοντέλων GUH στις πρακτικές FRM σηματοδοτεί μια σημαντική μετάβαση προς μια πιο αποτελεσματική προσέγγιση της αντιμετώπισης φυσικών κινδύνων σε λεκάνες χωρίς μετρήσεις.

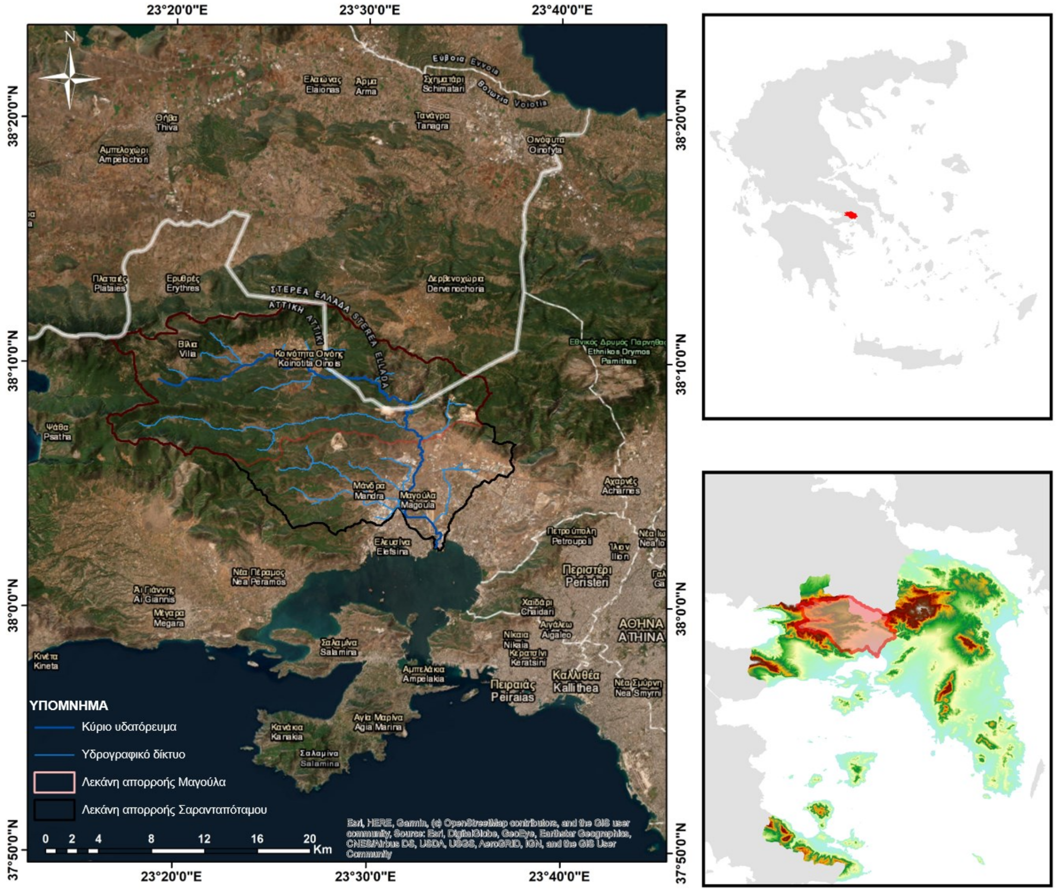
Η εφαρμογή των NBS για τη FRM αντιπροσωπεύει μια σημαντική μεταστροφή προς βιώσιμες και περιβαλλοντικά φιλικές προσεγγίσεις για την αντιμετώπιση των επιπτώσεων των πλημμυρών. Οι NBS όχι μόνο βοηθούν στη διαχείριση των κινδύνων πλημμύρας αλλά ενισχύουν επίσης τη βιοποικιλότητα και προσφέρουν επιπλέον οικολογικά οφέλη. Αυτές οι λύσεις αναγνωρίζονται όλο και περισσότερο για την αποτελεσματικότητά τους όχι μόνο στη μείωση των κινδύνων πλημμύρας αλλά και στη συμβολή τους στην ανθεκτικότητα των οικοσυστημάτων και των κοινοτήτων έναντι των επιπτώσεων της κλιματικής αλλαγής (Οδηγία 2007/60/ΕΚ). Με την ενσωμάτωση των NBS στις παραδοσιακές μηχανικές λύσεις, επιτυγχάνεται μια πιο ολιστική και βιώσιμη προσέγγιση της διαχείρισης των πλημμυρών, η οποία είναι ιδιαίτερα σημαντική στο πλαίσιο της ευρωπαϊκής νομοθεσίας και των διεθνών περιβαλλοντικών πολιτικών που προωθούν τη χρήση της πράσινης υποδομής και των βιώσιμων πρακτικών σχετικά με τις χρήσεις γης για την αντιμετώπιση των πλημμυρών. Αναγνωρίζοντας τη σημασία των NBS στη διαχείριση των υδάτων, η Ευρωπαϊκή Ένωση Υδάτων έχει τονίσει τον κρίσιμο ρόλο τους στην αντιμετώπιση των προκλήσεων της κλιματικής αλλαγής σε όλη την Ευρώπη (Beceiro et al. 2022). Η παγκόσμια σημασία των NBS αναγνωρίζεται όλο και περισσότερο, με πολλές ευρωπαϊκές πρωτοβουλίες να ερευνούν τις NBS για την προσαρμογή στην κλιματική αλλαγή και τη μείωση του κινδύνου καταστροφών στο πλαίσιο προγραμμάτων όπως το Horizon 2020. Οι NBS είναι επίσης αναπόσπαστο κομμάτι αρκετών πολιτικών της Ευρωπαϊκής Επιτροπής, συμπεριλαμβανομένων της Οδηγίας πλαίσιο για τα νερά και των σχεδίων διαχείρισης κινδύνων πλημμύρας, τα οποία εστιάζουν στη μετρίαση και προσαρμογή στην κλιματική αλλαγή. Το Δεκέμβριο του 2014, η Ελλάδα ξεκίνησε μια εθνική στρατηγική προσαρμογής για την ευθυγράμμιση με τις κλιματικές προτεραιότητες της ΕΕ. Αυτό εξελίχθηκε στον Νόμο 4936/2022, ο οποίος ψηφίστηκε τον Μάιο του 2022 και περιγράφει τη μετάβαση της Ελλάδας στην κλιματική ουδετερότητα έως το 2050, θέτοντας ενδιάμεσους στόχους για το 2030 και το 2040, και καθιερώνοντας ένα μηχανισμό προϋπολογισμού άνθρακα για τη μείωση των εκπομπών σε βασικούς τομείς όπως η ενέργεια, η κατασκευή και οι μεταφορές.

Ο κύριος στόχος της παρούσας διδακτορικής διατριβής είναι η ανάπτυξη και εφαρμογή ενός ολοκληρωμένου μεθοδολογικού πλαισίου που στοχεύει στη βελτίωση των στρατηγικών FRM, εστιάζοντας στη λεκάνη απορροής του ποταμού Σαρανταπόταμου στη Δυτική Αττική. Αυτή η περιοχή, γνωστή για την ευπάθειά της σε επαναλαμβανόμενες πλημμύρες, απαιτεί καινοτόμες προσεγγίσεις για τη μείωση των κινδύνων και την προστασία της δημόσιας ασφάλειας, των υποδομών και του περιβάλλοντος. Οι ερευνητικές ερωτήσεις που αποσκοπεί να απαντήσει η διατριβή δομούνται σε τρία κύρια τμήματα. Η πρώτη αφορά: *Μπορεί η βέλτιστη σχεδίαση δικτύου υδρομετρικών-υδρομετεωρολογικών σταθμών μέσω τεχνικών GIS να επιτευχθεί χωρίς αξιολόγηση στο πεδίο; Η δεύτερη ερώτηση αφορά: Ποια είναι η σημασία της εξαγωγής εμπειρικών σχέσεων μεταξύ των γεωμορφολογικών δεικτών και των χαρακτηριστικών των GIUH για τη βελτίωση των υδρολογικών μοντέλων με σκοπό τη FRM σε λεκάνες χωρίς μετρήσεις;* Η τρίτη ερώτηση αφορά: *Ποιος είναι ο ρόλος των NBS στη μείωση των κινδύνων πλημμύρας και πώς μπορεί να αξιολογηθεί ποσοτικά η αποτελεσματικότητά τους στο πλαίσιο μιας στρατηγικής για τη FRM;* Για την αποτελεσματική απάντηση αυτών των ερευνητικών ερωτήσεων, η παρούσα διδακτορική διατριβή περιλαμβάνει διάφορες φάσεις, καθεμία από τις οποίες επικεντρώνεται σε κρίσιμες πτυχές της FRM μέσω της ένταξης καινοτόμων μεθοδολογιών και προηγμένων υδρολογικών μοντέλων.

Η διατριβή οργανώνεται σε πέντε κύρια κεφάλαια για να ερευνήσει και να αντιμετωπίσει εκτενώς αυτά τα ζητήματα. Το Κεφάλαιο 1 θέτει τα θεμέλια με μια εισαγωγή και μια ανασκόπηση της βιβλιογραφίας για τη FRM, συζητώντας το σχεδιασμό των υδρομετρικών-υδρομετεωρολογικών δικτύων, την ανάπτυξη των GUHs και την εφαρμογή των NBS. Το Κεφάλαιο 2 περιγράφει λεπτομερώς τις γεωμορφολογικές και υδρομετεωρολογικές συνθήκες της περιοχής μελέτης, και παραθέτει τα δεδομένα που χρησιμοποιήθηκαν για την έρευνα. Το Κεφάλαιο 3 περιγράφει το μεθοδολογικό πλαίσιο που χρησιμοποιήθηκε, αναφέροντας τον σχεδιασμό του δικτύου σταθμών, την ανάπτυξη των GUHs και την ανάλυση της εφαρμογής των NBS. Το Κεφάλαιο 4 παρουσιάζει τα αποτελέσματα και τις συζητήσεις που προέκυψαν από τις εφαρμοσμένες μεθοδολογίες, παρέχοντας επισημάνσεις για την αποτελεσματικότητα των προτεινόμενων στρατηγικών FRM. Τέλος, το Κεφάλαιο 5 καταλήγει στη συνοπτική παρουσίαση των συμπερασμάτων, απαντώντας στις ερευνητικές ερωτήσεις και προτείνοντας κατευθύνσεις για μελλοντική έρευνα.

Περιοχή Μελέτης και Δεδομένα

Η παρούσα διατριβή εξετάζει τη λεκάνη απορροής του ποταμού Σαρανταπόταμου στη Δυτική Αττική, αντιπαραβάλλοντας τα φυσικά και βιομηχανικά της περιβάλλοντα με την αστική τάση του κεντρικού τομέα της Αττικής. Η συγκεκριμένη λεκάνη καλύπτοντας 341 km^2, συμπεριλαμβανομένων των δήμων Μάνδρα-Ειδυλλία, Ελευσίνα και Τανάγρα, λειτουργεί ως κρίσιμη υδρολογική λεκάνη. Ο Σαρανταπόταμος περιλαμβάνει παραπόταμους όπως ο Άγιος Βλάσης, το Ξηρόρεμα και το ρέμα της Αγίας Αικατερίνης. Η λεκάνη αποτελείται από αστικές περιοχές με 70000 κατοίκους, ενώ στα ανάντη μέρη περιλαμβάνει αγροτικές περιοχές με διάσπαρτα χωριά. Η έρευνα επικεντρώνεται επίσης σε μια υπολεκάνη 226 km^2, που βρίσκεται ανάντη του οικισμού της Μαγούλας, όπως φαίνεται στο Σχήμα 1, το οποίο απεικονίζει τα όρια και τη θέση των λεκανών απορροής εντός της Ελλάδας. Παρά την αστικοποίηση, το 89.4% του εδάφους της Δυτικής Αττικής παραμένει φυσικό, περιλαμβάνοντας γεωργικές εκτάσεις, βοσκοτόπια και δάση, σε αντίθεση με το αστικό πεδίο των Αθηνών. Η λεκάνη του Σαρανταπόταμου περιλαμβάνει τόσο αστικές όσο και βιομηχανικές περιοχές, καλύπτοντας περίπου 28.15 km^2 συνδυαστικά με βασικές υποδομές όπως δρόμοι και σιδηρόδρομοι που αναδεικνύουν τον ρόλο της ως κόμβος δραστηριοτήτων. Ωστόσο, η λεκάνη κυρίως παρουσιάζει εκτεταμένες γεωργικές και δασώδεις εκτάσεις, τονίζοντας τον αγροτικό της χαρακτήρα και τη βιοποικιλότητα. Αυτές οι περιοχές περιλαμβάνουν ποικιλία καλλιεργειών και παραδοσιακής γεωργίας, ζωτικής σημασίας για τη διατήρηση της οικολογικής ισορροπίας και της άγριας ζωής. Η λεκάνη του Σαρανταπόταμου, συμπεριλαμβανομένης της υπολεκάνης ανάντη της Μαγούλας, παρουσιάζει τις περιβαλλοντικές δυναμικές της Δυτικής Αττικής υπό το μεσογειακό κλίμα. Με ήπιους χειμώνες και ζεστά καλοκαίρια, η βροχόπτωση κυμαίνεται από 350 mm στις πεδινές περιοχές έως 1000 mm στα ορεινά, προκαλώντας περιστασιακά πλημμύρες το καλοκαίρι. Η λεκάνη και η υπολεκάνη της, περικυκλωμένες από βουνά όπως το όρος Πάτερα και η Πάρνηθα, υποστηρίζουν ποικίλα οικοσυστήματα, από δάση έως θαμνώδεις περιοχές, με τυπικές θερμοκρασίες μεταξύ 17 έως 19 °C (Baltas 2008). Ο Σαρανταπόταμος και οι παραπόταμοί του όπως ο Άγιος Βλάσης διαδραματίζουν κρίσιμο ρόλο στην υδρολογία και την οικολογική ποικιλότητα της περιοχής (Theochari και Baltas 2024). Η Δυτική Αττική έχει αντιμετωπίσει πολλές καταστροφικές πλημμύρες, επισημαίνοντας την ανάγκη για βελτίωση των περιβαλλοντικών στρατηγικών διαχείρισης και τονίζοντας την ανάγκη για βελτιωμένη υποδομή για την πρόληψη μελλοντικών καταστροφών. Παρόλο που η λεκάνη του Σαρανταπόταμου αρχικά δεν διέθετε ένα ενιαίο δίκτυο παρακολούθησης, σημαντικές πλημμύρες οδήγησαν στην εγκατάσταση ενός τηλεμετρικού συστήματος με τρεις υδρομετεωρολογικούς σταθμούς από την υπηρεσία FloodHub της NOAA (Beyond-eocenter 2021). Αυτή η εγκατάσταση είναι κρίσιμη για την ενίσχυση της περιφερειακής διαχείρισης του περιβάλλοντος και της προετοιμασίας για καταστροφές.



Σχήμα 2: Περιοχή μελέτης.

Τα κύρια σύνολα δεδομένων που χρησιμοποιούνται σε αυτή την έρευνα περιγράφονται παρακάτω:

- **Μοναδιαία Υδρογραφήματα (UH) και όρια λεκανών απορροής**: Η έρευνα αυτή χρησιμοποιεί ένα σύνολο δεδομένων δεκατεσσάρων UH που παρέχονται από τη Δημόσια Επιχείρηση Ηλεκτρισμού (ΔΕΗ) της Ελλάδας, καλύπτοντας διάφορες διάρκειες όπως μισής ώρας, μίας ώρας και δύο ωρών. Αυτά τα UH είναι ουσιαστικά για τη μελέτη της υδρολογικής απόκρισης λεκανών απορροής χωρίς μετρήσεις εντός της Ελλάδας. Με τη χρήση τεχνολογίας GIS, τα όρια των λεκανών γεωαναφέρθηκαν και ψηφιοποιήθηκαν για να εξασφαλιστεί η ακριβής αναπαράστασή τους σε ψηφιακή μορφή. Οκτώ από τα αρχικά δεκατέσσερα υδρογραφήματα, που τυποποιήθηκαν βάσει μεγέθους λεκάνης, θεωρήθηκαν ολοκληρωμένα και κατάλληλα για την ανάπτυξη του μοντέλου GUH.
- **Δεδομένα Συντελεστή Τραχύτητας**: Η έρευνα επικεντρώνεται στον συντελεστή τραχύτητας, ο οποίος είναι καίριος για τον ακριβή υπολογισμό των

ταχυτήτων του νερού στα υδρολογικά μοντέλα. Αυτός ο συντελεστής ενσωματώνει ταχύτητες στα διαφορετικά τοπία, λαμβάνοντας υπόψη παράγοντες όπως η κάλυψη του εδάφους, η κλίση και η τάξη των ρεμάτων. Οι τιμές προέρχονται από τη βιβλιογραφία, ειδικά από τους Haan et al. 1994 και McCuen 1997, βοηθώντας στην ακριβή αξιολόγηση των ταχυτήτων της επιφανειακής ροής. Αυτή η λεπτομερής διαχείριση δεδομένων βελτιώνει την ακρίβεια του GUH.

- **Δεδομένα βροχομετρικών σταθμών:** Η έρευνα αυτή χρησιμοποιεί δεδομένα από τον υδρομετεωρολογικών σταθμό της Μάνδρας, εφαρμόζοντας τη Μέθοδο των Εναλλασσόμενων Μπλοκ για τον υπολογισμό των υετογραφημάτων σχεδιασμού βάσει των όμβριων καμπυλών Έντασης-Διάρκειας-Συχνότητας (IDF). Για τα μελλοντικά κλιματικά σενάρια—μέσο, ανώτερο και κατώτερο—με περίοδο επαναφοράς 100 ετών, εφαρμόζονται οι αναθεωρημένες καμπύλες IDF από Kourtis et al. 2023. Αυτές οι είναι κρίσιμες για την πρόβλεψη μελλοντικών πλημμυρογραφημάτων και την αξιολόγηση των NBS υπό διάφορες κλιματικές συνθήκες. Τα δεδομένα IDF που χρησιμοποιήθηκαν σε αυτή την έρευνα προέρχονται από τα Σχέδια Διαχείρισης Κινδύνου Πλημμύρας (FRMPs) για την Ελλάδα, τα οποία παρέχονται από το Υπουργείο Περιβάλλοντος, Ενέργειας και Κλιματικής Αλλαγής. Ο Πίνακας 1 παρουσιάζει τις συγκεκριμένες παραμέτρους για τον σταθμό και το υπολογισμένο αθροιστικό ύψος βροχής, H, την ένταση της βροχόπτωσης, i, το χρόνο συγκέντρωσης, tc, μέσω της εξίσωσης Giandotti, για την επιλεγμένη διάρκεια για κάθε σενάριο και την περίοδο επαναφοράς 100 ετών.

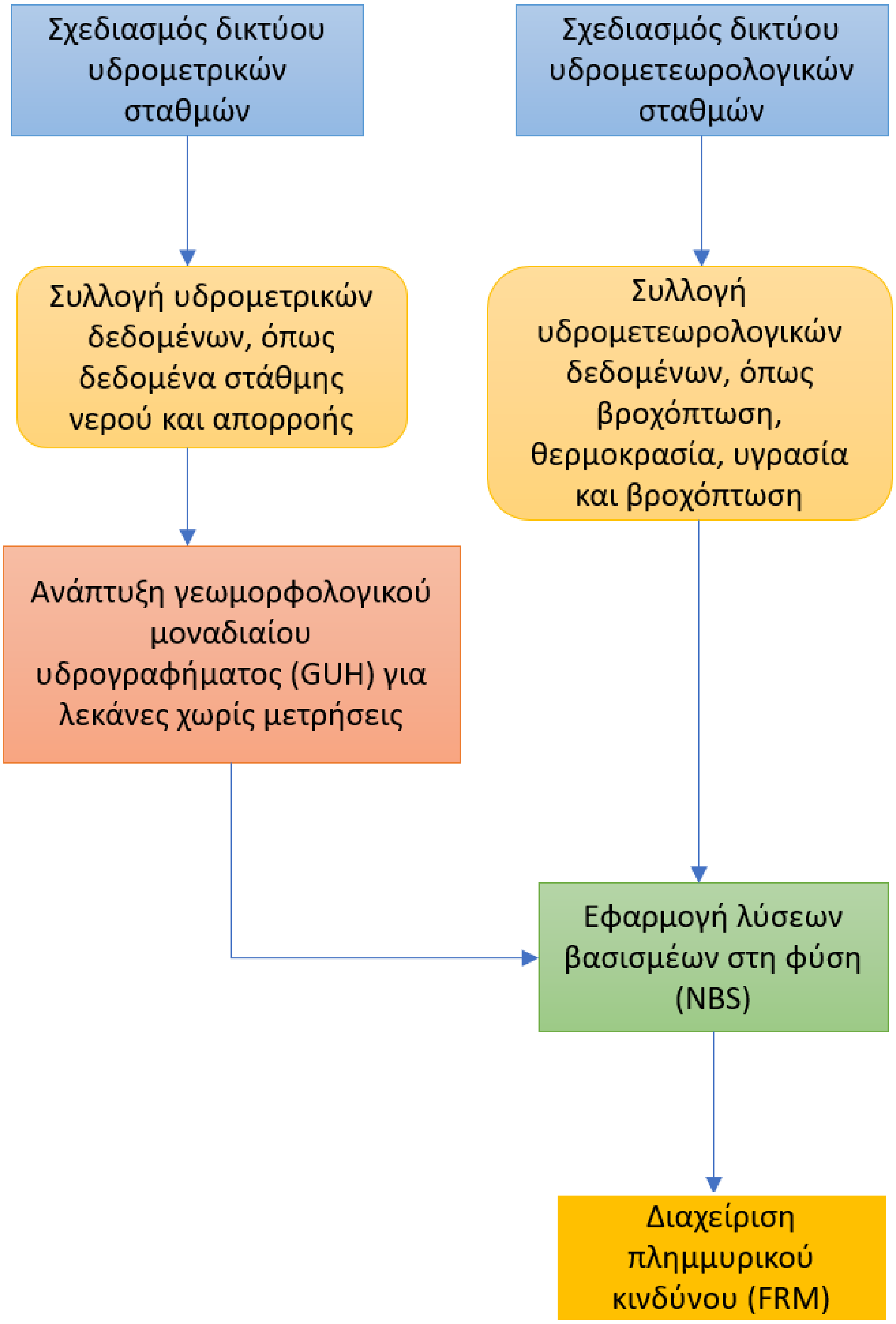
Πίνακας 1: Οι παράμετροι IDF του σταθμού της Μάνδρας και τα υπολογισμένα χαρακτηριστικά βροχόπτωσης

Υδρομετεωρολογικός σταθμός	Μάνδρα			
Όμβρια καμπύλη (ID)	292			
Υψόμετρο	258			
IDF παράμετροι	η		0.622	
	κ		0.125	
	λ		213.4	
	ψ		0.641	
	θ		0.124	
Σενάριο	**Current**	**Mean**	**Upper**	**Lower**
tc(h)	6.5	6.5	6.5	6.5
d(h)	24	24	24	24
T(y)	100	100	100	100
i(mm/h)	9.15	13.54	40.09	6.43
H (mm)	219.53	325.02	962.27	154.23

- **Ψηφιακό Υψομετρικό Μοντέλο Εδάφους (DEM):** Αποκτήθηκε από το Εθνικό Κτηματολόγιο & Υπηρεσία Χαρτογράφησης Α.Ε. Αυτό το υψηλής ανάλυσης DEM χρησιμοποιήθηκε ως το βασικό δεδομένο για όλες τις χωρικές αναλύσεις, με χωρική ανάλυση 5 m x 5 m.
- **Δεδομένα Κάλυψης Γης CORINE (CLC, 2018):** Το σύνολο δεδομένων URBAN Atlas 2018 παρέχει έναν κατάλογο της κάλυψης γης για την Ευρώπη και ειδικά επιλεγμένες αστικές περιοχές.
- **Δεδομένα Δικτύου Οδών:** Αυτό το σύνολο δεδομένων περιλαμβάνει λεπτομερείς πληροφορίες για το δίκτυο οδών από το OpenStreetMap (OSM), το οποίο αποκτήθηκε μέσω της ιστοσελίδας Geofabrik. Ήταν σημαντικό για τον σχεδιασμό του υδρομετρικού-υδρομετεωρολογικού δικτύου.
- **Δεδομένα Γεωτρήσεων:** Δεδομένα που αποκτήθηκαν από το Εθνικό Μητρώο Σημείων Ύδρευσης στην ιστοσελίδα του Υπουργείου Περιβάλλοντος, Ενέργειας και Κλιματικής Αλλαγής της Ελλάδας. Αυτό το επίθεμα περιλαμβάνει τις τοποθεσίες και τα χαρακτηριστικά των γεωτρήσεων σε όλη την περιοχή μελέτης.
- **Ιστορικά Αρχεία Πλημμυρικών Εκδηλώσεων:** Συγκεντρώθηκαν από την ιστοσελίδα του Υπουργείου Περιβάλλοντος και Ενέργειας της Ελλάδας. Αυτό το αρχείο καταγράφει σημαντικά ιστορικά πλημμυρικά γεγονότα στην Ελλάδα, παρέχοντας ένα χωρικό αρχείο παλαιότερων πλημμυρών.
- **Περιοχές Ευάλωτες σε Πλημμύρες:** Πληροφορίες από ανάλυση Πολλαπλών Κριτηρίων Αποφάσεων (MCDM) με βάση GIS από την Feloni et al. 2020, που εντοπίζει ζώνες ευάλωτες σε πλημμύρες στην περιοχή της Αττικής, ειδικά στη λεκάνη του Σαρανταπόταμου, βοηθώντας στη στρατηγική τοποθέτηση σταθμών παρακολούθησης για τη διαχείριση κινδύνου πλημμύρας.
- **Διοικητικά Όρια Δήμων:** Προέρχονται από ανοιχτές πηγές GIS, όπως το geodata.gov.gr, αυτά τα διοικητικά όρια επιτρέπουν την εστιασμένη ανάλυση των κινδύνων πλημμύρας και τη διαχείριση εντός συγκεκριμένων δήμων.
- **Γεωλογικές Πληροφορίες:** Αποκτήθηκαν από την ιστοσελίδα της Ελληνικής Γεωλογικής Υπηρεσίας (ΕΑΓΜΕ), αυτό το σύνολο δεδομένων περιλαμβάνει χάρτες και δεδομένα για τα περιφερειακά γεωλογικά χαρακτηριστικά, ουσιαστικά για τη μελέτη της σύνθεσης του εδάφους και της γεωλογίας.
- **Σταθμοί IDF:** Αυτό το αποθετήριο περιλαμβάνει σταθμούς IDF με τις αντίστοιχες παραμέτρους τους, οι οποίοι αναπτύχθηκαν για τα FRMPs για την Ελλάδα από το Υπουργείο Περιβάλλοντος, Ενέργειας και Κλιματικής Αλλαγής, και διατίθενται σε μορφή shapefile.

Μεθοδολογικό Πλαίσιο

Η εν λόγω διδακτορική διατριβή παρουσιάζει ένα μεθοδολογικό πλαίσιο για τη FRM στη λεκάνη του ποταμού Σαρανταπόταμου, όπως φαίνεται στο Σχήμα 2.



Σχήμα 2: Διάγραμμα ροής του μεθοδολογικού πλαισίου για τη διαχείριση πλημμυρικού κινδύνου (FRM)

Αρχίζει με 1) τη στρατηγική τοποθέτηση υδρομετρικών-υδρομετεωρολογικών σταθμών βάσει ανάλυσης πολλαπλών κριτηρίων GIS, εστιάζοντας σε παράγοντες όπως η ευπάθεια σε πλημμύρες και η περιβαλλοντική σημασία. Αυτή η διαμόρφωση υποστηρίζει 2) την ανάπτυξη GUH για μη λεκάνες χωρίς μετρήσεις, χρησιμοποιώντας γεωμορφολογικούς δείκτες για τη σύνδεση της βροχόπτωσης με την απορροή. Το πλαίσιο ολοκληρώνεται με 3) την εφαρμογή NBS, όπως αλλαγές στην κάλυψη του εδάφους και λίμνες συγκράτησης νερού, χρησιμοποιώντας πλημμυρογραφήματα βασισμένα σε δεδομένα για την αποτελεσματική διαχείριση των κινδύνων πλημμύρας. Αυτή η προσέγγιση εξασφαλίζει μια ανθεκτική, κλιμακούμενη στρατηγική για την ενίσχυση της ανθεκτικότητας σε πλημμύρες των ευάλωτων περιοχών.

1. **Σχεδιασμός Δικτύου Υδρομετρικών-Υδρολογικών Σταθμών με χρήση τεχνικών GIS:** Αυτή η φάση εισάγει μια μεθοδολογία MCDM βασισμένη στο GIS για την ταυτοποίηση πιθανών θέσεων για χωροθέτηση υδρομετρικών και υδρομετεωρολογικών σταθμών εντός της λεκάνης του ποταμού Σαρανταπόταμου. Αυτοί οι σταθμοί είναι σημαντικοί για τη διαχείριση των υδατικών πόρων και τα συστήματα προειδοποίησης πλημμυρών, ανταποκρινόμενοι στις κρίσιμες ανάγκες για ακριβή συλλογή δεδομένων και έγκαιρη ανταπόκριση σε πλημμύρες. Η μεθοδολογία, βασισμένη στους Theochari et al. 2019, 2021, χρησιμοποιεί προκαθορισμένα σύνολα γεωμορφολογικών, τεχνικών και χωρικών κριτηρίων για την αξιολόγηση της καταλληλότητας των θέσεων. Τα κύρια βήματα της ανάλυσης περιλαμβάνουν την επιλογή κριτηρίων για το σχεδιασμό δικτύου, την κανονικοποίηση των τιμών τους μέσω τυποποίησης και ταξινόμησης, τον σχηματισμό των κριτηρίων σε περιβάλλον GIS και τον καθορισμό των βαρών για κάθε κριτήριο. Για τους υδρομετεωρολογικούς σταθμούς, χρησιμοποιείται μια απλοποιημένη προσέγγιση όπου όλα τα κριτήρια έχουν ίσο βάρος. Για τους υδρομετρικούς σταθμούς, τα βάρη των κριτηρίων καθορίζονται χρησιμοποιώντας τη μέθοδο της Αναλυτικής Ιεραρχικής Διαδικασίας (AHP) όπως πρότεινε ο Saaty το 1977, καθώς και τη μέθοδο Fuzzy AHP (FAHP). Αυτό το κομμάτι της μεθοδολογίας επιτρέπει μια λεπτομερή ανάλυση της καταλληλότητας κάθε θέσης με βάση συγκεκριμένες υδρολογικές και γεωγραφικές απαιτήσεις. Τα κριτήρια σχεδιασμού διατυπώνονται εντός του πλαισίου GIS όπως περιγράφεται στους Theochari et al. 2019, 2021. Το GIS είναι απαραίτητο για τη διαχείριση χωρικών δεδομένων από διάφορες πηγές και τη διευκόλυνση των διαδικασιών χωρικής λήψης αποφάσεων. Τα κριτήρια ενσωματώνονται και αναλύονται χρησιμοποιώντας την τεχνική του σταθμισμένου γραμμικού συνδυασμού (WLC) για την παραγωγή λεπτομερών χαρτών καταλληλότητας. Η διαδικασία MCDM βασισμένη στο GIS εντοπίζει αρκετές ιδανικές θέσεις χωροθέτησης,

επιλέγοντας εκείνες με τις υψηλότερες τελικές βαθμολογίες (FS) για την εγκατάσταση του δικτύου.

2. **Ανάπτυξη Γεωμορφολογικού Μοναδιαίου Υδρογραφήματος (GUH):** Το μεθοδολογικό πλαίσιο στοχεύει στην εξέλιξη της υδρολογικής μοντελοποίησης στην Ελλάδα μέσω της ανάπτυξης GUH για λεκάνες χωρίς μετρήσεις. Αυτή η φάση επικεντρώνεται στην αξιοποίηση των γεωμορφολογικών χαρακτηριστικών για ακριβείς υδρολογικές εκτιμήσεις σε περιοχές με περιορισμένα δεδομένα. Η προσέγγιση περιλαμβάνει τη στατιστική επαλήθευση των UH που υπολογίζονται μέσω της μεθόδου των ισόχρονων καπυλών, εφαρμοζόμενη με τη χρήση ArcPy σε περιβάλλοντα GIS. Οι πρόσφατες πρόοδοι στα εργαλεία GIS και τα DEM επιτρέπουν τους ακριβείς υπολογισμούς γεωμορφολογικών και υδρολογικών μετρήσεων, ενισχύοντας την ακρίβεια του μοντέλου. Η διαδικασία περιλαμβάνει την ενσωμάτωση εμπειρικών υδρολογικών δεδομένων από τη ΔΕΗ της Ελλάδας και τη βελτιστοποίηση των εύρων ταχυτήτων εντός του υδρογραφικού δικτύου για να ταιριάζουν αποτελεσματικά με τα παρατηρούμενα UH. Η μέθοδος των ισόχρονων καμπυλών χρησιμοποιείται για την ανάλυση των χαρακτηριστικών των υδρογραφημάτων σε 70 λεκάνες απορροής εντός της περιοχής μελέτης, φτάνοντας συνολικά τις 100 λεκάνες. Ο κύριος στόχος είναι ο υπολογισμός του UH για κάθε λεκάνη. Αυτή η μέθοδος περιλαμβάνει την εξέταση διαφορετικών χαρακτηριστικών των υδρογραφημάτων μαζί με τις αντίστοιχες γεωμορφολογικές μετρήσεις για κάθε λεκάνη. Αυτοί οι συσχετισμοί βοηθούν στη δημιουργία συνδέσεων μεταξύ των χαρακτηριστικών των υδρογραφημάτων και των γεωμορφολογικών δεικτών, κρίσιμων για τον καθορισμό του GUH για κάθε λεκάνη. Στη συνέχεια διατυπώνονται εξισώσεις που εκφράζουν κάθε χαρακτηριστικό του υδρογραφήματος σε σχέση με την συναφή γεωμορφολογική παράμετρο με βάση αυτούς τους συσχετισμούς. Η επαλήθευση σε 30 λεκάνες επιβεβαιώνει την εγκυρότητα του μοντέλου, προσφέροντας ένα αξιόπιστο εργαλείο για την κατανόηση των υδρολογικών συμπεριφορών σε διαφορετικές λεκάνες απορροής. Αυτή η καινοτόμος προσέγγιση GUH αντιμετωπίζει την πρόκληση των περιορισμένων δεδομένων, βελτιώνοντας τη διαχείριση πλημμυρών και τις υδρολογικές προβλέψεις στην Ελλάδα.
3. **Ανάλυση NBS:** Αυτή η φάση επικεντρώνεται στην εφαρμογή και ανάλυση των NBS, ειδικότερα της αλλαγής κάλυψης γης, της κατασκευής λίμνες συγκράτησης υδάτων και των συνδυασμών τους στη λεκάνη του ποταμού Σαρανταπόταμου, ανάντη του οικισμού της Μαγούλας στην Ελλάδα. Η έρευνα

αυτή αξιολογεί την αποτελεσματικότητα αυτών των NBS εξετάζοντας τα πλημμυρογραφήματα για να προσδιορίσει αλλαγές στην παροχή αιχμής, τον όγκο και τη χρονική στιγμή της αιχμής, τόσο υπό τις τρέχουσες όσο και τις προβλεπόμενες μελλοντικές κλιματικές συνθήκες. Η έρευνα χρησιμοποιεί τις αναθεωρημένες καμπύλες IDF από τους Kourtis et al. 2023 για μελλοντικές κλιματικές προβολές και χρησιμοποιεί τη μέθοδο User-Specified UH με το λογισμικό HEC-HMS για την υδρολογική μοντελοποίηση. Αυτή η ανάλυση στοχεύει στην αξιολόγηση των NBS για την ενίσχυση της ανθεκτικότητας στις πλημμύρες και στην προσαρμογή τους σε διαφορετικές κλιματικές συνθήκες, παρέχοντας κρίσιμες προβλέψεις για τη βιώσιμη διαχείριση των υδάτων και τη μείωση του κινδύνου πλημμύρας. Η επιλεγμένη περιοχή μελέτης με σημαντικό ιστορικό πλημμυρών και ευπάθεια τονίζει τη σημασία αυτής της καινοτόμου προσέγγισης στη FRM, προσφέροντας πολύτιμη καθοδήγηση για περιβαλλοντικούς φορείς, πολιτικούς και κοινότητες. Κατά τη φάση εφαρμογής, με επίκεντρο τις NBS για τη FRM, η έρευνα διερευνά επίσης τη χρήση των αλλαγών κάλυψης γης ως NBS σε περιοχές που επηρεάστηκαν από τις σοβαρές πυρκαγιές στη Βόρεια Εύβοια τον Αύγουστο του 2021. Καταλήγει σε τροποποιήσεις της κάλυψης γης σε πέντε λεκάνες απορροής. Αναλύοντας τις αλλαγές στην κάλυψη γης και την υιοθέτηση των NBS στη Βόρεια Εύβοια μετά την πυρκαγιά, αυτή η έρευνα συμβάλλει στην προώθηση της υδρολογικής μοντελοποίησης, προσφέροντας μια στρατηγική για την αντιμετώπιση των υδρολογικών επιπτώσεων που προκαλούνται από τις πυρκαγιές.

Αποτελέσματα και Συζήτηση

Βέλτιστη χωροθέτηση δικτύου υδρομετρικών-υδρομετεωρολογικών σταθμών

Βέλτιστη χωροθέτηση δικτύου υδρομετρικών σταθμών

Το δίκτυο υδρομετρικών σταθμών χρησιμοποιεί τη μέθοδο AHP για την ανάθεση βαρών σε κριτήρια, όπως απεικονίζεται στον Πίνακα 2(α) μέσω πινάκων σύγκρισης ζευγών βάσει της κλίμακας του Saaty του 1977. Για να αντιμετωπιστεί η δυνητική υποκειμενικότητα αυτών των συγκρίσεων, παρουσιάζεται ένα εναλλακτικό σενάριο χρησιμοποιώντας τη μέθοδο FAHP στον Πίνακα 2(β), οδηγώντας σε διαφορετικά σενάρια: «3a» για AHP και «3b» για FAHP. Η FAHP περιλαμβάνει ασαφείς αριθμούς στις συγκρίσεις και προτείνει μηδενικά βάρη για κριτήρια που θεωρούνται λιγότερο σημαντικά, εν αντιθέσει με την AHP όπου τα βάρη είναι κοντά στο μηδέν αλλά όχι απόλυτα (Özdağoğlu και Özdağoğlu 2007). Παρόλο που η FAHP μειώνει την υποκειμενικότητα με γλωσσικές τιμές, ενδέχεται να μην είναι ιδανική για τον σχεδιασμό δικτύων υδρομετρικών σταθμών λόγω της μη πρακτικήςαύξησης των προτεινόμενων θέσεων που απαιτούν εκτεταμένη επιτόπια εργασία. Σε όλα τα σενάρια, η σημασία των τοπογραφικών κλίσεων (W_{C1}) τονίζει τον κρίσιμο ρόλο του εδάφους στην κίνηση του νερού και την ακρίβεια των υδρολογικών δεδομένων, επισημαίνοντας τη σημασία της κατανόησης των διαφορετικών δυναμικών της ροής του νερού.

Στο Σενάριο 1, οι τοπογραφικές κλίσεις (W_{C1}) έχουν προτεραιότητα, αντανακλώντας τον κρίσιμο ρόλο τους στη μέτρηση της επιφανειακής ροής, όπου οι απότομες κλίσεις αυξάνουν τον κίνδυνο πλημμύρας και οι ήπιες κλίσεις επιβραδύνουν τη ροή, επηρεάζοντας το σχεδιασμό του δικτύου και την ακρίβεια των υδρολογικών δεδομένων. Στο Σενάριο 2, που επικεντρώνεται στην προστασία από πλημμύρες, η σημασία των κλίσεων (W_{C1}) μειώνεται ελαφρώς αλλά παραμένει κρίσιμη. Η έμφαση μετατοπίζεται στην απόσταση από περιοχές ευάλωτες σε πλημμύρες (W_{C5}), αντανακλώντας τον κρίσιμο ρόλο της στην μετρίαση των πλημμυρών και τη στρατηγική τοποθέτηση σταθμών για τη βελτίωση της διαχείρισης πλημμυρών και των προγνωστικών δυνατοτήτων. Το Σενάριο 3a δείχνει ότι το βάρος για τις κλίσεις (C1) ευθυγραμμίζεται στενά με το Σενάριο 1, τονίζοντας τους τοπογραφικούς παράγοντες σε μια ισορροπημένη προσέγγιση. Ωστόσο, το βάρος για την απόσταση από τους οικισμούς (C4) μειώνεται από το αρχικό 0.060, υποδεικνύοντας μια μικρότερη προτεραιότητα για την εγγύτητα στους οικισμούς υπό την προσέγγιση AHP σε σύγκριση με το αρχικό τεχνικό σενάριο. Αυτή η αλλαγή δείχνει μια μεταβολή στις προτεραιότητες αξιολόγησης. Το Σενάριο 3b, χρησιμοποιώντας FAHP, διατηρεί υψηλό βάρος για τις τοπογραφικές κλίσεις (W_{C1}) αλλά αναθέτει μηδενικό βάρος στις αποστάσεις από το οδικό δίκτυο (W_{C2}), συμβολών των ρεμάτων (W_{C3}), και απόσταση από οικισμούς (W_{C4}), τονίζοντας τα φυσικά υδρολογικά χαρακτηριστικά και τον κίνδυνο πλημμύρας (W_{C5}) στη λήψη αποφάσεων. Η συγκριτική ανάλυση αναδεικνύει ότι, ενώ οι τοπογραφικές κλίσεις διατηρούν σταθερά το υψηλότερο βάρος, η έμφαση στην απόσταση από τους οικισμούς διαφέρει ανάμεσα στα σενάρια. Αυτό τονίζει τις μεθοδολογικές διαφορές στην προτεραιοποίηση των ανθρωπογενών παραγόντων και υπογραμμίζει την πολυπλοκότητα της ισορροπίας διαφόρων στόχων στον σχεδιασμό δικτύου σταθμών. Ο Πίνακας 3 παρουσιάζει τα υπολογισμένα βάρη κριτηρίων για διάφορα σενάρια με σκοπό τη βέλτιστη χωροθέτηση υδρομετρικών σταθμών.

Πίνακας 2: Πίνακας σύγκρισης ζευγών για κάθε σενάριο, όπως αναφέρεται στους Theochari et al. 2019.

a)	*Σενάριο 1*					*Σενάριο 2*					*Σενάριο 3 (3a)*				
	C1	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**	**C3**	**C4**	**C5**
C1	**1**	5	9	7	5	**1**	7	9	5	3	**1**	5	7	9	3
C2	1/5	**1**	3	3	3	1/7	**1**	1	1/7	1/9	1/5	**1**	3	5	1/5
C3	1/9	1/3	**1**	3	3	1/9	1	**1**	1/7	1/9	1/7	1/3	**1**	3	1/7
C4	1/7	1/3	1/3	**1**	1	1/5	7	7	**1**	1/3	1/9	1/5	1/3	**1**	1/9
C5	1/5	1/3	1/3	1	**1**	1/3	9	9	3	**1**	1/3	5	7	9	**1**

b)	*Σενάριο (3b)*														
		C1			**C2**			**C3**			**C4**			**C5**	
C1	1	**1**	1	4	5	6	6	7	8	9	9	9	2	3	4
C2	1/6	1/5	1/4	1	**1**	1	2	3	4	4	5	6	1/6	1/5	1/4
C3	1/8	1/7	1/6	1/4	1/3	1/2	1	**1**	1	2	3	4	1/8	1/7	1/6
C4	1/9	1/9	1/9	1/6	1/5	1/4	1/4	1/3	1/2	1	**1**	1	1/9	1/9	1/9
C5	1/4	1/3	1/2	4	5	6	6	7	8	9	9	9	1	**1**	1

Πίνακας 3: Τα βάρη κριτηρίων για κάθε σενάριο, όπως αναφέρεται στους Theochari et al. 2019

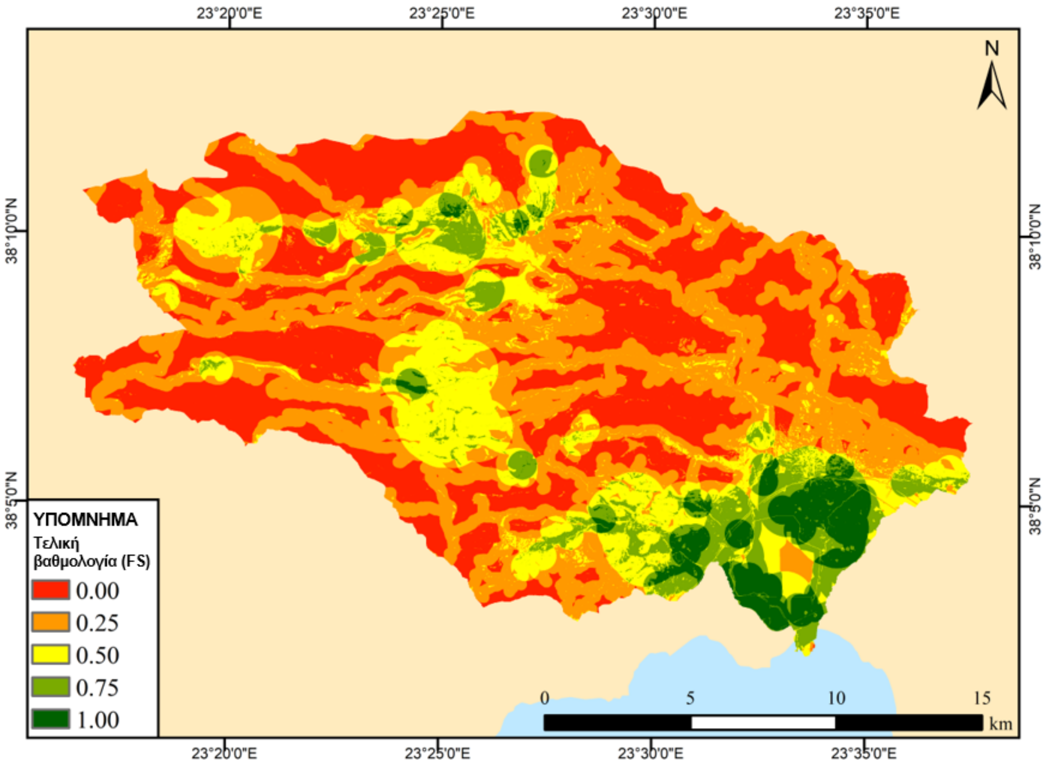
	Σενάριο 1	*Σενάριο 2*	*Σενάριο 3a*	*Σενάριο 3b*
W_{C1}	0.566	0.474	0.476	0.565
W_{C2}	0.183	0.039	0.118	0.000
W_{C3}	0.124	0.036	0.061	0.000
W_{C4}	0.060	0.166	0.032	0.000
W_{C5}	0.067	0.284	0.312	0.435

Ο σχεδιασμός δικτύου υδρομετρικών σταθμών χρησιμοποιεί τη μέθοδο WLC ενσωματώνοντας βάρη από τις μεθόδους AHP και FAHP για την παραγωγή ενός χάρτη ενιαίου σκορ καταλληλότητας. Αυτό διασφαλίζει ότι η χωροθέτηση των σταθμών είναι σύμφωνη με τις ειδικές ανάγκες για κάθε σενάριο. Χρησιμοποιώντας GIS και Map Algebra, τα κριτήρια τυποποιούνται και συνθέτονται, εστιάζοντας την τοποθέτηση σταθμών κατά μήκος του κύριου υδατορεύματος της λεκάνης του Σαρανταπόταμου. Το FS κυμαίνεται από 0 έως 1 και βοηθά στον εντοπισμό ιδανικών τοποθεσιών χρησιμοποιώντας κατώφλια. Σύμφωνα με τους Theochari et al. το 2019, οι τοποθεσίες κατηγοριοποιούνται σε δύο κατηγορίες: αυτές με FS κάτω από 0.90 ή 0.95, και αυτές με FS πάνω από αυτά τα κατώφλια. Αυτή η μέθοδος διαχωρίζει οπτικά και ποσοτικά τις πιο κατάλληλες από τις λιγότερο κατάλληλες τοποθεσίες. Ο αριθμός των κατάλληλων τοποθεσιών διαφέρει ανάλογα με τα κατώφλια FS, για παράδειγμα, ένα σενάριο αναγνωρίζει μόνο τέσσερις υψηλά κατάλληλες τοποθεσίες. Η προσέγγιση FAHP συνήθως παράγει περισσότερες πιθανές τοποθεσίες, καθώς χρησιμοποιεί λιγότερα περιοριστικά κριτήρια επιλογής.

Στη μελέτη των Theochari et al. το 2021, οι τιμές FS κατηγοριοποιούνται σε δύο κλάσεις: αυτές με FS κάτω από 0.90 και αυτές με FS πάνω από αυτό το κατώφλι. Το κριτήριο των "κλίσεων" είναι το πιο κρίσιμο σε όλα τα σενάρια, ενώ η "απόσταση από οικισμούς" ποικίλλει σε σημασία, ειδικότερα είναι λιγότερο σημαντική στο πρώτο και τρίτο σενάριο. Αντίθετα, η "απόσταση από τη συμβολή με άλλο ρέμα" είναι η λιγότερο σημαντική στο δεύτερο σενάριο, εκτός από τα συστήματα προειδοποίησης πλημμυρών όπου η "απόσταση από οικισμούς" είναι κρίσιμη. Όλα τα σενάρια προτείνουν τις ίδιες θέσεις υψηλού δυναμικού για τιμές FS πάνω από 90%, κυρίως στο νότιο τμήμα του ποταμού. Το σενάριο 3a (AHP) εντοπίζει 59 θέσεις υψηλού FS, ενώ το σενάριο 3b (FAHP) εντοπίζει 437 λόγω λιγότερων κριτηρίων. Οι περισσότερες κατάλληλες τοποθεσίες βρίσκονται στα νότια χαμηλά της περιοχής κοντά σε οικισμούς και περιοχές ευάλωτες σε πλημμύρες, εκτός από το πρώτο σενάριο, το οποίο προτείνει θέσεις κατά μήκος ολόκληρου του ποταμού, τονίζοντας τις χαμηλές κλίσεις και την εγγύτητα στους δρόμους, ενώ αποφεύγει τις συμβολές ρεμάτων. Η διακύμανση στις προτεινόμενες θέσεις ανά σενάριο τονίζει την επίδραση διαφορετικών συνόλων δεδομένων και κριτηρίων στον σχεδιασμό του δικτύου υδρομετρικών σταθμών βασισμένο στο GIS, υπογραμμίζοντας τον κρίσιμο ρόλο της επιλογής δεδομένων στην επιρροή της λήψης αποφάσεων.

Βέλτιστη χωροθέτηση δικτύου υδρομετεωρολογικών σταθμών

Τα κριτήρια για τον σχεδιασμό του δικτύου υδρομετεωρολογικών σταθμών στη λεκάνη του Σαρανταπόταμου καθορίζουν αυστηρά τις κατάλληλες και μη κατάλληλες θέσεις για τη χωροθέτηση σταθμών. Αυτή η μέθοδος διασφαλίζει ότι λαμβάνονται υπόψη μόνο οι θέσεις που πληρούν όλα τα κριτήρια, βελτιστοποιώντας την αποτελεσματικότητα του δικτύου. Η διατύπωση των κριτηρίων ως περιορισμών καθοδηγεί τη διαδικασία WLC, παράγοντας έναν λεπτομερή χάρτη καταλληλότητας που παρουσιάζεται στο Σχήμα 3. Ο χάρτης διαιρεί το FS σε πέντε ίσες κλάσεις από "0" έως "1": "0", "0.25", "0.50", "0.75", και "1.00". Η κατανομή σε όλη τη λεκάνη του ποταμού δείχνει 34% για FS= 0, υποδεικνύοντας ζώνες όπου η τοποθέτηση σταθμών απαγορεύεται,·39% για FS = 0.25; 16% για FS = 0.50; 7% για FS = 0.75; και 4% για την υψηλότερη βαθμολογία FS = 1.0, το οποίο υποδεικνύεται με σκούρο πράσινο για να τονίσει τις βέλτιστες θέσεις χωροθέτησης. Αυτή η ταξινόμηση διευκολύνει τη λήψη αποφάσεων και αντανακλά την πολυπλοκότητα της αναγνώρισης θέσης χωροθέτησης σε μια λεκάνη απορροής, τονίζοντας τη σημασία της προσεκτικής επιλογής κριτηρίων και χωρικής ανάλυσης στον σχεδιασμό ενός αποδοτικού και αξιόπιστου δικτύου σταθμών.

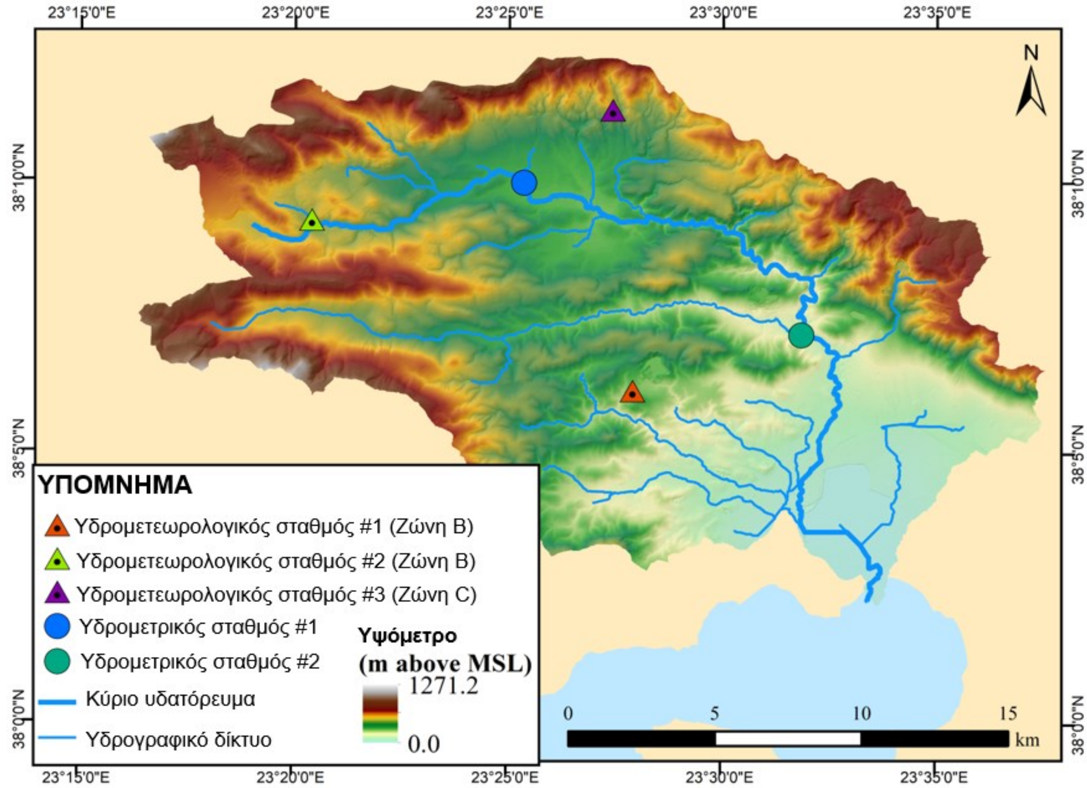


Σχήμα 3: Σταθμισμένος γραμμικός συνδυασμός (WLC) μεταξύ των κριτηρίων για το σχεδιασμό δικτύου υδρομετεωρολογικών σταθμών. Πηγή: (Theochari et al. 2021)

Η χωροθέτηση των υδρομετεωρολογικών σταθμών στη λεκάνη του Σαρανταπόταμου εκτιμά την κατανομή των σταθμών με βάση το υψόμετρο για να διασφαλιστεί ότι το δίκτυο είναι τόσο επιστημονικά έγκυρο όσο και οικονομικά αποδοτικό. Αυτή η διαδικασία περιλαμβάνει τη χρήση ενός κριτηρίου πυκνότητας που σχετίζεται με το υψόμετρο, για να υπολογιστεί ο ελάχιστος απαραίτητος αριθμός σταθμών για αποτελεσματική παρακολούθηση σε κάθε ζώνη υψομέτρου. Βάσει του κριτηρίου πυκνότητας σταθμών, καθορίζονται βέλτιστα τρεις σταθμοί για τη λεκάνη του Σαρανταπόταμου. Αυτή η απόφαση ενσωματώνει αξιολογήσεις καταλληλότητας, περιορισμούς και περιορισμούς λόγου υψομέτρων. Οι περιοχές που δεν καλύπτονται από σταθμούς λόγω υψομέτρου είναι ελάχιστες, δικαιολογώντας τον περιορισμένο αριθμό σταθμών.

Τοποθεσία βέλτιστων υδρομετρικών-υδρομετεωρολογικών σταθμών

Το σχήμα 4 απεικονίζει την κατανομή των υδρομετεωρολογικών και υδρομετρικών σταθμών στη λεκάνη απορροής του Σαρανταπόταμου. Το προτεινόμενο δίκτυο περιλαμβάνει τρεις υδρομετεωρολογικούς σταθμούς και δύο στρατηγικά τοποθετημένους υδρομετρικούς σταθμούς, εξασφαλίζοντας λεπτομερή κάλυψη της υδρολογίας της λεκάνης.



Σχήμα 4: Επιλογή θέσεων δικτύου υδρομετεωρολογικών και υδρομετρικών σταθμών. Πηγή: (Theochari et al. 2021)

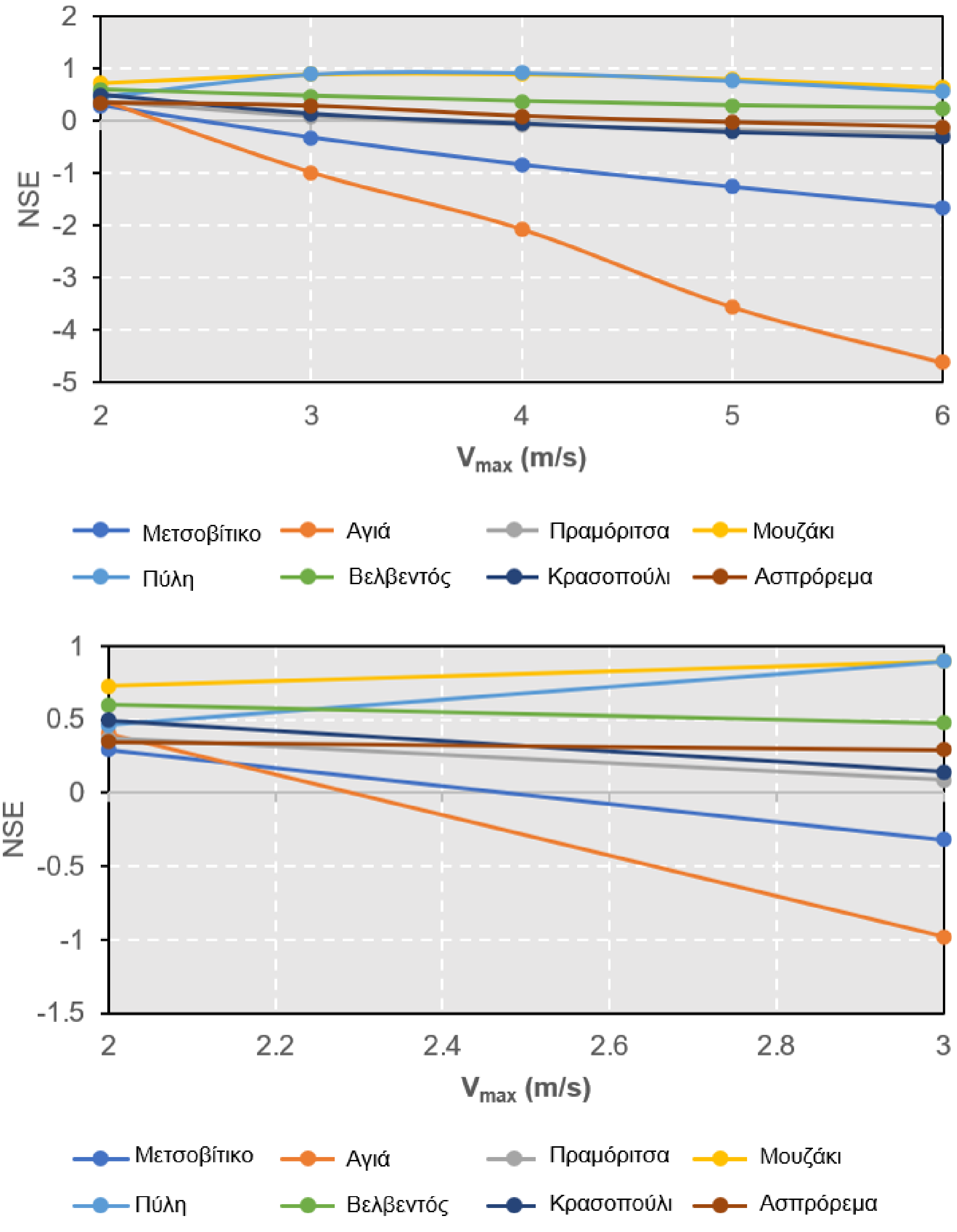
Οι υδρομετεωρολογικοί σταθμοί τοποθετούνται βάσει κριτηρίων που στοχεύουν στην επίτευξη βέλτιστης πυκνότητας και χωρικής κατανομής σε όλη τη λεκάνη, καταγράφοντας μια ποικιλία μετεωρολογικών δεδομένων ουσιαστικά για την ακριβή πρόγνωση καιρού και την ανάλυση του κλίματος. Παράλληλα, οι υδρομετρικοί σταθμοί επιλέγονται για την τεχνική τους ακρίβεια και τη σχετικότητά τους με τις ανάγκες διαχείρισης πλημμυρών της λεκάνης. Για παράδειγμα, ο βόρειος σταθμός, που βρίσκεται κατά μήκος της επαρχιακής γέφυρας Οινόης-Πανακτού, επιλέγεται για την ικανότητά του να καταγράφει δεδομένα ροής που δεν επηρεάζονται από αντίστροφες ροές, βελτιώνοντας την ποιότητα των υδρολογικών μετρήσεων. Ο νότιος σταθμός, κοντά στον δρόμο Οινόης-Μαγούλα και πλησίον των Μάνδρας και Μαγούλας, αναγνωρίζεται συνεχώς σε διάφορα σενάρια ως σημείο υψηλής καταλληλότητας (FS > 0.9), στρατηγικά σημαντικό για την ενίσχυση των προσπαθειών προστασίας από πλημμύρες και λειτουργώντας ως σημείο πρόωρης προειδοποίησης για τις γύρω κοινότητες. Αυτή η στρατηγική τοποθέτησης ενσωματώνει τεχνική ακρίβεια με πρακτικές ανάγκες, εξασφαλίζοντας ότι το δίκτυο παρέχει περιεκτικά δεδομένα για αποτελεσματική διαχείριση και στρατηγικές μετριασμού. Η προσέγγιση αυτή αντανακλά μια ισορροπία μεταξύ ακρίβειας και ευελιξίας, απαραίτητη για την προσαρμογή σε δυναμικές περιβαλλοντικές συνθήκες και την αποτελεσματική διαχείριση των υδατικών πόρων.

Ανάπτυξη Γεωμορφολογικού Μοναδιαίου Υδρογραφήματος

Ανάλυση συστήματος της ταχύτητας εντός υδρογραφικού δικτύου

Η ανάλυση του συστήματος ερευνά την επίδραση της ταχύτητας εντός του υδρογραφικού δικτύου στον υπολογισμό του UH εφαρμόζοντας τη μέθοδο τη μέθοδο των ισόχρονων καμπυλών, παράγοντας οκτώ διακριτά υδρογραφήματα για να αξιολογηθεί η ακρίβεια του μοντέλου σε διάφορα εύρη ταχυτήτων. Για την αξιολόγηση της απόδοσης του μοντέλου, εφαρμόζεται ο δείκτης αποτελεσματικότητας Nash-Sutcliffe (NSE). Το γράφημα στο Σχήμα 5 εμφανίζει τις τιμές NSE σε διαφορετικά εύρη ταχυτήτων, συμβάλλοντας στην αναγνώριση του βέλτιστου εύρους για ακριβείς υδρολογικές προβλέψεις.

Στη λεκάνη του Μετσοβίτικου, οι τιμές NSE κυμαίνονται από 0.293 έως -1.647, κάνοντας εμφανή τη διαφοροποιημένη απόδοση του μοντέλου. Η υψηλότερη τιμή NSE, 0.293, παρατηρείται για μέγιστη ταχύτητα 2 m/s, υποδεικνύοντας ότι ταχύτητες εντός 0.1-2 m/s παράγουν πιο ακριβείς προβλέψεις. Αντίστοιχα, στη λεκάνη της Πραμόριτσας, οι τιμές NSE κυμαίνονται από 0.37 έως -0.234, με την καλύτερη απόδοση, 0.37, επίσης στο εύρος 0.1-2.0 m/s. Στη λεκάνη του Μουζακίου, το μοντέλο δείχνει συνεπή ακρίβεια με τιμές NSE μεταξύ 0.73 και 0.641, βέλτιστες στο εύρος 0.1-4.0 m/s, αν και το εύρος 0.1-2.0 m/s είναι επίσης αποτελεσματικό. Η λεκάνη του Βελβεντού εμφανίζει καλή απόδοση με τιμές NSE από 0.599 έως 0.243, και στη λεκάνη της Πύλης, οι τιμές NSE μεταξύ 0.465 και 0.561 υποδηλώνουν σταθερά καλή απόδοση στο εύρος 0.1-4.0 m/s, με θετικά αποτελέσματα ακόμη και στο εύρος 0.1-2.0 m/s. Στη λεκάνη του Κρασοπουλίου, οι τιμές NSE κυμαίνονται από 0.496 έως -0.301, δείχνοντας πιο ευνοϊκά αποτελέσματα σε χαμηλότερες ταχύτητες, ιδιαίτερα εντός 0.1-2.0 m/s. Η λεκάνη του Ασπρορέματος έχει τιμές NSE από 0.35 έως -0.117, ευνοώντας επίσης χαμηλότερες ταχύτητες για καλύτερη απόδοση του μοντέλου. Τέλος, στη λεκάνη της Αγιάς, οι τιμές NSE κυμαίνονται από 0.405 έως -4.614, με την υψηλότερη στο 0.405 για 0.1-2.0 m/s, παρουσιάζοντας λογική ακρίβεια του μοντέλου σε χαμηλότερες ταχύτητες. Ωστόσο, οι τιμές NSE μειώνονται απότομα με την αύξηση των ταχυτήτων έως -4.614, υποδεικνύοντας σημαντική επιδείνωση της απόδοσης του μοντέλου σε ταχύτερες ροές. Αυτή η ανάλυση επιβεβαιώνει ότι σε αυτές τις λεκάνες, οι χαμηλότερες ταχύτητες συνήθως συνδέονται με υψηλότερες και πιο αξιόπιστες τιμές NSE, υποδηλώνοντας ότι το εύρος ταχυτήτων 0.1-2.0 m/s είναι βέλτιστο για την επίτευξη των πιο ακριβών υδρολογικών προβλέψεων.



Σχήμα 5: Συγκριτική ανάλυση της αποδοτικότητας Nash-Sutcliffe (NSE) για διάφορα εύρη ταχυτήτων.

Regression analysis

Η έρευνα σε 70 από τις 100 λεκάνες απορροής έχει βελτιώσει σημαντικά την κατανόηση της αλληλεπίδρασης μεταξύ των γεωμορφολογικών δεικτών και των χαρακτηριστικών των υδρογραφημάτων. Χρησιμοποιώντας τη μέθοδο των ισόχρονων καμπυλών, η παρούσα έρευνα υπολογίζει το UH για κάθε λεκάνη, προκειμένου να διερευνήσει τις υδρολογικές διεργασίες σε διαφορετικά εδάφη. Η έρευνα χρησιμοποιεί ιστογράμματα για να συνοψίσει τις σχέσεις μεταξύ των γεωμορφολογικών χαρακτηριστικών των λεκανών και των χαρακτηριστικών των υδρογραφημάτων τους. Αυτά τα ιστογράμματα παρέχουν εικόνες για το πώς διαφορετικοί γεωμορφολογικοί δείκτες επηρεάζουν τα χαρακτηριστικά των υδρογραφημάτων, αποκαλύπτοντας μοτίβα και πιθανές συσχετίσεις μέσα στα δεδομένα. Για παράδειγμα, η εξέταση της αιχμής της απορροής (Q_{max}) σε σχέση με γεωμορφολογικούς δείκτες όπως το Rc και το FF δείχνει διαφορετικούς βαθμούς συσχέτισης. Ενώ το Rc και το FF εμφανίζουν διασκορπισμένες ράβδους ιστογραμμάτων που υποδηλώνουν ασθενείς συσχετίσεις, ενώ άλλοι δείκτες εμφανίζουν πιο συγκεντρωμένες κατανομές, υποδεικνύοντας μέτριες συσχετίσεις. Αυτό το μοτίβο διαφοροποιείται καθώς η ανάλυση επεκτείνεται σε άλλα χαρακτηριστικά του υδρογραφήματος όπως το t_{Qmax}, το t_b, το t_{Q50L} και το t_{Q50R}, δείχνοντας συνεπώς ότι μεταβλητές όπως το Cc και το Re υποδηλώνουν ισχυρότερες συσχετίσεις. Περαιτέρω στατιστική ανάλυση, συμπεριλαμβανομένης της παλινδρόμησης, ποσοτικοποιεί αυτές τις σχέσεις, παρέχοντας εξισώσεις που συνοψίζουν τις αλληλεπιδράσεις μεταξύ των χαρακτηριστικών των υδρογραφημάτων και των γεωμορφολογικών δεικτών. Αυτά τα ευρήματα ενισχύουν την κατανόηση των υδρολογικών διεργασιών, βοηθώντας στη διαχείριση των υδατικών πόρων και στην αξιολόγηση του κινδύνου πλημμύρας, καθιερώνοντας μια ποσοτική βάση για την πρόβλεψη της συμπεριφοράς των υδρογραφημάτων από γεωμορφολογικά χαρακτηριστικά.

Validation Regression analysis

Η επαλήθευση της ανάλυσης παλινδρόμησης αποτελεί κρίσιμο στάδιο της μελέτης, εστιάζοντας στις υπόλοιπες 30 λεκάνες από το σύνολο των 100, για να καθορίσει τις πλέον κατάλληλες εξισώσεις παλινδρόμησης για την πρόβλεψη των χαρακτηριστικών των υδρογραφημάτων με βάση τους γεωμορφολογικού δείκτες. Αυτό το στάδιο χρησιμοποιεί στατιστικές μετρήσεις όπως ο Συντελεστής Προσδιορισμού (R^2), το μέσο απόλυτο ποσοστιαίο σφάλμα (MAE), και τη ρίζα της μέσης τετραγωνικής απόκλισης (RMSE) για να αξιολογήσει την απόδοση και την αξιοπιστία κάθε εξίσωσης, εξασφαλίζοντας ακριβείς προβλέψεις σε διάφορα χαρακτηριστικά των λεκανών. Παρακάτω παρουσιάζεται μια συνοπτική περίληψη των αποτελεσμάτων για κάθε παραγόμενη εξίσωση παλινδρόμησης από την ανάλυση, εστιάζοντας στην απόδοση των δεικτών και στις παραγόμενες εξισώσεις για την πρόβλεψη διαφόρων χαρακτηριστικών των υδρογραφημάτων:

T-Polynomial Model για το Qmax

Εξίσωση: $y = 8.6049x^2 + 78.275x + 6.3238$ (1)

- **Όπου**: y (Q_{max}) αντιπροσωπεύει την αιχμή της απορροής του UH (m^3/s), x (T) είναι ο γεωμορφολογικός δείκτης που σχετίζεται με την υφή της απορροής.
- **Απόδοση**: Έχει το χαμηλότερο MAE και RMSE, δείχνοντας υπεροχή στην προγνωστική ακρίβεια για την παροχή αιχμής.

Cc-Linear Model για t_{Q50L}

Εξίσωση: $y = 0.6835x$ (2)

- **Όπου**: y (t_{Q50L}) αντιπροσωπεύει τον χρόνο για το 50% του ανερχόμενου κλάδου του υδρογραφήματος, x(Cc) αντιστοιχεί στη γεωμορφολογική παράμετρο Cc που συσχετίζεται με το δείκτη συμπαγούς.
- **Απόδοση**: Προσφέρει μια ισχυρή ισορροπία υψηλού R^2 και χαμηλών δεικτών σφάλματος, προβλέποντας αποτελεσματικά τον χρόνο για το 50% του ανερχόμενου κλάδου.

Cc-Linear Model για t_{Q50R}

Εξίσωση: $y = 2.4892x$ (3)

- **Όπου:** y (t_{Q50R}) αντιπροσωπεύει τον χρόνο για το 50% του κατερχόμενου κλάδου του υδρογραφήματος, x(Cc) αντιστοιχεί στη γεωμορφολογική παράμετρο Cc που συσχετίζεται με το δείκτη συμπαγούς.
- **Απόδοση**: Διακρίνεται από το χαμηλότερο RMSE και MAE, υποδηλώνοντας εξαιρετική ακρίβεια στην πρόβλεψη του χρόνου για το 50% του κατερχόμενου κλάδου.

Cc-Linear Model για t_{Q75R}

Εξίσωση: $y = 2.0333x$ (4)

- **Όπου:** y (t_{Q75R}) αντιπροσωπεύει τον χρόνο για το 75% του κατερχόμενου κλάδου του υδρογραφήματος, x(Cc) αντιστοιχεί στη γεωμορφολογική παράμετρο Cc που συσχετίζεται με το δείκτη συμπαγούς.
- **Απόδοση**: Εμφανίζει υψηλό R^2 μαζί με το χαμηλότερο RMSE και MAE, δείχνοντας ισχυρή ακρίβεια στην πρόβλεψη του χρόνου για το 75% του κατερχόμενου κλάδου.

Cc-Linear Model για t_{Q75L}

Εξίσωση: $y = 0.9958x$ (5)

- **Όπου:** y (t_{Q75L}) αντιπροσωπεύει τον χρόνο για το 75% του ανερχόμενου κλάδου του υδρογραφήματος, x(Cc) αντιστοιχεί στη γεωμορφολογική παράμετρο Cc που συσχετίζεται με το δείκτη συμπαγούς.
- **Απόδοση**: Δείχνει την καλύτερη προσαρμογή με το υψηλότερο R^2 και τις χαμηλότερες τιμές σφάλματος, προβλέποντας αποτελεσματικά το χρόνο για το 75% του ανερχόμενου κλάδου.

Cc-Linear Model για το t_b (χρόνος βάσης)

Εξίσωση: $y = 9.0156x$ (6)

- **Όπου:** y (t_b) αντιπροσωπεύει τον χρόνο βάσης του υδρογραφήματος, x(Cc) αντιστοιχεί στη γεωμορφολογική παράμετρο Cc που συσχετίζεται με το δείκτη συμπαγούς.
- **Απόδοση**: Επιτυγχάνει το υψηλότερο R^2 και τις χαμηλότερες τιμές σφάλματος μεταξύ των μοντέλων, καθιστώντας το το πιο αξιόπιστο προγνωστικό μοντέλο για το χρόνο βάσης του υδρογραφήματος.

Cc-Linear Model για t_{Qmax} (χρόνος αιχμής)

Εξίσωση: $y = 1.4738x$ (7)

- **Όπου:** y (t_{Qmax}) αντιπροσωπεύει το χρόνο αιχμής του υδρογραφήματος, x(Cc) αντιστοιχεί στη γεωμορφολογική παράμετρο Cc που συσχετίζεται με το δείκτη συμπαγούς.
- **Απόδοση**: Παρά το υψηλό R^2, αυτό το μοντέλο διατηρεί χαμηλό MAE και RMSE, δείχνοντας αξιόπιστες προβλέψεις για το χρόνο αιχμής του υδρογραφήματος.

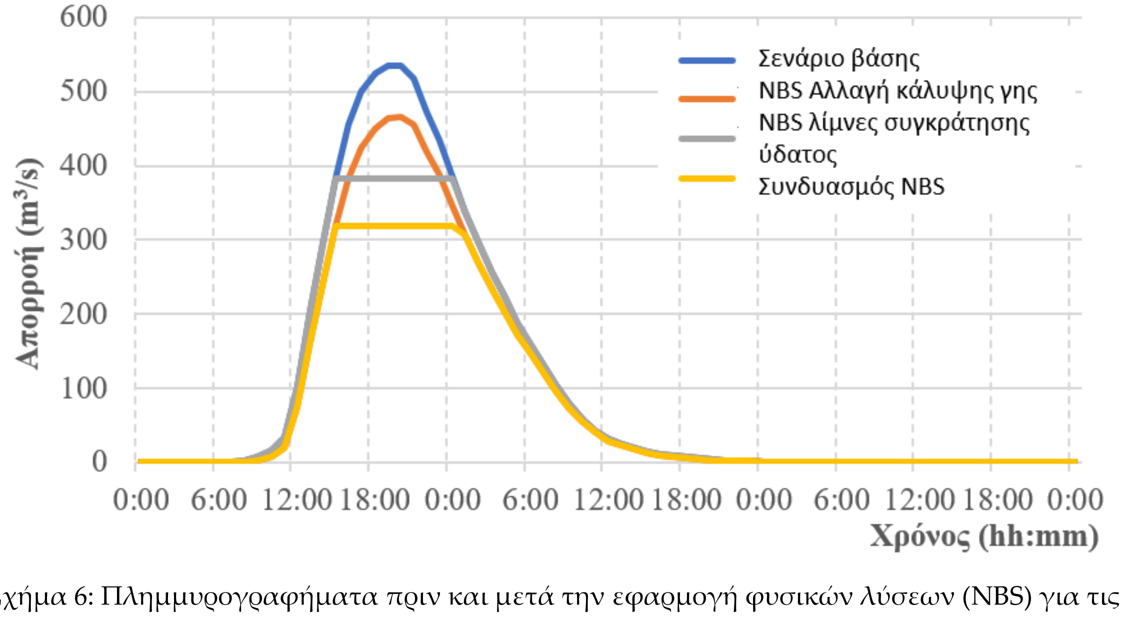
Τα μοντέλα αυτά επιλέγονται με βάση την ικανότητά τους να παρέχουν τις πιο αξιόπιστες προβλέψεις σε διάφορα σύνολα δεδομένων. Η ανάλυση παλινδρόμησης δείχνει μια σημαντική εξάρτηση από τον συντελεστή συμπαγούς (Cc), τονίζοντας τον κρίσιμο ρόλο του στη βελτίωση της ακρίβειας του μοντέλου.

Η επαλήθευση της ανάλυσης παλινδρόμησης τονίζει τη σημασία των υπολοίπων στην αξιολόγηση της καλής προσαρμογής των εξισώσεων παλινδρόμησης. Τα υπόλοιπα, που αντιπροσωπεύουν τη διακύμανση μεταξύ των παρατηρούμενων και προβλεπόμενων τιμών, παρέχουν κρίσιμες πληροφορίες για την ακρίβεια και την αξιοπιστία του μοντέλου. Σύμφωνα με την ανάλυση των υπολοίπων, για το Q_{max}, υπάρχει μια λογική συμφωνία μεταξύ των παρατηρούμενων και των προβλεπόμενων τιμών, με κάποιες διακυμάνσεις. Τα υπόλοιπα υποδεικνύουν προβλεπτική ικανότητα αλλά με αποκλίσεις. Όσον αφορά το t_{Q50R}, παρατηρείται καλή συμφωνία, με ήπια μην ικανοποιητική πρόβλεψη για τις υψηλότερες τιμές. Για το t_{Q50L}, παρατηρείται θετική γραμμική σχέση, με μεταβλητότητα στις προβλέψεις. Για το t_{Q75L}, είναι εμφανής μια θετική γραμμική τάση, με κάποια ακραία σημεία που υποδεικνύουν πεδία για βελτίωση. Για το t_{Qmax}, υπάρχει θετική συσχέτιση αλλά και κάποια διακύμανση. Για το

t_{Q75R}, το μοντέλο αποτυπώνει την τάση με ήπια υπερεκτίμηση. Τέλος, για το t_b, υπάρχει θετική σχέση, αλλά οι προβλέψεις αποκλίνουν περισσότερο καθώς το t_b αυξάνεται. Η ενδελεχής ανάλυση των δεικτών αξιολόγησης του μοντέλου οδηγεί στην επιλογή ακριβών εξισώσεων παλινδρόμησης, βελτιώνοντας την πρόβλεψη των χαρακτηριστικών των υδρογραφημάτων.

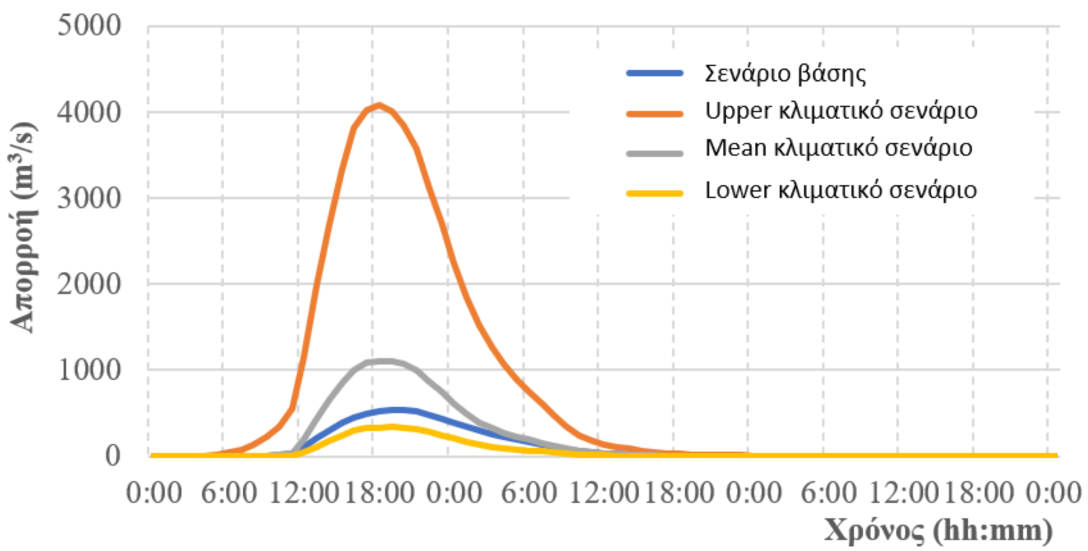
Ανάλυση των λύσεων βασισμένες στη φύση

Η συγκριτική ανάλυση παρουσιάζει τον αντίκτυπο των NBS στην απομείωση των πλημμυρών στη λεκάνη του Σαρανταποτάμου στην Ελλάδα. Τα αρχικά αποτελέσματα δίνουν μια παροχή αιχμής στα 535.7 m^3/s υπό τις τρέχουσες κλιματικές συνθήκες. Η εφαρμογή αλλαγών στην κάλυψη του εδάφους μειώνει την αιχμή σε 465.8 m^3/s, με καθυστέρηση του χρόνου αιχμής στις 20 ώρες και μια αξιοσημείωτη μείωση στον όγκο της πλημμύρας. Η κατασκευή λιμνών αποθήκευσης ύδατος περαιτέρω μειώνει την αιχμή σε 383.3 m^3/s, με επιτάχυνση του χρόνου αιχμής στις 15 ώρες και σημαντική μείωση του όγκου της πλημμύρας. Η συνδυαστική εφαρμογή και των δύο NBS οδηγεί σε παροχή αιχμής 318.5 m^3/s, δείχνοντας μια μείωση κατά 41% σε σύγκριση με το σενάριο πριν την εφαρμογή NBS. Ο όγκος της πλημμύρας μειώνεται σε 99.7 hm^3, γεγονός που αντιστοιχεί σε μείωση 15.3% σε σύγκριση με το βασικό σενάριο. Αξιοσημείωτο είναι ότι η επίτευξη αυτών των αποτελεσμάτων απαιτεί την κατασκευή 250 λιμνών αποθήκευσης. Το Σχήμα 6 απεικονίζει οπτικά τις επιδράσεις των NBS στα πλημμυρογραφήματα, υπογραμμίζοντας το δυναμικό των μέτρων που είναι συμβατά με τη φύση στη μείωση του κινδύνου πλημμυρών.



Σχήμα 6: Πλημμυρογραφήματα πριν και μετά την εφαρμογή φυσικών λύσεων (NBS) για τις τρέχουσες κλιματικές συνθήκες.

Αρχικά, η καταιγίδα σχεδιασμού χαρακτηρίζεται από μέγιστη βροχόπτωση 61.6 mm, με αθροιστικό ύψος 219.5 mm και ένταση 9.1 mm/h. Στο ανώτερο σενάριο, αυτά τα νούμερα αυξάνονται, περιπλέκοντας τη διαχείριση των πλημμυρών, ενώ το κατώτερο σενάριο δείχνει μειώσεις, προσφέροντας μια πιο διαχειρίσιμη προοπτική. Το μέσο σενάριο αποκαλύπτει αύξηση στην παροχή αιχμής και τον όγκο της πλημμύρας, τονίζοντας την ανάγκη για NBS και στρατηγικές προσαρμογής στο κλίμα. Ειδικότερα, το ανώτερο σενάριο δείχνει μια αιχμή στα 4075 m^3/s, και αύξηση 600% στον όγκο της πλημμύρας. Το μέσο σενάριο παρουσιάζει μια αιχμή 1107.4 m^3/s, δηλαδή 79.2% αύξηση. Το κατώτερο σενάριο, ωστόσο, παρουσιάζει μειώσεις και στα δύο μέτρα. Οπτικές συγκρίσεις στο Σχήμα 7 τονίζουν την αξία των NBS στη διαχείριση των διαφορετικών επιπτώσεων του κλίματος στις πλημμύρες. Η υδρολογική ανάλυση επιλέγει τα ανώτερα και μέσα σενάρια για να δοκιμάσει την αποτελεσματικότητα των NBS, εξερευνώντας τις αλλαγές ύστερα από την κάλυψη του εδάφους και την κατασκευή των λιμνών αποθήκευσης ξεχωριστά και σε συνδυασμό. Οι αλλαγές στην κάλυψη του εδάφους μειώνουν την αιχμή σε 3945.5 m^3/s, πτώση 3.7%, διατηρώντας το χρόνο αιχμής στις 18 ώρες.



Σχήμα 7: Πλημμυρογραφήματα πριν και μετά την εφαρμογή φυσικών λύσεων (NBS) για μελλοντικές κλιματικές συνθήκες.

Οι λίμνες αποθήκευσης ως NBS μειώνουν σημαντικά τους κινδύνους πλημμύρας. Η εφαρμογή τους μειώνει την αιχμή σε 2702.9 m^3/s και τον χρόνο αιχμής σε 14 ώρες, με μείωση 75% από την αρχική αιχμή. Η παρέμβαση αποθηκεύει 29.4 hm^3 νερού, και ο συνολικός όγκος της πλημμύρας μειώνεται σε 797.4 hm^3. Για να επιτευχθούν οι στόχοι μείωσης της πλημμύρας, απαιτούνται 2198 λίμνες αποθήκευσης. Οι συνδυαστικές στρατηγικές NBS περαιτέρω μειώνουν την αιχμή της εκροής σε 2567.4 m^3/s. Οι αυτόνομες λίμνες αποθήκευσης βελτιστοποιούν την αποθήκευση νερού σε 30.2 hm^3, μειώνοντας τον συνολικό όγκο της πλημμύρας κατά 7.2% σε 767.55 hm^3. Περίπου 2258 λίμνες απαιτούνται, τονίζοντας τις προκλήσεις στον σχεδιασμό της διαχείρισης πλημμύρας. Στο μέσο κλιματικό σενάριο, η αιχμή μειώνεται σε 999.8 m^3/s, δείχνοντας μείωση 9.73% από 1107.4 m^3/s λόγω αποτελεσματικής διαχείρισης της κάλυψης του εδάφους. Ο χρόνος αιχμής παραμένει στις 18 ώρες, ενώ ο συνολικός όγκος της πλημμύρας μειώνεται κατά 9.25% σε 192.1 hm3. Η εφαρμογή λιμνών αποθήκευσης περαιτέρω μειώνει την αιχμή σε 851.7 m^3/s, με τον χρόνο αιχμής να μειώνεται σε 15 ώρες. Οι λίμνες μειώνουν τόσο το μέγεθος όσο και την ταχύτητα της αιχμής της ροής, αποθηκεύοντας 4.6 hm^3 νερού. Ο τελικός συνολικός όγκος της πλημμύρας προσαρμόζεται σε 207.1 hm3 μετά την κατασκευή των λιμνών, απαιτώντας 340 λίμνες για βέλτιστη μετρίαση. Μια συνδυαστική προσέγγιση περαιτέρω μειώνει την αιχμή σε 755.9 m^3/s με σταθερό χρόνο αιχμής 15 ώρες και χωρητικότητα αποθήκευσης 4.4 hm3, με αποτέλεσμα συνολικό όγκο πλημμύρας 207.3 hm3. Περίπου 327 λίμνες αποθήκευσης προβλέπεται να είναι απαραίτητες για να επιτευχθούν οι στόχοι μείωσης της πλημμύρας.

Η αξιολόγηση των NBS αναδεικνύει ότι ο συνδυασμός της διαχείρισης της κάλυψης του εδάφους με την κατασκευή λιμνών αποθήκευσης μειώνει σημαντικά τις αιχμές και τους όγκους των πλημμυρών. Οι βέλτιστες NBS πρέπει να λαμβάνουν υπόψη συγκεκριμένα χαρακτηριστικά της λεκάνης απορροής, όπως η μορφολογία και η χρήση γης. Η αποτελεσματική σχεδίαση και εφαρμογή των NBS απαιτεί την ένταξη επιστημονικών γνώσεων, τη συμμετοχή των ενδιαφερόμενων μερών και την οικολογική ευαισθησία, ενισχύοντας την ανθεκτικότητα στις πλημμύρες.

<u>Αλλαγή κάλυψης γης σαν φυσική λύση κάτω από μεταβαλλόμενες συνθήκες (πυρκαγιά)</u>

Η παρούσα περιπτωσιολογική μελέτη αξιολογεί τις NBS για την αντιμετώπιση των αλλαγών του εδάφους μετά από πυρκαγιά στη Βόρεια Εύβοια, η οποία επλήγη από σοβαρές δασικές πυρκαγιές τον Αύγουστο του 2021. Οι πυρκαγιές κατέκαψαν πάνω από 507950 στρέμματα, επηρεάζοντας οικοσυστήματα, κοινότητες και την οικονομία. Η μελέτη επικεντρώνεται στις λεκάνες απορροής των ποταμών Ξηροπόταμος και Κηρέας στη Βόρεια Εύβοια (Σχήμα 8) και εξετάζει πώς οι NBS μπορούν να αντιμετωπίσουν τους αυξημένους κινδύνους πλημμύρας μετά τις πυρκαγιές. Δεδομένου του μεσογειακού κλίματος της περιοχής, το οποίο χαρακτηρίζεται από ζεστά καλοκαίρια και κρύους χειμώνες, και ενός μέσου ετήσιου υετού 1200 mm, η έρευνα τονίζει τον ρόλο των NBS στην ενίσχυση της ανθεκτικότητας απέναντι στις περιβαλλοντικές ακρότητες.

Οι Theochari και Baltas το 2022 χρησιμοποιούν MCDM και GIS για να εντοπίσουν ζώνες ευπαθείς σε πλημμύρες σε δύο λεκάνες απορροής, εστιάζοντας στους αυξημένους κινδύνους απορροής στις ανάντη περιοχές. Επέλεξαν πέντε σημεία προσομοίωσης (Σχήμα 8) για να αναλύσουν τις επιπτώσεις των δασικών πυρκαγιών στις πλημμύρες και να αξιολογήσουν την αποτελεσματικότητα των NBS στη διαχείριση των πλημμυρών μέσω αλλαγών στην κάλυψη του εδάφους σε καμένες εκτάσεις. Η μελέτη περιλαμβάνει επίσης συγκρίσεις υδρολογικών αποκρίσεων χρησιμοποιώντας το λογισμικό HEC-HMS για να υπολογίσει πλημμυρογραφήματα πριν και μετά τις πυρκαγιές. Αυτό το λογισμικό μοντελοποιεί τις διαδικασίες βροχής-απορροής χρησιμοποιώντας μοντέλα λεκάνης και μετεωρολογικά μοντέλα, και εφαρμόζει τη μέθοδο Soil Conservation Service (SCS) CN για να υπολογίσει τις απώλειες βροχοπτώσεων που επηρεάζονται από αλλαγές στη χρήση γης και στον τύπο του εδάφους μετά την πυρκαγιά. Ενσωματώνει τη συνολική απορροή με το UH για να εκτιμήσει την απορροή. Η ανάλυση δείχνει ότι οι πυρκαγιές αλλάζουν σημαντικά τα πλημμυρογραφήματα σε κάθε υπολεκάνη, αυξάνοντας την αιχμή της απορροής και μειώνοντας τους χρόνους αιχμής λόγω της μεγαλύτερης αδιαπέρατης επιφάνειας της γης. Οι τιμές CN μετά την πυρκαγιά αυξάνονται, αυξάνοντας τις τιμές των πλημμυρογραφημάτων στις προσομοιώσεις του HEC-HMS. Σημειωτέον, οι αιχμές στις υπολεκάνες 2, 3, 4, και 5 είναι τρεις έως τέσσερις φορές υψηλότερες από τα προ-πυρκαγιάς επίπεδα, με το χρόνο αιχμής να μειώνεται στο μισό στις υπολεκάνες 2, 3, και 4. Η μελέτη καταδεικνύει τη σημασία των NBS, όπως η αναδάσωση, στη μείωση των αυξημένων κινδύνων πλημμύρας λόγω πυρκαγιών. Στη Βόρεια Εύβοια, προκειμένου να εφαρμοστεί η αλλαγή κάλυψης γης σαν NBS, οι περιοχές εντός των λεκανών που μελετώνται και επλήγησαν από τη φωτιά επαναφυτεύτηκαν με δάση "Κωνοφόρα" και "Φυλλοβόλα" για να αποκατασταθούν τα οικοσυστήματα και να μειωθεί η απορροή. Υδρολογικές αναλύσεις στις πέντε υπολεκάνες αξιολογούν την αποτελεσματικότητα της αναδάσωσης από 3.26 km^2 έως 60.52 km^2, με σκοπό τη βελτίωση της διήθησης του νερού και της διαχείρισης της απορροής. Λεπτομέρειες για τα χαρακτηριστικά κάθε υπολεκάνης πριν και μετά την πυρκαγιά αναφέρονται στον Πίνακα 4. Η ανάλυση παρουσιάζει νέα πλημμυρογραφήματα που λαμβάνουν υπόψη τις αλλαγές στην κάλυψη του εδάφους μετά τη φωτιά ως NBS, επιδεικνύοντας πώς αυτές μπορούν να αλλάξουν τις υδρολογικές αποκρίσεις. Οι προσαρμοσμένες τιμές CN προσομοιώνουν συνθήκες που πλησιάζουν ένα αποκατεστημένο οικολογικό σύστημα, δείχνοντας βελτιωμένη διήθηση και μειωμένη δυνατότητα απορροής μετά τα NBS. Τα αποτελέσματα δείχνουν σημαντικές μειώσεις στην αιχμή λόγω των NBS, με μειώσεις που κυμαίνονται από 5.3% στην υπολεκάνη 1 έως 17.8% στην υπολεκάνη 2. Τα NBS επηρεάζουν επίσης θετικά το χρόνο αιχμής, έναν κρίσιμο παράγοντα στη διαχείριση του κινδύνου πλημμύρας, δείχνοντας μια συνολικά βελτιωμένη υδρολογική απόκριση.

Πίνακας 4: Τα γεωμορφολογικά και υδρολογικά χαρακτηριστικά κάθε υπολεκάνης.

Υπολεκάνη		1	2	3	4	5
Εμβαδόν (km^2)		103	14	55	104	160
Καμένη έκταση (km^2)		76	14	55	103	155
CN	**Pre-fire**	80	80	75	75	75
	Pro-fire	88	90	85	85	84
	NBS pro-fire	83	80	75	75	74
Παροχή αιχμής (m^3/s)	**UH pre-fire**	10	3	9.6	11	17
	UH pro-fire	29.5	10	21	28	47
	Πλημμυρογράφημα pre-fire	192	31	84	180	261
	Flood hydrograph pro-fire	505	118	247	446	709
	NBS Πλημμυρογράφημα pro-fire	478	97	210	414	598
Χρόνος αιχμής (hr)	**UH pre-fire**	14	6.5	8.5	20	14
	UH pro-fire	12	4	3.5	9	10
	Πλημμυρογράφημα pre-fire	25	9	14	31	25
	Πλημμυρογράφημα pro-fire	23	6.5	11.5	21	21
	NBS Πλημμυρογράφημα pro-fire	23	6.5	10.5	22	21

Συμπεράσματα και Μελλοντική Έρευνα

Αυτή η ενότητα παρέχει μια σύντομη παράθεση των κύριων ευρημάτων της παρούσας διατριβής σχετικά με τις στρατηγικές διαχείρισης του κινδύνου πλημμύρας. Περιλαμβάνει το βέλτιστο σχεδιασμό των δικτύων υδρομετρικών και υδρομετεωρολογικών σταθμών, την ανάπτυξη ενός GUHμε βάση τα γεωμορφολογικά χαρακτηριστά της κάθε λεκάνης για την οποία δεν υπάρχουν μετρήσεις, και αξιολόγηση δύο NBS για τη διαχείριση των πλημμυρών. Η περίληψη περιγράφει τα δεδομένα, τις μεθοδολογίες, τα αποτελέσματα και τα κύρια συμπεράσματα για κάθε πτυχή.

Σχετικά με το βέλτιστο σχεδιασμό δικτύου υδρομετρικών-υδρομετεωρολογικών σταθμών, η έρευνα τονίζει την επίδραση των κριτηρίων και της ενσωμάτωσης GIS στον σχεδιασμό, επισημαίνοντας τη σημασία των ακριβών γεωχωρικών δεδομένων. Ο WMO καθορίζει τον συνιστώμενο αριθμό σταθμών, επιτρέποντας ευέλικτες θέσεις σε περιοχές ευπαθείς στις πλημμύρες. Ενώ η ασαφής Fussy AHP μειώνει την υποκειμενικότητα, ενδέχεται να μην είναι τόσο αποτελεσματική όσο η AHP σε σενάρια με αυξημένες επιλογές θέσεων. Ωστόσο, μπορεί να είναι αποτελεσματική σε περίπλοκες καταστάσεις. Συνολικά, η μεθοδολογία είναι κοστοαποδοτική και αποτελεσματική για τον εντοπισμό κατάλληλων θέσεων χωροθέτησης σταθμών σε μεγάλες λεκάνες απορροής, υπογραμμίζοντας την αξία των εργαλείων GIS στη διαχείριση πλημμυρών.

Όσον αφορά στην ανάπτυξη του GUHs για λεκάνες χωρίς μετρήσεις, είναι εμφανές ότι οι ταχύτητες εντός υδρογραφικού δικτύου μεταξύ 0.1-2.0 m/s συνεπάγονται σταθερά θετικές τιμές στον δείκτη NSE σε διάφορες λεκάνες, υποδεικνύοντας ακριβείς προσομοιώσεις σε σύγκριση με τα παρατηρούμενα υδρογραφήματα. Αυτό το εύρος ταχυτήτων προτιμάται για περαιτέρω έρευνα. Η μελέτη επίσης ερευνά τη μέθοδο των ισόχρονων καμπυλών σε 70 λεκάνες, παράγοντας σχέσεις μεταξύ των χαρακτηριστικών των υδρογραφημάτων και των γεωμορφολογικών δεικτών, με οπτικές βοήθειες όπως ιστογράμματα που ενισχύουν την κατανόηση αυτών των σχέσεων. Αυτή η προεργασία διευκολύνει την ανάλυση παλινδρόμησης για την πρόβλεψη των χαρακτηριστικών των υδρογραφημάτων με βάση τους γεωμορφολογικούς δείκτες, ειδικά το δείκτη Cc, ο οποίος επηρεάζει σημαντικά την ακρίβεια αυτών των προβλέψεων. Η έρευνα δίνει προτεραιότητα στη μείωση των σφαλμάτων πρόβλεψης (MAE και RMSE) και στη μεγιστοποίηση των τιμών R^2 στην ανάλυση παλινδρόμησης για να εξασφαλίσει αξιόπιστες και ισχυρές προβλέψεις. Μοντέλα όπως το T-Polynomial για το Q_{max} και το Cc-Linear για διάφορους χρόνους των υδρογραφημάτων επιδεικνύουν ισχυρές προβλεπτικές ικανότητες, με την ανάλυση των υπολοίπων να επιβεβαιώνει την εγκυρότητά τους μέσω διαγραμμάτων διασποράς και διαγραμμάτων υπολοίπων που εμφανίζουν στοιχεία ευθυγράμμισης και τυχαία κατανομή γύρω από το μηδέν, δείχνοντας την αξιόπιστη πρόβλεψη των μοντέλων για τα χαρακτηριστικά των υδρογραφημάτων.

Σχετικά με την αποτελεσματικότητα των NBS στη μείωση της παροχής αιχμής, αυτή καταδεικνύεται σαφώς. Υπό τις τρέχουσες κλιματικές συνθήκες, οι αλλαγές στην κάλυψη του εδάφους οδηγούν σε μείωση 9.3% από τη βασική τιμή, ενώ οι λίμνες αποθήκευσης επιτυγχάνουν μια πιο σημαντική μείωση 28%. Ο συνδυασμός NBS οδηγεί στην πιο σημαντική μείωση, περίπου 40.5%. Ομοίως, οι συνολικοί όγκοι πλημμύρας παρουσιάζουν αξιοσημείωτες μειώσεις σε όλα τα σενάρια NBS, με μειώσεις 12.3%, 15.3% και 15.7% για τις αλλαγές στην κάλυψη της γης, τις λίμνες αποθήκευσης και τον συνδυασμό NBS, αντίστοιχα. Τα σενάρια αλλαγής κλίματος περαιτέρω υπογραμμίζουν την επίδραση των NBS, με την εντατικοποίηση των βροχοπτώσεων στο ανώτερο σενάριο να αυξάνει την αιχμή και τον όγκο της πλημμύρας, ενώ το κατώτερο σενάριο δείχνει μειώσεις. Συνολικά, ο συνδυασμός NBS παρέχει τα πιο αποτελεσματικά μέσα για τη μείωση της αιχμής κάτω από διαφορετικές κλιματικές συνθήκες. Η μελέτη στη

Βόρεια Εύβοια εξετάζει τις επιδράσεις των αλλαγών στην κάλυψη της γης μετά την πυρκαγιά στη δυναμική των πλημμυρών και την αποτελεσματικότητα των NBS στην αντιμετώπιση αυτών των επιπτώσεων. Διαπιστώνει σημαντικές αυξήσεις στην αιχμή μετά τη φωτιά σε όλες τις υπολεκάνες, γεγονός που συνδέεται με τις υψηλότερες τιμές CN στις εκτεταμένες καμένες περιοχές. Οι προσομοιώσεις δείχνουν ότι τα NBS μπορούν να μειώσουν την αιχμή και να επιταχύνουν τους χρόνους απόκρισης στις βροχοπτώσεις. Τα ευρήματα τονίζουν τον ρόλο των NBS στην ενίσχυση της ανθεκτικότητας απέναντι σε υδρολογικές ακρότητες σε περιοχές επιρρεπείς σε πυρκαγιές.

Οι προτάσεις για μελλοντική έρευνα που προκύπτουν από τους περιορισμούς αυτής της μελέτης περιλαμβάνουν την εξερεύνηση προηγμένων μεθόδων για την εκτίμηση των βαρών στο σχεδιασμό δικτύου υδρομετρικών-υδρομετεωρολογικών σταθμών καθώς και εφαρμογή της παρούσας μεθοδολογίας σε διαφορετικές χωρικές κλίμακες. Επιπλέον, η ενσωμάτωση εναλλακτικών υδρολογικών δεδομένων, πιθανώς από δορυφορικές παρατηρήσεις, θα μπορούσε να συμπληρώσει τα περιορισμένα δεδομένα που παρέχονται από την ΔΕΗ της Ελλάδας για την ανάπτυξη των GUH. Όσον αφορά στην αποτελεσματικότητα των NBS, ο καθορισμός κριτηρίων σχεδιασμού για τις λίμνες αποθήκευσης απαιτεί μελλοντικές προσπάθειες για την καθιέρωση ενός τυποποιημένου πλαισίου που να λαμβάνει υπόψη την τοπογραφία, τις κλίσεις του εδάφους, και την πυκνότητα του υδρογραφικού δικτύου. Επιπρόσθετα, η έρευνα της επίδρασης της διάβρωσης του εδάφους στην αποτελεσματικότητα των λιμνών αποθήκευσης είναι ουσιώδης για μια περιεκτική κατανόηση και βελτίωση.

1. Introduction

1.1 Floods

Floods are among the most severe natural disasters, especially in the Mediterranean region, due to its unique geographical and climatic characteristics. They affect millions worldwide annually and are classified as natural disasters as defined in Annex A-1-1 of Ministerial Decision 1299/2003. Furthermore, insights from recent catastrophic flooding episodes in the broader region, such as those in 2013, 2014, and 2015 in the plains, and the 2017 floods in Mandra, alongside historical catastrophic flood events in the vicinity, including within the broader Greek territory (e.g., the 2017 Samothrace flood, the 2020 Ianos flooding, and the 2023 Daniel-Elias flooding in the Karditsa region), underscore the urgent need for comprehensive understanding and preparedness measures. The terms "floods" and "flooding" are often confused when discussing high water levels or peak discharges. More specifically, a flood is a temporary event where water levels or discharge exceed a specific threshold, causing it to overflow from its usual boundaries. However, this only sometimes results in flooding. However, flooding occurs when water overflows the regular limits of rivers, streams, lakes, and seas or when heavy precipitation overwhelms drainage systems. This affects areas that are not usually submerged (Douben 2006).

Floods can lead to injuries, loss of life, significant economic burdens, and damage to the environment and cultural landmarks. Within Europe, severe flooding incidents are becoming more frequent. Over the past few years, medium to large-scale flash floods have more than doubled compared to the latter part of the 1980s. In 2020, floods emerged as the predominant form of disaster on a global scale, comprising 62% of all reported incidents (Peng et al. 2024). Their origins are varied, including intense rainfall, rapid snowmelt, hurricane-induced storm surges, and the failure of artificial structures like dams and levees. This diversity in origins underscores the need for a comprehensive understanding of different types of floods, their consequences, and the strategic approaches necessary for mitigating their impact. Their impacts range from disrupting urban transportation and daily routines to damaging homes and infrastructure and causing various forms of pollution (Elsadek et al., 2024). Between 1980 and 2017, hydrological events cost the European Union

(EU) about 166 billion euros, roughly one-third of the total damage caused by climate-related events. If things continue as they are, the yearly flood damage in the EU is predicted to rise from 7 billion euros in the period from 1981 to 2010 to 20 billion euros in the 2020s, 46 billion euros in the 2050s, and 98 billion euros in the 2080s (Ciabatti et al. 2018). Climate change is anticipated to amplify the severity and occurrence of weather-related disasters like flash floods, riverine and coastal flooding, and pluvial floods due to altered precipitation patterns. The Intergovernmental Panel on Climate Change (IPCC) forecasts a rise in the frequency of climate-related extreme events across Europe, causing widespread sectoral impacts and substantial economic losses, with climate change already influencing the intensity and distribution of extreme weather occurrences (Allegri et al. 2024). Floods are a focal point for multidisciplinary research and action, reflecting the urgent need for integrated approaches to mitigate their impacts and enhance community resilience.

1.1.1 Types of floods

River floods or fluvial floods

Regardless of size, rainfall can prompt river floods, often combined with snowmelt (Blöschl et al. 2015). A fluvial event, commonly known as a river flood, occurs when the water level in rivers, lakes, or streams overflows beyond their banks onto adjacent lands. This increase can be caused by excessive precipitation or snowmelt. The effects of a river flood can be significant, affecting smaller rivers downstream and possibly causing dams and dikes to break, flooding nearby areas. According to Zurich Insurance Group, the severity of such floods depends on several factors, including the area's topography, the duration and intensity of rainfall within the river's drainage basin, soil moisture levels, and the influence of climate change on precipitation patterns. In flat terrains, floods tend to rise gradually and persist for days. In contrast, floods can occur rapidly following intense rainfall in hilly or mountainous regions, leading to swift drainage and potential damage from debris flow. These floods, seen in significant rivers like the Danube, Rhine, or Elbe, might occur long after rainfall and persist for months.

Coastal Floods

Coastal floods can arise from seismic activity in the ocean, leading to phenomena like tsunamis, as seen in the 2004 Indonesian and 2011 Japanese events. Additionally, they can result from powerful winds coinciding with exceptionally high tides (i.e. storm surge) (Blöschl et al. 2015). Storm surge, driven by high winds, is the primary cause, posing significant risks during hurricanes or typhoons, notably when coinciding with high tide. These floods can be catastrophic, leading to loss of life and property. Various factors determine the severity of coastal flooding, including the strength, size, speed, and direction of the windstorm and the local topography. Coastal flood models integrate this information with data from past storms to assess the likelihood and scale of storm surges. With rising sea levels due to climate change, coastal cities and communities face increasing vulnerability to such flooding events (Zurich Insurance Group).

Flash Floods

Flash floods occur when there is a sudden, intense surge of water due to heavy rain over a short period, either locally or in nearby elevated areas. Additionally, they can result from a sudden water discharge from an upstream levee or dam. These floods are hazardous and destructive, not only because of the force of the water but also because of the debris carried along in the current. Flash floods have substantially harmed infrastructure such as road networks, agricultural activities and residential areas and have threatened human lives through pedestrian and vehicular accidents. Frequent and devastating flash floods occur more frequently in specific areas of the Mediterranean than in other parts of Europe due to the local climate, characterised by sudden and intense rainfall. The geographical features surrounding the Mediterranean Sea, such as terrain, facilitate the convergence of atmospheric flows at lower altitudes and the upward movement of warm, moisture-laden air masses from the sea, resulting in active convection and an increased risk of flash floods along the coastlines (Gaume et al. 2016).

1.1.2 The 2007/60/EC Flood Directive

After the destructive floods in Central Europe and southern France in 2002, the EU implemented Directive 2007/60/EC of the European Parliament and of the Council on 23 October 2007 to assess and manage flood risks. The Floods Directive (2007/60/EC) aims to create a structure for evaluating and handling flood risks to mitigate the adverse impacts of flooding on human health, economic endeavours, the environment, and cultural heritage within the EU. It involves evaluating flood risks in river basins and coastal areas, identifying high-risk zones, and developing Flood Risk Management Plans (FRMPs) through collaboration among EU member states. These plans are not static but dynamic documents that adapt to new data, evolving climate conditions, and the effectiveness of implemented measures. The assessments were initially published on December 22, 2011, and underwent review by December 22, 2018, and will subsequently undergo review every six years. Since many river basins across Europe span multiple countries, addressing this issue at the EU level proves more effective. This approach enables improved risk evaluation and coordinated actions among EU member states. This directive mandates the latter to evaluate flood risks in coastal regions and river basins by gathering relevant data, including historical flood occurrences and detailed maps depicting boundaries, land uses, and terrain features.

The directive underscores a continuous improvement cycle, mandating updates every six years to ensure that risk management plans remain pertinent and efficacious. Moreover, it promotes a culture of collaboration and shared responsibility, urging member states to cooperate, particularly in managing shared river basins, which are prevalent in Europe. This cooperative approach is essential in a continent where rivers cross political boundaries and flood hazards in one country can significantly affect neighbouring nations.

Members must assess the probability of future significant floods and their potential impacts. More specifically, they are responsible for executing the Floods Directive, concentrating on the comprehensive management of flood risks. This includes appointing local authorities at the river basin level, conducting assessments of flood risks, mapping areas and populations vulnerable to flooding, and implementing measures to reduce risks. Additionally, member states are also responsible for coordinating flood risk management (FRM) across transboundary river basins, avoiding actions that might worsen flood risks in neighbouring countries. Implementation cycles, covering 2016-2021 and 2022-2027, provide guidance for directive execution. The flood-risk maps and the management plans align with the Water Framework Directive (WFD). The implementation of the WFD, alongside this directive and other water-related directives, is guided by a standard implementation strategy aimed at integrating water policies with other EU sectors such as agriculture, transportation, research, and regional development. The Directorate-General for Environment within the Commission holds a key position in supervising the implementation of the Floods Directive. It ensures its incorporation into national laws and its enforcement. Other Directorates-General, like Agriculture and Rural Development and Regional and Urban Policy, contribute to flood-related endeavours, aligning with their duties under the European Structural and Investment Funds (ESI). Concerning ESI Funds programs, member States prepare programming documents for assessment and approval by the Commission. These programs, co-financed by the ESI Funds, may support flood protection initiatives outlined in the Rural Development Programme (RDPs).

EU nations are required to develop maps delineating areas prone to substantial flood risks and outlining various flood occurrence scenarios categorised by probability levels (high, medium, or low). These maps should be first issued by December 22, 2013, with subsequent reviews scheduled every six years. Furthermore, member states must devise FRMPs coordinated at the river basin or coastal district level. The deadline for completing these plans was December 22, 2015, with subsequent reviews every six years. In Greece, compliance with the EU Floods Directive is reflected in national laws and strategies that outline a holistic approach to managing flood risks. The country has made significant investments in conducting thorough flood risk assessments, enhancing infrastructure resilience, and fostering community. Directive 2007/60/EC recognises floods' varied origins and consequences, advocating for a comprehensive approach to FRM. Integrating technical, environmental, social, and economic considerations enhances resilience to floods and mitigates their adverse effects on communities and ecosystems.

1.1.3 Flood risk management

Efforts to tackle flooding increasingly focused on protection and human capability. Physical flood control, such as levees and dams, prevailed from the 1960s to the 1980s. Policies and laws guide FRM across all government levels, often in response to international or national policies. For instance, the US Congress passed the National Environmental Policy Act in 1969, mandating environmental impact assessments for major projects. Similarly, Australia and New Zealand published "FRM in Australia: Best Practice Principles and Guidelines" in 2000. In the UK, Project Appraisal Guidance was issued in 1993, followed by Planning Policy Statement 25 in 2006, both addressing FRM (Sayers et al. 2013). Aligned with European legislation and international literature, FRM has evolved into a multidisciplinary field integrating technical, strategic, and administrative measures to reduce flood impacts and bolster societal resilience. These efforts occur at various scales, including national, regional (basin), provincial (subbasin), and local (subbasin) levels, often in an iterative and occasionally disorderly manner. European legislation towards FRM emphasises collaborative approaches and integrated strategies. It aims to mitigate the impacts of flooding through comprehensive planning, risk assessment, and the promotion of Nature-Based Solutions (NBS). Additionally, it emphasises the importance of community engagement, early warning systems, and sustainable land use practices to enhance resilience against floods.

According to Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, EU countries must develop FRMPs coordinated within river basins or coastal districts. These plans set out goals for FRM, with a primary focus on prevention, such as avoiding construction in flood-prone areas, protection through measures to minimise the likelihood of flooding in specific areas, and preparedness by informing the public about flood risks and appropriate actions to take in the event of a flood. Member States are responsible for developing FRMPs and coordinating proactive measures at the river basin level. FRM comprises two main components: flood risk analysis and assessment on one hand and risk mitigation on the other. In essence, flood risk assessment aims to identify areas with unacceptably high risk and determine where mitigation measures are necessary. Risk mitigation involves suggesting, evaluating, and selecting measures to reduce risks in these identified areas. Hence, conducting a thorough analysis and assessment of flood risk is crucial within the broader risk management framework (Vojtek and Vojteková 2016). FRM involves activities to recognise, evaluate, and alleviate potential flood hazards. The latter concerns the likelihood of a potentially devastating flood event within a given period. FRM employs a holistic approach encompassing (Radulescu et al. 2017):

1. Prevention: Activities aimed at decreasing the likelihood of floods and minimising their consequences. This includes regulating land use in flood-prone areas, enhancing soil absorption, and preserving natural waterways.
2. Protection: Physical barriers such as levees, floodwalls, and surge barriers are implemented to shield vulnerable areas from inundation. Sustainable urban drainage systems (SUDS) and green infrastructure like wetlands and permeable pavements also contribute to managing surface water and mitigating runoff.
3. Preparedness: Emphasis on early warning systems, emergency planning, and public education initiatives. Communities are educated about flood risks and response protocols, ensuring prompt action by individuals and authorities when faced with flooding.
4. Response and Recovery: Focus on post-flood activities, including life-saving measures, assistance to affected populations, and restoration of everyday life. This entails deploying emergency services, conducting cleanup operations, and repairing damaged infrastructure and ecosystems.

1.1.4 Floods and climate change

Climate change alters rainfall patterns and raises sea levels, leading to more frequent and intense flooding events. Due to climate change, the EU experiences more frequent heavy rainfall, storms, and rising sea levels. According to the European Environment Agency (EEA), the overall impact of river floods, precipitation inundations, and coastal flooding within Europe is anticipated to worsen due to increased frequency and intensity of floods at local and regional scales. Current climate patterns and future forecasts indicate notable regional discrepancies in European rainfall patterns. In certain European regions, winter precipitation could increase by over 25% during the last two decades of this century. Alteration in seasonal rainfall, as a percentage, spanning from 2071-2100, compared to the period from 1961-1990 under a two °C global temperature increase.

Throughout Europe, there is an anticipation of increased rainfall intensity. Intense, localised rainfall in specific areas could lead to sudden floods, causing casualties and significant damage, especially in urban areas with insufficient drainage systems. These incidents, becoming more frequent, especially in Mediterranean and mountainous regions, present forecasting challenges due to their reliance on local meteorological dynamics such as topography and wind patterns. Along the Mediterranean shores of the EU, there has been a potential decrease of more than 50% in annual rainfall over the last two decades of this

century. Prolonged dry periods may threaten land stability, leading to erosion and increased runoff during storm events (Ciabatti et al., 2018).
As climate change escalates, observations of infrequent yet severe storms and devastating flash floods underscore the urgent need for innovative FRM strategies. Adaptive management strategies are essential, characterised by flexibility and the ability to adjust to changing conditions. Incorporating traditional engineering methods and NBS, such as restoring floodplains and wetlands, offers a promising approach to enhance resilience and adapt to evolving climate conditions. International collaboration is crucial for tackling global issues like climate change and water management, especially in addressing flood challenges. Global frameworks, agreements, and local innovation are essential for protecting communities and ecosystems from floods in a warming world.

1.2 Hydrometric-Hydrometeorological Stations

To ensure effective and equitable management of water resources and protection against flood-related challenges, the optimal design of hydrometric and hydrometeorological networks is essential. These networks play a crucial role in gathering comprehensive and dependable data, which serves as the lifeblood of hydrological models and is central to the simulation of river flow conditions, especially in rational water resource management (Theochari et al. 2021). A comprehensive network design encompasses various aspects of hydrological data collection. It addresses the hydrological variables requiring observation, determines suitable locations for observations, specifies the frequency of observations, establishes the duration of the observation program, and defines the necessary level of observation accuracy (WMO 2008a). Figure 1-1 illustrates the conceptualisation of this design process as a pyramid.
The precision of hydrometeorological measurements necessitates the establishment of well-structured networks that include both hydrometeorological and hydrometric stations. Interest in designing such networks has been significant since the 1970s (Mishra and Coulibaly 2009). Various techniques have been devised for designing an optimal station network tailored to specific objectives (e.g., Rodda et al. 1969; Fujioka 1986; Sestak 1989; Moss and Tasker 1991; Shepherd et al. 2004; Barca et al. 2008; Baltas and Mimikou 2009; Hong et al. 2016; Kemeridis et al. 2017; Feloni et al. 2018; Theochari et al. 2019; Nguyen et al. 2021; Theochari et al. 2021; Mazi et al 2023; Liu et al 2023; Brunet and Milbrandt 2023; Singhal et al. 2024; Suri and Azad 2024). Moreover, the World Meteorological Organization (WMO) (WMO 2008b; 2010) has thoroughly conducted investigations into developing and disseminating technology for designing hydrometeorological data networks. Geographic

Information Systems (GIS) are crucial in the design of an optimal network. GIS is essential for handling spatial data, analysing it, creating extra thematic layers related to river basin features, displaying data, outlining watersheds, and depicting stream networks (Baltas and Mimikou 2009) through suitable algorithms (e.g., Maidment 2002).

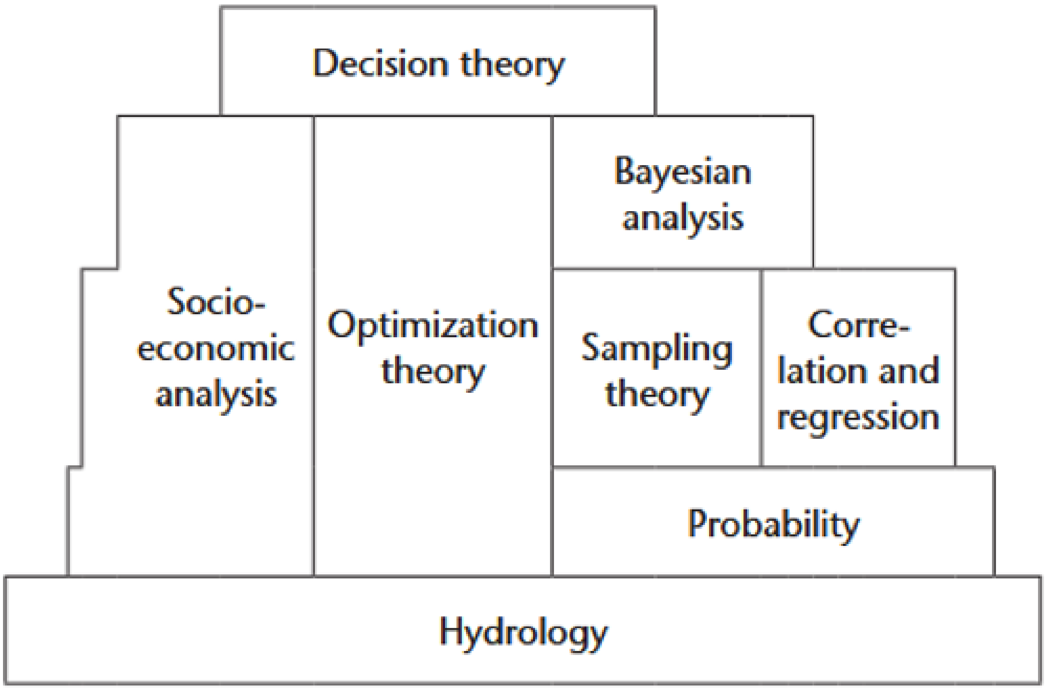


Figure 1-1: The design process of the network
Source: (WMO 2008a)

Unfortunately, the climate crisis extends beyond just a rise in the planet's average surface temperature. The disruption of the atmosphere caused by this rise will result in more frequent and severe extreme weather events, including floods, hurricanes, droughts, and more. According to the United Nations, climate change is worsening natural disasters worldwide. In the past twenty years, extreme weather events have doubled, causing nearly three trillion dollars in total economic losses. Poorer countries are hit hardest, pushing millions into extreme poverty. For example, in 2019, around eighteen million people were forced from their homes due to severe weather linked to climate change.

The EU and the international community are working to tackle climate change and its impacts. They often use satellite technology to manage and respond to crises (https://sentinels.space.noa.gr/) effectively. The United Nations' 2030 Agenda, a global plan for sustainable development, encompasses 17 Sustainable Development Goals (SDGs) to end poverty and foster sustainable development worldwide by 2030. Alongside this agenda, the Sendai Framework for Disaster Risk Reduction (DRR) (2015-2030) emphasises collaborative efforts among nations to mitigate disaster risks, recognising the government's leading role and the involvement of various stakeholders, including businesses. Additionally, the Paris Agreement on climate change underscores the necessity of international cooperation in addressing climate issues and outlines a collective action plan to mitigate global temperature rise. These agreements collectively highlight the need for unified global efforts in tackling pressing environmental and developmental challenges. In this context, the design and enhancement of hydrometeorological-hydrometric networks play a crucial role. More specifically, establishing a dependable warning system requires access to precise information, particularly real-time meteorological and river-level data. With these data, experts can feed them into suitable hydrological and hydraulic models, predicting regions at higher risk of flooding events.

The need to design and install an extensive network of measurement stations is particularly significant in countries like Greece. This is due to the country's unique and complex topography and disparate distribution of water resources resulting from distinct geomorphological and climatic conditions in its eastern and western regions. Greece generally experiences a Mediterranean climate, but it encompasses various climatic variations, ranging from humidity in the northwestern areas to arid conditions in the east. The diverse landscape contributes to the country's division into numerous hydrological basins and several local station networks. Due to the differences in rainfall and water resources across different areas and times in the country, it is essential to record meteorological conditions accurately. This is necessary for effectively managing water resources and sensibly planning infrastructure. Creating a representative network that adequately captures the unique local characteristics is a pressing and challenging task.

Greece has multiple hydrometeorological networks managed by different government agencies, totalling over 1000 stations. These agencies have a significant number of stations under their purview. The Public Power Corporation (PPC) manages around 300 stations in areas with high hydropower potential. The National Meteorological Service (NMS) operates more than 100 stations for weather forecasting purposes. The Ministry of Rural Development and Food oversees 357 stations dedicated to agricultural purposes. Lastly, the Ministry of Environment and Energy is responsible for approximately 270 stations focused on rational water management and network planning. Additionally, various research institutions, universities, and municipalities operate smaller networks. The Department of Water Resources, Hydraulic and Maritime Engineering at the School of Civil Engineering, National Technical University of Athens (NTUA), has set up a network of meteorological and flow measurement stations, along with a Joss-Walvogel RD-69 disdrometer (JWD), to monitor the meteorological and hydrological conditions in Athens. Various organisations also invest in costly infrastructure for meteorological, climatological, and hydrological observations. These entities include departments within the General Secretariat for Public Works, the Academy of Athens, the National Observatory of Athens (NOA)- Institute of Environmental Research and Sustainable Development, the Hellenic Center for Meteorological Applications and Remote Sensing (HELMAS), the Institute of Forest Research, the Center for Renewable Energy Sources and Saving (CRES), municipalities throughout the country with their networks, as well as several research centres and universities with smaller networks.

In the past, researchers like Baltas and Mimikou (2009) demonstrated the ability to optimise the existing national network of about 1041 stations using GIS methods. Feloni et al. (2018) proposed a multicriteria GIS-based approach to optimise a regional station network in Northern Greece. They aimed to develop an up-to-date real-time flood warning system and manage agricultural water resources. Additionally, Theochari et al. 2019, 2021 suggested a method for evaluating suitable sites for installing hydrometric-hydrometeorological stations for various scenarios in West Attica, depending on the network's purpose, whether water resource management or flood warning systems.

In the late 1980s, efforts were made to document meteorological and rainfall stations in Greece fully. At that time, 1613 stations were recorded, with 1066 operational. Today, according to data from the Hydroscope website (http://www.hydroscope.gr/ geodata/), are 2313 stations recorded by central public sector entities producing climate data. Only 1321 stations have some basic time series data, meaning data without interruptions, gaps, or missing observations. However, existing station networks in Greece have several drawbacks, as pointed out by Baltas and Mimikou in 2009. Creating a representative network that adequately captures the unique local characteristics is challenging. Stations are not evenly distributed spatially because each service focuses on different fields for data collection purposes. Consequently, the majority of stations (e.g. >30%) are situated in low-altitude zones (e.g. 0-200 m), with many stations from different services located close to each other. Conversely, only a few stations are positioned at high altitudes, above 1200 m, leading to difficulties in estimating rainfall magnitude in mountainous areas.

The accuracy of available historical records varies due to unsuitable station positions. Numerous criteria must be considered before installing a station in a specific location, including terrain slope, as stations situated on steep slopes may be susceptible to local wind effects. Moreover, the different types of instruments each service uses reduce the reliability of measurements in the network. The wide variety of sensors with varying sensitivities contributes to this issue. Maintaining individual networks for specific purposes increases the cost of everyday activities across different entities. Joint planning and collaboration among national agencies is necessary for effective network operation. These challenges have resulted in establishing and maintaining costly, fragmented, and incompatible technological infrastructures. Many researchers, scientists, and technicians work independently across various agencies, leading to duplication of efforts. Furthermore, there needs to be more collaboration among public authorities, hindering Greece's representation in international research and technological development organisations. Looking ahead, there is a need to develop a unified and reliable national network of stations for sharing multiple data across various applications.

European Directives such as Inspire and Law 3882/2010 aim to integrate observation and recording networks for climate and meteorological data to achieve economies of scale. At the European level, recent Directives for meteorological and environmental data aim to create services that gather and share ecological information across national and European levels while limiting market distortions. With these directives, Europe seeks to maximise public sector information's economic and social benefits, making it available for commercial reuse at minimal cost. The Inspire Directive, adopted in 2010 (Tsiavos 2010), addresses the need for harmonised practices and rules for collecting, producing, and sharing geospatial data. According to Article 18 of Law 3882/2010, the competent authority for the National Infrastructure for Geospatial Information was previously the Cadastral and Mapping Agency of Greece. However, following the enactment of Law 4164/2013, responsibilities were transferred to the National Cadastral and Mapping Company S.A. Since then, the Minister of Environment, Energy, and Climate Change has issued regulatory acts. Collecting reliable hydrometeorological data is essential for water resource management and flood protection. Well-organized networks of hydrometeorological and hydrometric stations are required, especially in countries like Greece, which have rugged terrain and uneven rainfall distribution.

Integrated monitoring networks are crucial in regions prone to flooding, such as the Sarantapotamos River basin in the Attica region. In this context, according to the General Secretariat for Research and Innovation of the Ministry of Development, on September 24, 2020, three telemetry meteorological stations were installed at three critical locations in the Mandra-Magoula-Elefsina drainage basin. This was done as part of the ongoing research activities of the FloodHub service at the Center for Earth Observation and Satellite Remote Sensing (Beyond-EoCenter FloodHub) of the National Observatory of Athens (NOA), funded by the European program SMURBS/ERA-PLANET and in collaboration with the Attica Region and the company METRICA. The stations provide measurements for ten parameters every 5-15 minutes: precipitation, water level, water flow, average surface water velocity, wind direction, wind speed, air temperature, barometric pressure, relative humidity, and solar radiation. The positions of the stations are at the entrance junction of Mandra, at the bend of Agia Ekaterini/Katsimidi stream towards Sures stream, and Sures stream (http://beyond-eocenter.eu/index.php/web-services/floodhub).

To update and modernise the data collection network, the Action Plans of the FRMPs for the country's river basins, formulated by the fourteen River Basin Districts, incorporate a specific measure. This measure involves conducting a technical and economic evaluation to restructure and modernise the current network of meteorological and hydrometeorological stations managed by various entities such as the National Meteorological Service, the Ministry of Environment and Energy, Regional Authorities, the Ministry of Rural Development and Food, the Hellenic Agricultural Organization "DEMETER," and the Public Power Corporation. The objective is to enhance available information, enabling more precise estimation of hydrological parameters and updating rainfall curves/calibration of hydrological models developed under FRMPs.

1.2.1 Hydrometeorological stations

Meteorological observations serve various purposes. They are utilised for real-time weather analyses, forecasts, and severe weather warnings, studying climate patterns, facilitating local weather-dependent operations, supporting hydrology and agricultural meteorology efforts, and conducting research in meteorology and climatology (WMO 2008b). Among the various data parameters, rainfall information is most significant in flood forecasting models (Kar et al. 2015). Precise and reliable spatiotemporal precipitation estimation is indispensable for accurately predicting how a catchment area responds hydrologically (Volkmann et al. 2010). Hydrological data are vital for decision-making, water resource planning, and management. A hydrological data network is a collection of activities to achieve a specific goal or a set of related goals. Hence, the data collection process is essential to provide hydrological information for various purposes, including spatial planning, water resource design, and associated activities, all of which facilitate well-informed decision-making (WMO 2008a).

It is common for a particular hydrological station or gauge to be part of multiple networks if its data serve more than one purpose, which is often the case worldwide. Conversely, a single network may comprise various types of stations or gauges if they all contribute to the network's overarching objective. For instance, a flood forecasting network might incorporate rain and stream gauges (WMO 2008a). Central to the mission is preserving the historical archive of hydrological data, ensuring its continuous updating, and facilitating accessibility for those who require it. This archive is a valuable resource for researchers, policymakers, and experts, helping them understand past trends and patterns in hydrological data. Lastly, by providing accurate and up-to-date information, decision-makers and stakeholders can make informed choices that benefit society. Figure 1-2 illustrates the complete data measurement and transmission cycle, from observing a physical phenomenon, in this case, air temperature, to the reception of data by a user.

Subsequently, the hydrometeorological station network is not just a collection of instruments; it is an essential component in the functioning of society, facilitating the understanding, management, and sustainable use of water resources, thereby ensuring a safer and more resilient future for all. Despite the growing demand for water management, Greece still needs a unified network of such stations. As a result, there needs to be more monitoring of hydrometeorological conditions, with different services using varying measurement tools and not covering the entire country. Also, these services often focus mainly on lower elevations.

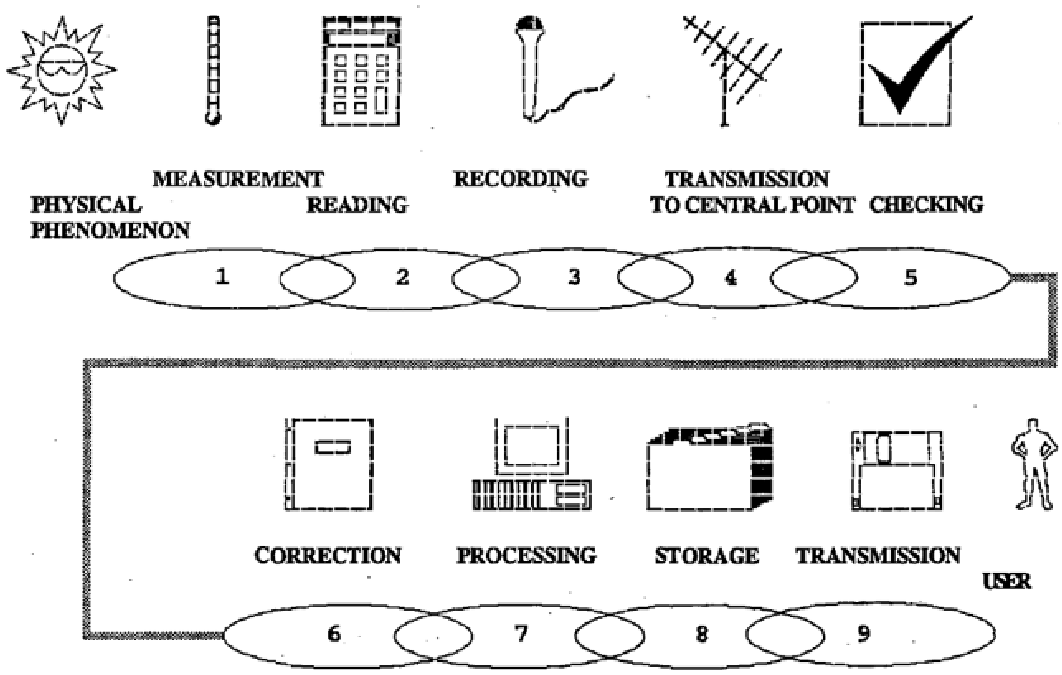


Figure 1-2: Overview of the Nine Principal Links in the Measurement and Transmission Chain for weather information: Source: (WMO 1993)

At the Ministry of Environment and Energy's Directorate of Water Environmental Protection and Management, the National Hydrological and Meteorological Data Bank (NHMDB) is crucial. It serves national operational needs and helps implement relevant European directives on water resources. Presidential Decree 132/2017 assigns the responsibility for operating and updating NHMDB to the Risk Management for Flooding and Droughts & Demand Management Division in collaboration with the Directorate of Geospatial Information. Around three hundred hydrometeorological stations are spread nationwide as mandated by Law 3027/1922. They collect data, which is then digitised and added to NHMDB by the Risk Management for Flooding and Droughts & Demand Management Division (http://www.hydroscope.gr/).

Various techniques have been developed for designing an optimal network of hydrometeorological stations. Sestak 1989 introduced a method to divide areas into smaller parts, each with its weather station. Fujioka 1986 described how to design a meteorological network to minimise analysis errors, especially when considering the risk of wildfires. This way of designing networks uses the ideas from the Kuhn-Tucker theory (Kuhn and Tucker 1951), offering versatility for tackling various challenges. Shepherd et al. 2004 concentrated their efforts on the urban sector of Atlanta, addressing the spatial variability of rainfall. Their approach involved implementing an extensive network of rain gauges alongside satellite data for rainfall estimation. To optimise the location of each station based on a set of criteria, they developed a GIS with a spatial decision support system (DSS). Other scientific studies also investigate the impact of specialised technical equipment. Melvin et al. 2008 propose a network and examine the effect of sensor accuracy on its ability to cover specific areas' spatial variability of surface rainfall.

1.2.2 Hydrometric stations

Stream gauging stations are monitoring devices designed to measure water flow rates in streams and rivers. Streamflow records are vital for assessing surface water availability and its fluctuations over time and space. They play a crucial role in the planning, designing, and managing surface water projects. Additionally, these records are essential for calibrating hydrological models used in flood forecasting. Given the shifting precipitation patterns due to climate change, the role of stream gauge stations becomes increasingly vital for effective water resource management (Joo et al. 2019). The IPCC has highlighted the inadequate spatial accuracy of existing data for assessing recent climate trends and building reliable climate models in developing nations. This limitation challenges watershed management and developing effective prevention, warning, and mitigation strategies. Therefore, there is an urgent need to enhance hydrometric monitoring in these countries to support the design of appropriate water management plans (Peña et al., 2019).

A stream gauging station's general location is contingent upon the hydrometric data record's intended purpose (Hong et al. 2016). According to the WMO 2010, the primary data required for regional flood frequency studies, crucial for designing dam spillways, bridges, and culverts and delineating floodplains, consists mainly of records of annual peak discharge at specific stream locations. Flood events resulting from excessive streamflow pose significant hazards, causing extensive damage. Therefore, accurate records of flood events are crucial for designing infrastructure like bridges, culverts, and flood control systems, as well as for delineating floodplains and issuing flood warnings. Similarly, documenting shallow flow and drought conditions is essential for designing water supply systems. Continuous discharge records obtained from stream-gauging stations are the primary source of streamflow data. These stations are equipped to provide continuous measurements of stage and discharge. Networks of such stations are designed to meet various needs for streamflow information, including assessing total water resources in a geographic area. Moreover, auxiliary networks of partial record stations are frequently utilised to meet specific streamflow information needs at lower costs. However, regional studies focusing on low flow magnitude and frequency are valuable for planning, designing, and managing water supply facilities. A more comprehensive network of low-flow partial record sites should be established to supplement low-flow data, encompassing natural flow streams in the region and incorporating a wide array of drainage, physiographic, and climatological characteristics.

The hydrological principles governing the selection of general station locations within the network should be applied to optimise the cost-effectiveness of data collection (Hong et al. 2016). Once the general area of a stream gauging station has been determined, the next step is to select a specific site for its installation, ensuring compliance with various criteria, many of which are defined by ISO 1100-1:1996 (WMO 2010) and its revision, ISO 18365:2013. Identifying suitable stream gauge locations necessitates an analysis to assess whether potential sites meet specific criteria. Subsequently, a spatial DSS is required for a given set of criteria, coupled with GIS, which offers powerful spatial analysis tools to capture, store, query, analyse, display, and output geographic information (Rikalovic et al. 2014). In particular, for the design of a stream gauging network, international literature recommends various approaches, all of which contribute to identifying appropriate sites that can be further evaluated on-site, thus eliminating the need for time-consuming field surveys for site selection. Figure 1-3 presents an indicative stream gauge site.

Figure 1-3: A stream gauge station
Source: (WMO 2010)

Hong et al. (2016) introduced a GIS-based method to establish an optimal meteo-hydrological station network on the Vu Gia-Thu Bon River basin and develop an up-to-date real-time flood warning system. Additionally, alternative methods involve applying graph theory to optimise low-flow networks by identifying the shortest path (Cui et al. 2009), employing entropy concepts to estimate regional hydrologic uncertainty and information at both gauged and ungauged locations within a basin (Husain 1989), integrating technologies like network analysis for regional information (NARI) and network analysis using generalised least squares (Moss and Tasker 1991), utilising a combined regionalisation and dual entropy-multiobjective optimisation (CRDEMO) approach (Samuel et al. 2013), and following detailed guidelines for stream gauging network design provided by WMO 2010. In conclusion, designing a stream-gauging network is typically a complex multi-criteria analysis problem involving considering various criteria to meet technical, social, economic, and environmental requirements.

In terms of network design, optimisation techniques are increasingly being employed. Finding optimal locations for hydrometric stations can be viewed as a multiobjective optimisation problem where several criteria must be simultaneously met (Li et al. 2012). The advantage of multiobjective optimisation and multicriteria analysis (MCA) lies in their ability to offer feasible solutions across different scenarios (Alfonso et al. 2010). This capability is particularly significant for multiple applications, including soil erosion estimation (e.g., Thomas et al. 2018; Roy 2019; Phinzi and Ngetar 2019) and, more broadly, for surface characteristics and land use planning (e.g., Hill et al. 2009).

Regarding station network design studies, Volkmann et al. (2010) emphasised the need for optimisation methods in regions where guidelines cannot be confidently applied in advance. According to Huang et al. 2011, GIS as a complementary tool in MCA for network design has gained traction in recent years due to advancements in GIS technology, making it an ideal tool for managing extensive spatial data from diverse sources (Karimi et al. 2016). GIS analysis offers a comprehensive set of feasible locations based on geographical criteria, including user requirements, various distances, land use patterns, terrain slope, elevation, and more. GIS's capacity to integrate spatial information makes it a suitable tool for decision-making in problems that involve multiple factors (Shepherd et al. 2004). Approaches to designing a stream gauging network to monitor river flow advocate for utilising GIS capabilities to identify appropriate sites rather than relying on labour-intensive field exploration. Although GIS-based analyses provide significant insights for the strategic placement of hydrometric-hydrometeorological stations, they are complemented by in-situ evaluations, which may be necessary to verify and refine the findings from remote assessments.

1.3 The Unit Hydrograph

1.3.1 Elements of a hydrograph

According to Subramanya 2008, the elements of a hydrograph are the following:

Rising Limb

The steep segment of the discharge line shows a positive slope, signifying a rise in discharge. The increase in flow is signalled by the accumulation of water in channels and across the catchment, initially affected by losses and significant infiltration during the early phases of a storm. As rainfall continues, flow from distant areas gradually reaches the basin outlet while infiltration losses diminish, resulting in a rapid acceleration of runoff during a uniform storm across the catchment.

Lag time

It is the duration between the peak precipitation and peak discharge. A lengthy lag time suggests a slow precipitation process entering the river, while a short lag time indicates a rapid influx of rainfall into the river.

Crest Segment

The crest segment, crucial in hydrographs, contains the peak discharge, which happens when runoff from different catchment areas combines to reach maximum flow at the basin outlet. Peak discharge in large catchments typically follows rainfall cessation, with the time to peak determined by basin and storm features.

Peak rainfall

It is the moment on a flood hydrograph when rainfall reaches its peak.

Falling Limb

It indicates a decrease in discharge. The falling limb, from the point of inflexion at the end of the crest segment to the start of natural groundwater flow, shows water withdrawal from the basin's stored water. It begins at the inflexion point, indicating maximum storage, and is shaped by basin characteristics rather than storm properties.

Base flow

Baseflow refers to the standard volume of water present in a river, even in the absence of a storm event. It fluctuates depending on factors such as the season and the prevailing climatic and drainage basin conditions.

1.3.2 The geomorphological unit hydrograph

Hydrological basin analysis is pivotal in effective water resource management, particularly in addressing hydrology-related challenges like natural hazards like floods. The necessity for innovative tools becomes increasingly apparent in the absence of hydrological monitoring stations, especially in ungauged basins. Forecasting in ungauged basins is indispensable for regions lacking measurement gauges, as emphasised by the research on Prediction in ungauged basins (Singh et al. 2014). An emerging tool that has been attracting considerable attention is the Geomorphological Unit Hydrograph (GUH), which incorporates the geomorphological characteristics of the basin, thereby providing a valuable instrument for comprehending the hydrological response of ungauged basins. Reliance on satellite data and remote sensing technologies has revolutionised hydrological modelling in ungauged basins. These technologies offer unprecedented access to data on precipitation, land use, soil moisture, and evapotranspiration rates across vast and inaccessible areas, providing a more comprehensive understanding of watershed dynamics. Integrating these data sources with advanced computational models has enabled the development of more accurate and reliable predictions for flood forecasting and water resource management, even in the absence of traditional monitoring infrastructure.

In geomorphology, morphometry involves quantifying the form and structure of land features. Metrics related to watershed morphometry offer insights into a river basin's shape and hydrological attributes. Sukristiyanti et al. 2018 suggest that conducting morphometric analysis on a watershed serves multiple purposes. It aids in understanding the watershed's shape and hydrological attributes, enabling researchers to make meaningful comparisons between various watersheds. Using geomorphological metrics in hydrological studies has significantly advanced our understanding of watershed behaviour. These metrics, which include parameters such as basin shape, relief ratio, drainage density, and stream frequency, are crucial for assessing the potential for water accumulation and the rate of runoff in various terrains. Specifically, the basin shape can indicate how quickly a watershed might respond to rainfall events, with more circular basins typically experiencing faster response times due to shorter flow paths. Relief ratio, a measure of the vertical elevation difference within a basin, aids in understanding the potential energy available for driving water flow. High relief ratios often correlate with rapid runoff and potentially higher erosion rates. Drainage density and stream frequency offer insights into the watershed's permeability and the likelihood of surface runoff versus infiltration. A higher drainage density suggests a densely packed river network, leading to quicker runoff and reduced infiltration, impacting flood risks and water availability. By integrating these geomorphological metrics into hydrological models, researchers can more accurately predict flood events and design effective water management strategies, especially in ungauged basins where direct hydrological data is sparse. These metrics not only enhance the resolution of hydrological predictions but also aid in comprehending the geomorphic processes that influence watershed responses to hydrological events.

The Unit Hydrograph (UH) theory, introduced by Sherman in 1932, has been widely utilised in watershed hydrology for over 75 years. Sherman's innovative approach marked the inception of recognising the potential for expanding UH theory, identifying crucial basin characteristics essential for estimating streamflow in ungauged basins based on provided rainfall data, including drainage area, size and shape, watercourse distribution, mainstream slope, valley side slope, and bondage due to obstructions (Singh et al. 2014). GIS has enhanced the ability to analyse and visualise watershed characteristics, facilitating a more detailed and explainable understanding of hydrological processes. GIS technologies enable researchers to overlay various data layers, such as topography, land use, and rainfall distribution, to simulate and predict hydrological responses under different scenarios. This spatial analysis capability is particularly beneficial for designing and implementing effective flood management strategies in ungauged basins, where direct measurements are still being determined.

Synthetic Unit Hydrograph (SUH) methods, particularly those that integrate geomorphological characteristics, are widely utilised in modelling flood hydrographs for ungauged basins. Sherman's groundbreaking concept laid the groundwork for various SUH procedures, with the geomorphological category utilising basin geomorphology as the basis for constructing Instantaneous UH(IUH) (Singh et al. 2014)—previous endeavours by researchers aimed at establishing correlations between model parameters and physically measurable watershed characteristics. In the 1960s, Shreve established a link between geomorphology and flow concentration, underscoring the terrain's impact. This observation suggested a causal relationship between geomorphology and the convergence of runoff (Chen et al. 2019). Expanding upon these fundamental theories, the Geomorphological Instantaneous Unit Hydrograph (GIUH) concept was initially proposed in 1979 by Rodriguez-Iturbe and Valdes, who introduced the 'geomorphologic IUH' (GIUH). This concept was later expanded by Gupta et al. in 1980 to achieve universality in hydrological analysis. The GIUH, interpreted as the travel time probability density function to the basin outlet, represented a groundbreaking integration of quantitative geomorphology and hydrology. This approach, grounded in a geomorphological state transition derived from Strahler’s ordering scheme and numerical experimentation, provided supporting evidence for key assumptions in UH and GIUH theories (Cudennec et al. 2004). Their quantitative understanding opened new avenues for hydrological analysis, particularly for ungauged river basins (Khaleghi et al. 2014).

In enhancing FRM in ungauged basins, the GUH, specifically the GIUH model, have played transformative roles. The GIUH model offers a straightforward and analytical approach to predict the hydrograph's shape and variations in runoff overtime at the basin outlet (Fleurant et al. 2006). Recent advancements in GIUH models, notably the analytical model proposed by Fleurant and colleagues in 2006, demonstrate its ability to accurately forecast hydrograph shapes and runoff variations without requiring calibration. The evolution of the GIUH, from its inception in 1932 by Sherman to the groundbreaking contributions of Rodriguez-Iturbe, Valdés, and Gupta in the late 1970s and early 1980s, signifies a significant shift in hydrological modelling, particularly for ungauged river basins. Integrating information about land shape and climate characteristics has yielded valuable insights into predicting water flow in various hydrological scenarios. Expanding on the fundamental concepts introduced by Rodriguez-Iturbe and Valdes regarding the geomorphologic approach, researchers have devoted efforts to refine outcomes, specifically focusing on simplifying predictions related to the UH. Since the early 1990s, there has been a notable surge in interest regarding the study of hydrology in ungauged basins. In 1992, Jin formulated the Gridded UH utilising a gamma distribution and introduced a method for parameterising the distribution. This method took into consideration various path types and streamflow velocities. Subsequently, between 2003 and 2012, attention was significantly increased towards the Predictions of the Ungauged Basins (PUB) concept, particularly under the auspices of the International Association of Hydrological Sciences (Singh et al. 2014). Grimaldi et al. 2012 contributed to the advancement of GUH models by introducing the Width Function Instantaneous UH with one parameter (WFIUH-1par), a concise model incorporating the width function approach and considering river network flow velocity.

Over the years, research in GIUH development has progressed, as evidenced by several notable studies. In 2012, Ghumman focused on generating direct surface runoff hydrographs for a sizable catchment in the semi-arid region of Pakistan. The research applied the concept of GIUH, dividing the catchment into linear cascades to compute hydrologic parameters essential for Nash's conceptual model. Khaleghi et al. (2014) adopted a spatially distributed strategy by formulating a UH model tailored to ungauged basins. This innovative model relied on spatial analysis functions within a raster GIS, indicating a significant advancement in incorporating spatial considerations into hydrograph modelling. Another significant contribution was made by Kumar in 2015, addressing the issue of inadequate rainfall-runoff data in India, specifically in the Himalayan region. To overcome this challenge, Kumar utilised geomorphological parameters and developed two models, GIUH-I and GIUH-II. These models were based on Horton's stream-order laws and Nash's conceptual model. Bamufleh et al. (2020) contributed substantially to the field by creating a GIUH to predict flash floods in arid regions. Their approach involved utilising equivalent Horton-Strahler ratios, showcasing advancements in enhancing the flexibility and applicability of GIUH concepts. In 2021, Wang et al. proposed a geomorphic UH based on the principle of energy conversion, offering a unique perspective on the development of GIUH. One of the most recent contributions comes from Niyazi et al. 2021, who focused on the Makkah Al-Mukarramah region in Saudi Arabia, aiming to establish connections between morphological and morphological-hydrological parameters to address flood mitigation. Their study was mainly focused on developing formulas and GIUH tailored to the arid environment of Saudi Arabia, marking a departure from traditional equations rooted in the Soil Conservation Service (SCS) UH theory.

The advancement of GUH is crucial for hydrological studies in ungauged basins. Incorporating geomorphological features offers a valuable framework for comprehending hydrological behaviours, particularly in varied terrains such as Greece, where numerous basins face a shortage of comprehensive measurement data. The GIUH methodology, grounded in theoretical principles and real-world implementations, emerges as a promising approach for managing floods and making hydrological forecasts in areas where data availability is limited.

Stream flow data sets play a pivotal role in understanding how watersheds respond to heavy rainfall events, especially in scenarios where FRM is essential. However, the absence of adequate stream flow records has led to the development of models primarily focused on estimating peak stream flows and generating hydrographs based on rainfall events. Utilising UH and IUH models, both gauged and ungauged watersheds can benefit from flood risk assessment and management strategies (Beskow et al., 2018). In gauged watersheds, these models rely on observed rainfall and stream flow data, employing numerical or conceptual modelling techniques such as the Clark and Nash models. Conversely, ungauged watersheds pose a challenge due to the need for more available data. In such cases, geomorphological characteristics of the watershed offer a viable alternative for determining appropriate parameters for synthetic models, known as geomorphological approaches.

Conceptual IUH models traditionally depend on observed rainfall and stream flow records. However, given the inherent difficulties in obtaining such data, geomorphological approaches have been proposed to derive IUHs in watersheds. These approaches utilise the geomorphological features of the watershed to estimate hydrological parameters, offering valuable insights into FRM strategies, even in environments with limited data availability.

The production of the GUH for ungauged basins significantly enhances FRM. This innovative approach utilises geomorphological characteristics to model basins' hydrological response even without direct observational data. By synthesising geomorphological data with rainfall events, GUH models can accurately simulate the timing, magnitude, and distribution of runoff, facilitating the prediction of flood peaks and the overall hydrograph shape. This capacity for accurate prediction is crucial for regions where traditional hydrological data is lacking, enabling authorities and water resource managers to implement pre-emptive measures and design effective flood mitigation strategies.

Furthermore, the adaptability of GUH models to various climatic and topographic conditions makes them invaluable tools in global efforts to reduce the impacts of flooding, particularly in vulnerable communities that traditionally lack the infrastructure for extensive hydrological monitoring. Integrating GUH models into FRM practices signifies a significant transformation towards a more resilient and proactive approach to addressing natural hazards in ungauged basins.

1.4 Nature-Based Solutions

The ongoing increase in global temperature is projected to alter the dynamics of the worldwide water cycle, impacting precipitation patterns and the frequency of both wet and dry weather extremes, as emphasised in the latest report by the IPCC (IPCC 2021). Over time, the severity of climate change has intensified, resulting in more frequent and severe natural disasters, such as floods, which pose significant risks to communities and the environment globally. This escalating impact also exacerbates the strength and frequency of severe storms, further heightening the threat of flooding and causing extensive damage to property and ecosystems (Edamo et al., 2023). Floods are particularly notable among natural hazards due to their profound effects on community development and economic stability (Youssef et al. 2021).

In Europe, river floods rank among the most perilous natural disasters, causing billions of Euros in economic losses annually (Tafel et al., 2022). Approximately 20% of European cities are susceptible to riverine flooding (Santoro et al. 2019). Climate change is expected to heighten the frequency and severity of extreme weather events in the Mediterranean region (European Commission 2019), thereby amplifying the threat of flash floods. The latter, in particular, represents a highly impactful form of natural disaster, resulting in significant human and economic losses and causing widespread damage to infrastructure, residential areas, agricultural lands, and livelihoods across various countries worldwide (Youssef et al., 2015). Naturally occurring disasters like flooding have undeniable consequences, necessitating a comprehensive understanding to develop effective strategies for mitigation and adaptation (Mishra and Nagaraju 2021). Various measures are employed to prevent, mitigate, and manage flood events, including traditional "grey" solutions like dam construction and innovative "green" solutions like river diversions.

In recent decades, governments and investors primarily favoured "grey" solutions, such as dams and embankments, to mitigate flood risks. However, past experiences have demonstrated the limitations of relying solely on these infrastructures, as they often prove inadequate and disruptive to natural processes (Santoro et al. 2019). Recognising that these measures can have significant economic and environmental impacts, prompting the exploration of more natural treatment approaches, where NBS play a crucial role (European Commission 2022). Applying NBS, such as retention ponds and land cover changes, has shown promising results in FRM in the context of river basins. Retention ponds, for instance, are designed to store floodwater temporarily and release it slowly, reducing the peak flow downstream and mitigating flood risks. Similarly, changes in land cover, such as reforestation or converting impermeable surfaces to permeable ones, can significantly increase the soil's capacity to absorb rainfall, thereby reducing runoff and the potential for flooding. These NBS approaches not only help manage flood risks but also contribute to restoring natural habitats and enhancing biodiversity within river basins. Implementing such strategies requires a comprehensive understanding of the local hydrology and ecosystem dynamics, underscoring the importance of integrated water resources management in achieving effective and sustainable flood mitigation outcomes. Recognising the significance of NBS in water management, the European Water Association has emphasised their role in addressing climate change, a prominent challenge across Europe (Beceiro et al. 2022).

The contribution of NBS to FRM extends beyond individual projects to encompass broader strategic planning and policy development. By integrating NBS into FRM frameworks, policymakers can harness the multifunctional benefits of these solutions. This extends beyond reducing flood risks to addressing water quality, climate change adaptation, and enhancing community resilience. For example, the strategic placement of NBS can help reconnect rivers with their floodplains, restore natural flood management (NFM) processes, and reduce the reliance on complex engineering solutions. The transition towards a more holistic approach to FRM underscores the importance of NBS in fostering resilient ecosystems and communities. These can withstand and adapt to the growing challenges posed by climate change.

Recently, NBS has gained traction in FRM as a promising and sustainable method to mitigate vulnerability to and consequences of various types of floods, including riverine floods, flash floods, and storm surges. Various global studies in the literature have explored the implementation of NBS to mitigate flood risk (Potočki et al. 2021; Staccione et al. 2021; Vojinovic et al. 2021; Spyrou et al. 2022; Mashiyi et al. 2023; Inácio et al. 2023; Penny et al. 2023; Unguendoli et al. 2023; Theochari and Baltas 2024 a). The relatively recent emergence of NBS in governance introduces uncertainties regarding its effectiveness and safety, thereby choosing between engineering-based approaches and NBS, a crucial concern in contemporary environmental governance (Liao et al. 2024). The increasing threat of flooding in natural basins necessitates efficient measures to protect downstream settlements.

The European Commission has prioritised NBS as a method to safeguard vulnerable areas by harnessing natural processes and the benefits of ecosystem services. These solutions encompass various measures, such as riparian buffer zones, land cover changes, and alterations to river roughness, aimed at enhancing infiltration and reducing peak discharge while increasing time to peak and minimising the vulnerability of downstream settlements to flooding. Despite advancements, uncertainties persist in implementing NBS effectively, highlighting the importance of promoting their mainstreaming while addressing challenges. This entails addressing the long-term effectiveness and the immediate impacts after implementation and comprehending the role of existing technical knowledge in conjunction with traditional grey infrastructure (Pagano et al. 2019).

Many indigenous populations have recognised the significance of ecosystems in human well-being for centuries. However, utilising nature or ecosystems emerged in the scientific literature in the 1970s. By the 1990s, a more systematic approach was widely adopted, explicitly promoting ecosystem conservation, restoration, and sustainable management (Millennium Ecosystem Assessment 2005). It was in the late 2000s that the term NBS first appeared, marking a significant shift in perspective on how human society interacts with nature. Humans have become agents in transforming and protecting natural ecosystems, turning them into tools for addressing social issues (Cohen-Shacham et al. 2016). The approach, known as NBS, encompasses various terms used interchangeably in hydrometeorological risk reduction. NBS refers to innovative solutions that utilise natural processes and ecosystems to address societal and environmental challenges, offering a departure from traditional methods towards more environmentally sustainable, socially acceptable, and economically viable outcomes (Vojinovic et al. 2021).

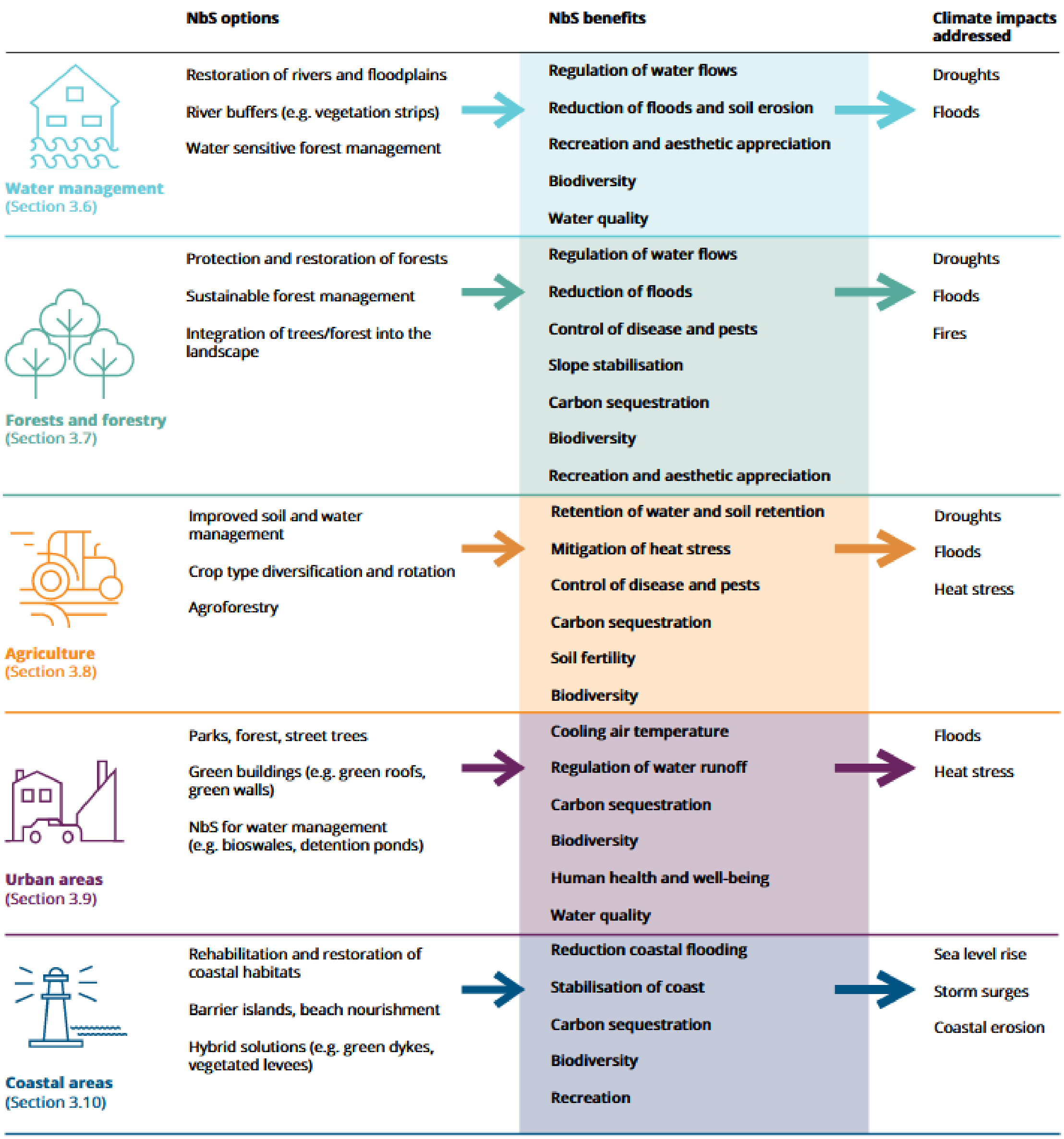
Efforts have been made by the Directorate-General for Research and Innovation of the EU (DG RTD) and the International Union for Conservation of Nature (IUCN) to find the appropriate description for NBS. Based on their programs and agendas, one potential difference in their perspectives is that DG RTD approaches NBS to address significant social challenges such as food security, DRR, and economic issues. IUCN views NBS as an opportunity to study and design based on natural environments, exploring the most fundamental functions of nature, such as how animal and plant organisms and their communities cope with extreme natural conditions (Nesshöver et al. 2017). Below are the definitions from both perspectives for better comparison: IUCN Actions for the protection, sustainable management, and restoration of natural and artificial ecosystems that effectively address social challenges, benefiting both people and nature (Cohen-Shacham et al. 2016). Directorate-General for Research and Innovation- DG RTD Solutions is inspired and supported by nature and is economically efficient while providing environmental, social, and economic benefits and helping build resilience. Such solutions increasingly integrate diverse and varied characteristics of nature into cities and landscapes through locally adapted and systemic interventions (Horizon Europe 2021-2027). In the broader field of NBS, studies indicate a lack of a complete definition, which means that the concept and practical applications of NBS remain unclear (Sowińska-Świerkosz and García 2022).

There is a growing recognition of the global significance of NBS. Research and innovation initiatives at the European level have been launched to tackle challenges and explore options for NBS, particularly concerning climate change adaptation (CCA) and DRR. These initiatives include several research projects under the Horizon 2020 program. NBS are increasingly addressed in various European Commission policy frameworks (e.g., Water Framework Directive, Floods Directive, Action Plan on the Sendai Framework for DRR 2015–2030, EU Strategy on Adaptation to Climate Change, etc.) to address climate change mitigation and adaptation. Various international bodies and panels, such as the Intergovernmental Panel on Climate Change, the Convention on Biological Diversity, the Intergovernmental Panel on Biodiversity and Ecosystem Services, and the United Nations Environmental Programme, also underscore their importance. An NBS coalition was launched at the UN Climate Summit in New York City in September 2019 (Vojinovic et al. 2021). The 26th COP contributes to achieving the Paris Agreement's climate goals by emphasising nature's critical role. Recognising nature's contribution is vital for maintaining global warming below 1.5°C and enhancing resilience to climate impacts. NBS must be central to the COP's official outcomes. Despite significant progress since the Paris Agreement, crucial issues remain unresolved under the Paris Agreement Work Program (PAWP). These include financing climate action and ensuring predictable funding for NBS solutions. Parties need to agree on these matters to achieve climate targets effectively. Limiting global warming to 1.5°C compared to pre-industrial levels is impossible without the vital contribution of natural ecosystems to mitigation and adaptation efforts. Establishing processes within the United Nations Framework Convention on Climate Change (UNFCCC) framework is crucial for further action on nature's role in climate negotiations.

According to the World Wildlife Fund 2021, Guiding relevant entities within the UNFCCC and the Paris Agreement, including the Green Climate Fund (GCF), regarding the adequate financing of NBS solutions is essential for addressing climate change. NBS offers multiple benefits, encompassing environmental, socio-cultural, and economic advantages and addressing challenges like CCA and DRR. These solutions mitigate damage from heavy precipitation and flooding, combat drought, and alleviate heat stress. They also contribute to biodiversity conservation, human health improvement, and climate change mitigation (Figure 1-4) (European Environment Agency 2021).

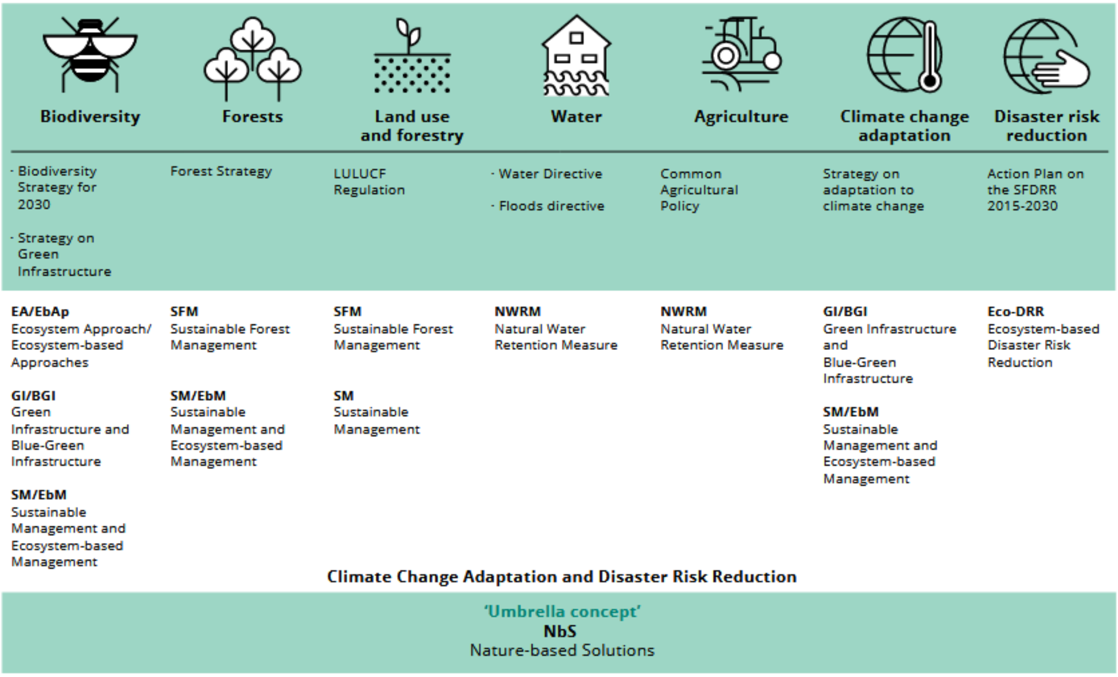
Over recent decades, various terms have emerged in policy and scientific circles to describe approaches utilising nature to address societal challenges. These approaches, called NBS, encompass ecosystem-based approaches, infrastructure-related strategies, and issue-specific approaches like CCA and DRR (European Environment Agency 2021). Figure 1-5 illustrates the interconnections between these concepts and policy areas.

NBS encompass actions inspired by, supported, or copied from nature (European Commission 2020). NBS, drawing inspiration from nature, offer a promising avenue to address social challenges by harnessing natural principles to provide cost-effective solutions that deliver societal, economic, and environmental benefits while enhancing resilience against natural disasters (Unguendoli et al. 2023). These approaches for mitigating risk and adapting in river catchments include Natural Water Retention Measures (NWRM), river space preservation, and strategies for resilient urban areas, such as green infrastructure, green roofs, and decentralised rainwater management (Hartmann et al. 2019). NFM and NWRM fall under the umbrella of NBS. NFM involves modifying, restoring, or utilising landscape features to mitigate flood risk. NWRM encompass various techniques, including interception holding water in and on plants, enhancing plant transpiration, improving soil infiltration, constructing ponds and wetlands, and reconnecting floodplains. These measures aim to decrease the intensity of flow discharge extremes, thereby mitigating flood impacts (Hartmann et al. 2019). NWRM are divided into two main categories by the European Commission (European Commission 2014): direct modifications within ecosystems, like restoring rivers and wetlands, and changes in land use and water management practices in agriculture, forestry, and urban settings, such as afforestation and green roofs, aimed at improving water quality and managing floods.



Source: EEA.

Figure 1-4: Various advantages of nature-based Solutions (NBS)in tackling climate-related risks within specific sectors and thematic domains. Source: (Castellari et al. 2021)



Note: LULUCF, Land use, land use change and forestry; SFDRR 2015-2030, Sendai Framework for Disaster Risk Reduction 2015-2030.

Source: EEA.

Figure 1-5: Relationships between nature-based concepts and EU policy sectors for climate change adaptation (CCA) and DRR. Source: (Castellari et al. 2021)

In flood risk management (FRM), various nature-based measures are consolidated into four flood management practices: flood prevention, enhanced flood conveyance, floodwater retention, riverbank erosion control, and flood impact reduction. These include retention ponds, reforestation or conversion of areas into forested areas, wetland restoration, embankment removal, river meander restoration, land cover change, and river roughness alteration. The restoration of floodplains, in particular, stands out as a nature-based solution (NBS) that has proven effective in mitigating water-related risks (European Commission 2020), providing a sense of security in our flood management strategies.

The concept of "making space for the rivers," introduced by the Dutch Government in response to major floods in the 1990s, shifts from flood defence to flood management, urging citizens to accommodate water. This approach aims to prevent flood damage and offers environmental benefits. Additionally, the European Commission acknowledged in 1999, through the European Spatial Development Programme, that river works and urban development in floodplains exacerbated flood risk (Hartmann et al. 2019). In April 2013, the European Commission approved the EU's CCA strategy. Its objectives include promoting national CCA strategies, financing capacity-building measures through the LIFE program, addressing knowledge gaps, enhancing the Climate-ADAPT online platform, and fortifying existing and future infrastructure against climate change impacts. In December 2014, the

Ministry of Environment and Energy issued a draft of a national adaptation strategy to align with EU priorities in Greece. An assessment of the strategy in 2016, completed in 2018, led to the issuance of Special Report-Directive 25/2018 on floods, observing an increase in flooding intensity in Europe since 1985. Furthermore, on May 27, 2022, the Greek government issued Government Gazette 105A, detailing Law 4936/2022, titled "National Climate Law - Transition to Climate Neutrality and Adaptation to Climate Change, Urgent Provisions for Addressing the Energy Crisis and Protecting the Environment." The law aims to create a coherent framework for enhanced national adaptation and climate resilience, ensuring a gradual transition to climate neutrality by 2050. It establishes interim emission reduction targets for 2030 and 2040, focusing on measures to reduce carbon usage, particularly in the energy production, building, and transportation sectors. Additionally, it mandates the creation of a carbon budget mechanism for vital economic sectors and governance systems, facilitating climate action. Finally, Article 10, paragraph 3, calls for establishing green infrastructure, using NBS for CCA, and absorbing its impacts' costs.

1.5 Research Aim

Floods are one of the most prevalent natural disasters worldwide, affecting millions of people yearly by threatening lives, damaging infrastructure, and disrupting economies. The increasing frequency and severity of flooding events, exacerbated by climate change and urban expansion, underscore the urgent need for advanced FRM strategies. This dissertation is framed against this urgent need, focusing on developing and implementing a comprehensive methodological framework to enhance FRM strategies. The research encompasses various phases, each addressing critical aspects of FRM through integrating innovative methodologies and solutions. It focuses on vulnerable regions, particularly the Sarantapotamos River basin in West Attica, which faces recurrent flooding, posing threats to public safety, infrastructure, and the environment. Unlike previous studies that may have focused on specific aspects or details of flood management, this research adopts a holistic approach that addresses the entire spectrum of FRM by integrating innovative technologies, advanced hydrological models, and sustainable environmental practices.

The first phase introduces a novel methodology for assessing suitable sites for installing hydrometric and hydrometeorological stations. This approach employs a GIS-based multicriteria decision analysis detailed in Theochari et al. (2019, 2021). The methodology is demonstrated through a case study in the Sarantapotamos River basin. This region, characterised by high susceptibility to flooding, particularly in residential areas like Mandra, necessitates establishing a stream flow data collection system and a hydrometeorological station network. The aim is to issue timely flood warnings crucial for public health and socioeconomic well-being while building a comprehensive database for water resource management and ecosystem protection. This research's core objectives encompass utilising a GIS-based multi-criteria decision-making (MCDM) approach to design a hydrometric-hydrometeorological network and assess location scores. Two distinct methods for weighting calculation and diverse handling of hydrometric station criteria underscore the versatility of this approach. Furthermore, the study investigates how selected design criteria and weighting methods influence the identification of suitable locations for hydrometric-hydrometeorological gauge installation. The emphasis on a GIS-based approach for site assessment fills a critical gap in flood management research, where the selection of monitoring locations often needs a more systematic, data-driven foundation. The second phase proposes an innovative approach to hydrological modelling in Greece by developing GUHs tailored for ungauged basins. This approach utilises geomorphological metrics to establish relationships, offering a precise tool for hydrological assessments in data-sparse regions. The research introduces a GUH development method designed explicitly for ungauged basins in Greece, addressing challenges associated with limited data availability. This methodology merges the time-area diagram method with validation regression analysis, thoroughly comprehending hydrograph features and their correlation with geomorphological parameters. By enhancing GUH's applicability and accessibility, particularly in landscapes with scarce hydrological data, this approach holds promise for flood management and hydrological predictions.

The final phase focuses on implementing two NBS, specifically land cover change and construction of retention ponds, within the Sarantapotamos River basin upstream of the Magoula settlement. This stage focuses on evaluating the effectiveness of NBS by analysing flood hydrographs at the basin outlet under present and future climate scenarios. This analysis is pivotal in assessing the performance, efficiency, resilience, and adaptability of NBS under various climate conditions. By assessing pre- and post-NBS conditions, the research provides insights into NBS efficacy in enhancing flood resilience and mitigating hazards to local populations and environments. Ultimately, this research informs decision-makers on selecting and implementing suitable NBS measures to reduce future flood impacts. In the implementation phase focusing on NBS for FRM, the research explores explicitly the application of land cover change as an NBS in areas affected by the catastrophic fire in North Evia in August 2021. It examines land cover alterations over five watershed regions. By exploring land cover modifications and the deployment of NBS in Northern Evia following the devastating fire, this research enriches the fields of hydrological modelling and environmental stewardship, presenting a practical approach for addressing the hydrological changes induced by wildfires.

Finally, the proposed methodological framework aims to present a scalable and effective FRM method tailored to the unique challenges faced by vulnerable regions like the Sarantapotamos River basin. It combines technological advancements, hydrological modelling, and sustainable environmental practices in response to climate change and data scarcity.

1.6 Scientific Significance, Questions, and Originality

The scientific significance of this dissertation extends beyond its immediate application to FRM. It represents a pioneering approach integrating advanced technologies, hydrological modelling, and NBS within a comprehensive framework. This research not only addresses the urgent challenges posed by climate change but also sets new benchmarks in the field of environmental science and hydrology.

A methodology for placing hydrometric stations in Greece has yet to be developed. At its core, the methods for the strategic optimal site selection of hydrometric and hydrometeorological stations using GIS-based multicriteria decision analysis represent a significant advancement in precision and relevance in data collection for flood risk assessment. Unlike traditional methods that may rely on arbitrary or less targeted approaches to station placement, this research ensures that data collection is systematically aligned with the area most vulnerable to flooding. This precision in data gathering enhances the reliability of flood forecasts and the effectiveness of early warning systems, directly contributing to safeguarding lives, infrastructure, and ecosystems. Previous studies have limitations, including the analysis scale and limited description of criteria handling in GIS. In contrast, this analysis operates at a river basin scale, incorporates numerous spatial criteria, and discusses various aspects of the methodology. As evident, many of the outlined criteria require on-site evaluation, highlighting the importance of implementing GIS-based methods for site selection. This process within a GIS environment can suggest potential station locations by considering various criteria, thus minimising the fieldwork required for site selection.

This research also makes a substantial scientific contribution to the development of GUHs tailored for ungauged basins in Greece. The research addresses a critical gap in FRM for regions needing more comprehensive hydrological data by employing geomorphological metrics for hydrological modelling. The calibration and validation of these models with data from the newly established stations improve the accuracy of flood predictions and demonstrate the innovative integration of field data with advanced modelling techniques.

This approach significantly advances the hydrological sciences, offering a replicable model for other data-sparse regions worldwide.
Moreover, implementing NBS within the Sarantapotamos River basin underscores the project's dedication to sustainable flood management practices. By evaluating the efficacy of NBS through detailed hydrological analysis and modelling, this research evaluates the effectiveness of NBS, highlighting their potential in mitigating flood risks while prioritising environmental sustainability. This focus on sustainability represents a shift towards more holistic flood management strategies that consider long-term ecological and social outcomes. Moreover, this analysis is pivotal in assessing the performance, efficiency, resilience, and adaptability of NBS across diverse climatic conditions. Notably, in Greece, the impact of NBS under various climatic conditions remains underexplored, and a methodology for their application has yet to be established. The scientific insights from this analysis contribute to the expanding body of knowledge on NBS, providing valuable guidance for policymakers, environmental agencies, and communities seeking to implement similar strategies.
Overall, the scientific significance of this dissertation lies in its holistic approach to FRM, which bridges the gap between traditional methods and the need for innovative, adaptable solutions in an era of increasing environmental challenges. The research advances the field of hydrological sciences through its methodical integration of data collection, modelling, and application of sustainable solutions, offering a comprehensive framework that can be adapted and applied to other vulnerable regions around the globe. Doing so contributes to the academic discourse on FRM and provides practical insights and tools that can potentially impact communities facing the threat of flooding.

This dissertation addresses three fundamental questions central to advancing FRM. Each primary question is supported by two sub-questions that delve deeper into the specifics of the methodology and its applications.

1. *"Can optimal hydrometric-hydrometeorological station network design through GIS techniques be achieved without on-site evaluation?"*
   - *"Does the formulation of station installation criteria within a GIS environment vary depending on the researcher's perspective, experience, and data availability?"*
   - *"How does the weight estimation method choice affect the resulting suitability map?"*

2. *"What is the significance of establishing empirical relationships between geomorphological metrics and GIUH attributes in enhancing the applicability of hydrological models for FRM in ungauged basins?"*

- *"How does the application of ArcPy and advanced GIS tools in hydrological modelling contribute to the development of GUHs for ungauged basins?"*
- *"How do the geomorphological metrics derived from GIS tools and DEMs inform the development and validation of GUH models?"*

3. *"What role do NBS play in mitigating flood risks, and how can their effectiveness be quantitatively assessed within the framework of an integrated FRM strategy?"*
   - *"How does implementing NBS, such as land cover change and the construction of retention ponds, contribute effectively to FRM?"*
   - *"In what ways can the assessment of NBS effectiveness in flood mitigation contribute to the broader understanding of flood resilience and management in the context of climate change?"*

Finally, the originality of this research is demonstrated by the actions taken in this thesis, which are presented in a list as follows:

- The research introduces a pioneering approach for selecting sites for hydrometric and hydrometeorological stations using GIS-based multicriteria decision analysis, addressing a gap in methodology development in Greece, where no methodology for the siting of hydrometric stations has been established.
- It systematically incorporates a wide range of geomorphological, technical, and spatial criteria in the network design process, showcasing a holistic approach to site selection not extensively covered in previous studies.
- The research introduces an innovative method for developing GUHs tailored to the unique geomorphological characteristics of ungauged basins in Greece, filling a critical gap in hydrological modelling.
- It explores and establishes empirical relationships between various geomorphological metrics and GIUH attributes, contributing to refining hydrological models based on basin-specific characteristics.
- The application of ArcPy for implementing the time-area diagram method represents a significant advancement in utilising Python scripting within GIS for precise hydrological analysis and model development.
- This research emphasises statistical analysis to validate the hydrographs generated, ensure the models' reliability for design purposes, and enhance their practical utility in FRM.
- The research outlines a detailed methodology for implementing NBS, integrating hydrological data and geomorphological insights to assess and enhance flood mitigation strategies' effectiveness under current and future climate change

conditions. However, in Greece, the impact of NBS under various climatic conditions has not been studied, nor has a methodology for their implementation been demonstrated.

1.7 Limitations

Despite this dissertation's innovative approach and comprehensive methodology, it is accompanied by several limitations that merit consideration. One of the limitations concerns the spatial installation of hydrometric stations. The criteria guiding the suitability of locations for hydrometric station installation can be divided into two main categories: general and special criteria based on technical standards outlined in ISO 1100-1 (WMO-No. 1044 2010). These technical standards, as described by Hong et al. 2016, dictate specific conditions for station placement. More specifically, the streambed should be relatively free of aquatic vegetation, while the banks should be stable and of adequate height to withstand flood events and free from brush. Furthermore, a "pool" should form upstream of the station location to ensure accurate stage recording even during extremely low flow conditions and to prevent high velocities at the stream ward end of recording instruments during high flow periods. As evident, these criteria outlined necessitate on-site evaluation. Therefore, selecting these criteria was challenging due to the large scale of the study, encompassing an entire watershed, and as such, they were not chosen for network design.

Regarding the development of GUH tailored for ungauged basins, the calibration and validation of GUHs tailored for ungauged basins rely heavily on the hydrometric data collected. This aspect of the research is particularly challenged by the limited hydrological data provided by the PPC of Greece. The scarcity of data necessitated a more focused system analysis for applying the time-area diagram method, which, while innovative, means that the research outcomes are based on a constrained dataset. This limitation underscores the need to interpret the model outputs carefully and suggests a potential area for future expansion as more comprehensive data becomes available. Moreover, the research needs to be revised to the effectiveness of the NBS. In the loss method, achieving a more precise estimation of the Curve Number (CN) parameter relies heavily on Greek data. Uncertainties in data accuracy and environmental dynamics may limit the effectiveness of the CLC change application as an NBS. Its single-criteria approach overlooks crucial ecological, hydrological, and socioeconomic factors. Integrating these factors is necessary for the application to accurately identify optimal areas for land cover modification, reducing its effectiveness as an NBS. Additionally, one limitation regarding the determination of design criteria for retention ponds is that they are ultimately reliant on the authors' discretion, based on factors such as the topography of the region, the slopes, the density of the river network, and the study of the cross-sections.

1.8 Thesis Structure

This research work is divided into five chapters.

Chapter 1: Introduction

This chapter introduces the thesis. Specifically, it conducts a literature review on FRM, including the design of hydrometric-hydrometeorological station networks, the development of GUHs, and the implementation of NBS. It also introduces the general aim, research questions, and novelty of the thesis.

Chapter 2: Study Area and Data Used

This chapter details the study area, the west Attica region, and the data utilised in this research. It delves explicitly into the area's geomorphological characteristics and hydrometeorological conditions. Lastly, it describes the datasets collected and employed in this study.

Chapter 3: Methodological Framework

This chapter presents the comprehensive methodological framework employed in this thesis for FRM. It is structured into five primary subsections: a) the methodology for designing the hydrometric-hydrometeorological station network, b) the development of GUH, and c) the analysis of NBS implementation. Each subchapter plays a crucial role in the overall methodological framework.

Chapter 4: Results and Discussion

This chapter showcases the outcomes of implementing the aforementioned methods. The results are thoroughly examined, and the key findings are emphasised.

Chapter 5: Conclusions and Future Research

This chapter encapsulates the fundamental discoveries made in this PhD thesis. It encompasses the findings of each subprocess individually, followed by the insights gained from addressing the research questions posed. Additionally, recommendations for future endeavours are provided within this chapter.

2. Study Area and Data Used

2.1 The West Attica Region

This dissertation focuses on the Sarantapotamos River basin, located within the larger region of Attica, specifically in its western part (Figure 2-1). Attica, which encompasses Athens, the nation's capital, is a dynamic centre of cultural, economic, and political activity. Within this dynamic region, West Attica distinguishes itself through a unique blend of natural landscapes and industrial development, contrasting with Central Athens's urban intensity. The Sarantapotamos river basin, spanning Mandra-Eidyllia, Elefsina, and Tanagra, represents a significant hydrological catchment, demonstrating the fragile balance between natural habitats and the expansion of urban development (Figure 2-2). This area, covering 341 km^2, is a significant catchment within West Attica, illustrating the intricate balance between urban expansion and natural ecosystems.

The Sarantapotamos River is nourished by key tributaries like Saint Vlassis, Ksirorema, and Grant Katerini, highlighting the hydrological importance of the basin. A comprehensive stream-gauging network enhances this significance. Urban development is most apparent in the downstream sections of Elefsina, Aspropyrgos, Mandra, and Magoula, where around 70000 people reside, highlighting the urban aspect of the area. In contrast, the upstream regions retain a rural charm with dispersed villages, showcasing a significant difference in settlement patterns. This spatial variation underscores the necessity of this research, particularly in addressing the challenges posed by extreme rainfall events to flood management and environmental sustainability. Additionally, this dissertation presents a case study focusing on a subbasin covering an area of 226 km^2 within the Sarantapotamos river basin, located upstream of the Magoula settlement. It represents a crucial component of the natural infrastructure, integral to implementing NBS for enhancing flood management and ecological sustainability. In Figure 2-1, the study area is depicted, illustrating the boundaries of the studied basins and their location in Greece.

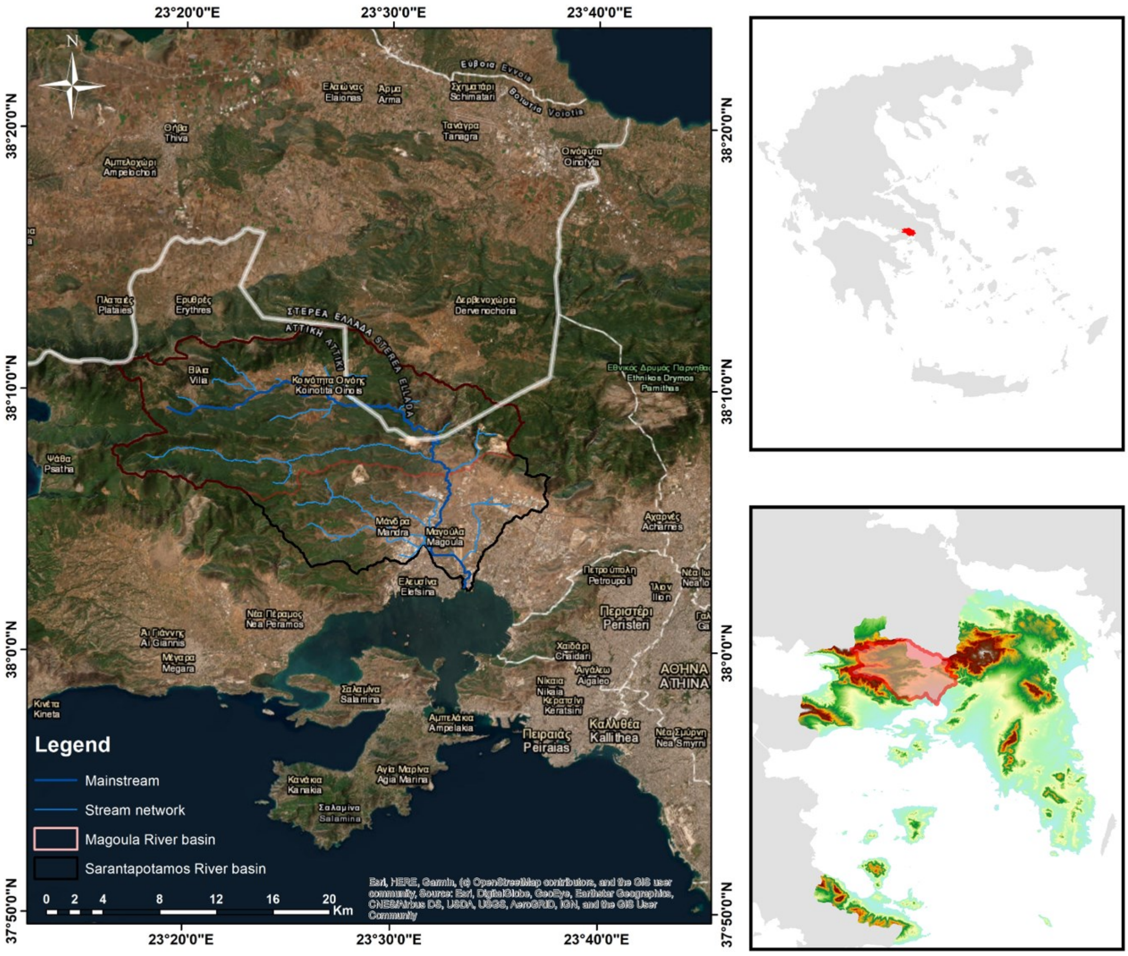


Figure 2-1: The Study area and its location in Greece (upper right panel) and Attica Region (lower right panel)

West Attica presents a unique demographic and economic profile within the Athens metropolitan area. While Attica's wider region houses a significant portion of Greece's population and contributes substantially to its Gross Domestic Product (GDP), West Attica's characteristics are distinctly marked by its industrial activity and population distribution (Bournas 2024). According to the Hellenic Statistical Authority (ELSTAT 2023), the region's economic fabric is particularly notable for its industrial vigour, especially in Aspropyrgos and the Thriasion Plain municipalities. The area between Aspropyrgos and Elefsina is densely populated with industrial facilities specialising in chemicals, metals, and plastics and is home to Greece's largest refinery, the Aspropirgos refinery. Despite hosting only a tiny fraction of Attica's population—1.6%—West Attica's industrial landscape significantly contributes to the economic output. This highlights a contrast of industrial strength within a predominantly urbanised and natural environment. The urbanisation in this area contrasts the pastoral tranquillity of the upstream, where smaller villages punctuate the landscape, demonstrating the diverse human settlement patterns of the region. Moreover, the basin's vulnerability to extreme rainfall events poses significant challenges, underscoring the importance of this study in contributing to flood management and environmental sustainability.

Figure 2-2: Municipalities comprising the Sarantapotamos River Basin

2.1.1 Land cover

Within the Sarantapotamos River basin in West Attica, the 2018 CLC data illustrates a landscape where nature and human activity coexist. The area is a mosaic of various land covers highlighting the ongoing interaction between urban expansion and ecological conservation. In West Attica, discontinuous urban fabric, represented by areas like Aspropirgos and Eleusis, highlights the region's semi-urban character. Despite the dominance of urbanisation in certain areas, West Attica remains predominantly natural, with 89.4% of its territory comprised of agricultural land, grassland, and forests. This starkly contrasts with the urban density in Athens and East Attica's more rural landscapes.

The Sarantapotamos basin itself serves as evidence of this diversity. The region demonstrates a significant urban footprint, with discontinuous urban areas and industrial or commercial zones marking the territory. Specifically, urban fabric covers approximately 8.7 km^2, while industrial and commercial units spread over 19.45 km^2. Infrastructure such as roads, railways, and even an airport contributes to the modified landscape, with areas of 1.48 km² and 5.39 km², respectively. These features underscore the area's role as a hub of human activity and economic development within West Attica. Contrasting sharply with the urban and semi-urban sprawl are the vast tracts of agricultural and forested land, reflecting the basin's rural essence. Agricultural lands, including non-irrigated arable land, vineyards, and olive groves, account for a substantial portion of the region, emphasising the prevalent traditional agricultural practices. These agricultural areas, alongside pastures and complex cultivation patterns, occupy 12.64 km², 1.95 km², 3.36 km², 13.8 km², and 16.8 km², respectively, reflecting the diversity of crops and farming methods employed. Forests and natural vegetation dominate the landscape, with coniferous and mixed forests, natural grasslands, sclerophyllous vegetation, and transitional woodland/shrub covering vast areas of 55.59 km², 9.71 km², 5.72 km², 96.97 km², and 70.37 km² respectively. This extensive coverage of natural land cover types indicates the basin's rich biodiversity and the critical role these areas play in maintaining ecological balance and supporting wildlife. Additionally, sparsely vegetated areas and even burnt areas, spanning 4.94 km² and 0.75 km², respectively, hint at the region's challenges, including the risk of wildfires and the impact of human activities on the natural environment. The Sarantapotamos River basin, with its blend of urban, agricultural, and natural landscapes, presents a complex picture of land cover.

Within the Sarantapotamos River basin in West Attica, the CLC data for 2018 not only illustrates the diverse landscape of the wider basin but also provides detailed insights into the land cover within the subbasin upstream of the Magoula settlement. This area highlights a dynamic interaction between human activities and the natural environment, underscoring the subtle differences in land cover that occur within relatively small geographical areas.

The subbasin has discontinuous urban areas and industrial or commercial zones, though they are on a smaller scale compared to the larger basin. These cover areas of 3.15 km² and 0.46 km², respectively. This indicates a degree of urban and industrial activity, though less intense than in other areas of West Attica. Additionally, mineral extraction sites cover 4.52 km², pointing to specific industrial activities unique to this subbasin. Agricultural practices continue to be a fundamental aspect of land cover, with non-irrigated arable land, vineyards, pastures, complex cultivation patterns and lands principally occupied by agriculture with significant areas of natural vegetation, accounting for 11.53 km², 1.95 km², 5.28 km², 7.56 km², and 6.86 km² respectively. These figures underline the importance of agriculture in the subbasin, supporting the local economy and biodiversity. Forested and natural areas dominate the landscape, with coniferous forests, mixed forests, natural grasslands, sclerophyllous vegetation, and transitional woodland/shrub covering substantial portions of the subbasin. Specifically, these areas measure 50.53 km², 4.99 km², 2.93 km², 64.84 km², and 59.37 km² respectively. This extensive coverage highlights the rich biodiversity of the area and the critical ecological roles these habitats play. Though relatively minor at 1.46 km² and 0.26 km², the presence of sparsely vegetated areas and burnt areas hints at environmental challenges such as the risk of wildfires. The Sarantapotamos River basin, particularly the subbasin upstream of Magoula, presents a complex tapestry of land cover that balances human development with natural preservation. Figure 2-3 depicts the land cover in the Sarantapotamos River basin.

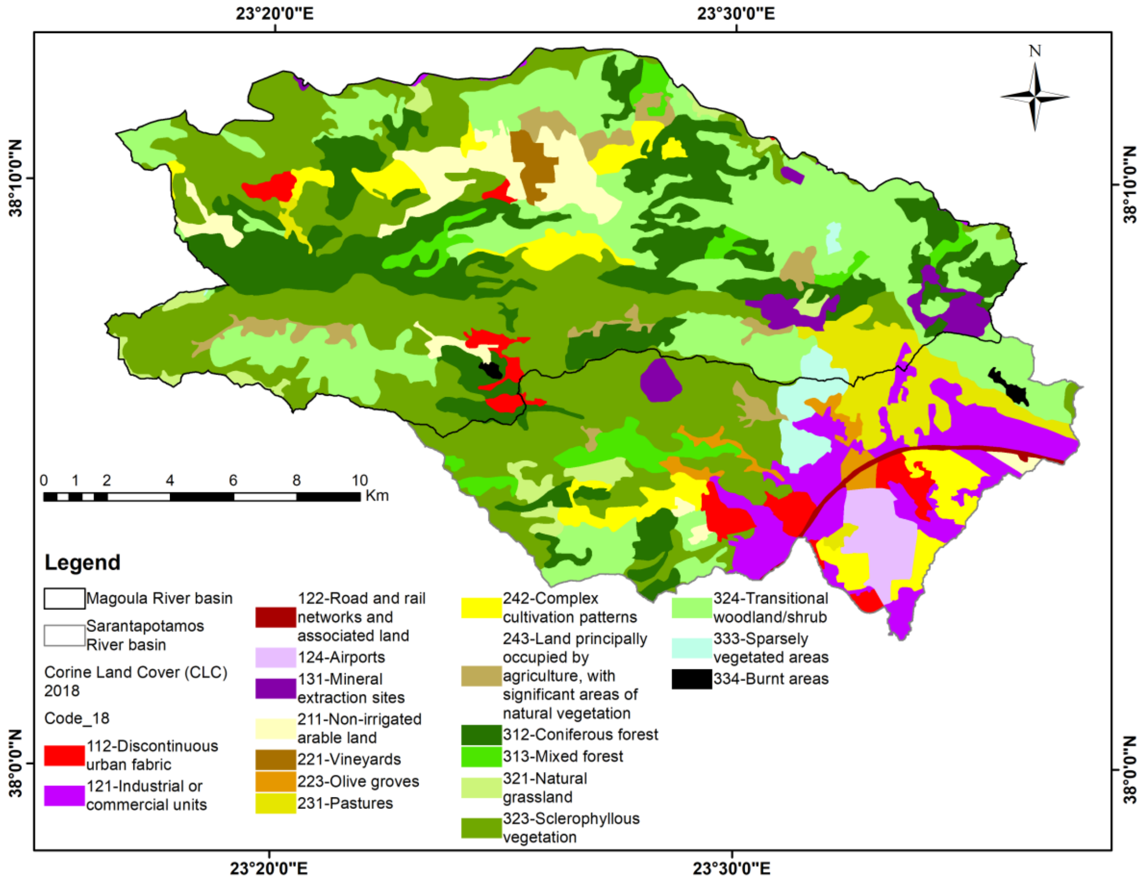


Figure 2-3: Land cover in Sarantapotamos river basin: Data Source: CORINE Land Cover (CLC) 2018

2.1.2 Hydrological scheme - climate

The hydrological scheme and climate of the Sarantapotamos river basin, including the subbasin upstream of the Magoula settlement, are central to understanding the environmental dynamics within this region of West Attica. Mirroring the broader climatic patterns of Athens, the area is enveloped by a Mediterranean climate characterised by mild, rainy winters and hot, dry summers. This climatic backdrop plays a pivotal role in shaping the basin's water resources and ecological conditions.

Athens, and by extension, the Attica region, falls under the Hot-Summer Mediterranean climate classification according to Köppen's system, with exceptions at higher altitudes where conditions verge into Humid continental (Bournas 2024). This classification captures the essence of the region's weather patterns, where summer temperatures average around 30°C, and winter temperatures hover around 10°C. The proximity to the sea moderates the climate, providing cooling breezes during the scorching summer months and contributing to the winter rainfall. Historical records from Elefsina and Tatoi in 1977 mark the European temperature record at 48°C, underscoring the intensity of the summer heat. Rainfall distribution in the region, including the Sarantapotamos basin, varies significantly, with annual averages ranging from 350 mm in lower areas to up to 1000 mm in mountainous regions. The rainfall regime is characterised by convective and stratiform events, leading to higher rainfall intensities during summer convective events, often precipitating flooding, especially after dry periods.

Delving into the specifics of the Sarantapotamos river basin and the subbasin upstream of Magoula, these areas are a testament to the unique Mediterranean climate, each with its own distinct geographical features. The basin and its subbasin, spanning 341 km^2 and 226 km^2 respectively, are embraced by the majestic Mount Pateras, Mount Parnitha, Mount Kitheronas, and Mount Pastra, with elevations ranging from 0.07 to 1271 meters. These mountains not only add to the region's scenic diversity but also significantly influence the local climate and hydrological patterns. The average annual rainfall within the Sarantapotamos basin is 300 to 400 mm, in line with the broader patterns observed in Attica. The area's average annual temperature hovers between 17 and 19 °C (Baltas 2008), creating a mild climate that nurtures a variety of land cover types, from coniferous forests to transitional woodlands and shrub areas.

The hydrological network, enriched by streams such as Saint Vlassis, Ksirorema, and Grant Katerini, is a testament to the basin's capacity to sustain a rich variety of ecological systems (Theochari and Baltas, 2024). The Sarantapotamos River, a defining feature of the basin, meanders through the valley of Inoi and the Thriassion basin, before finally emptying into the bay of Elefsina. The river bifurcates before entering the Thriassion basin into the Pelkes Stream, which crosses the valley of Inoi and the stream of Saint George. The study area currently requires a uniform network of stations. However, in the wake of a devastating flood, a telemetric system consisting of three hydrometeorological stations was established as part of the research initiatives of the FloodHub service, located at the Center for Earth Observation and Satellite Remote Sensing Sciences, NOA (Figure 2-4) (Beyond-eocenter 2021).

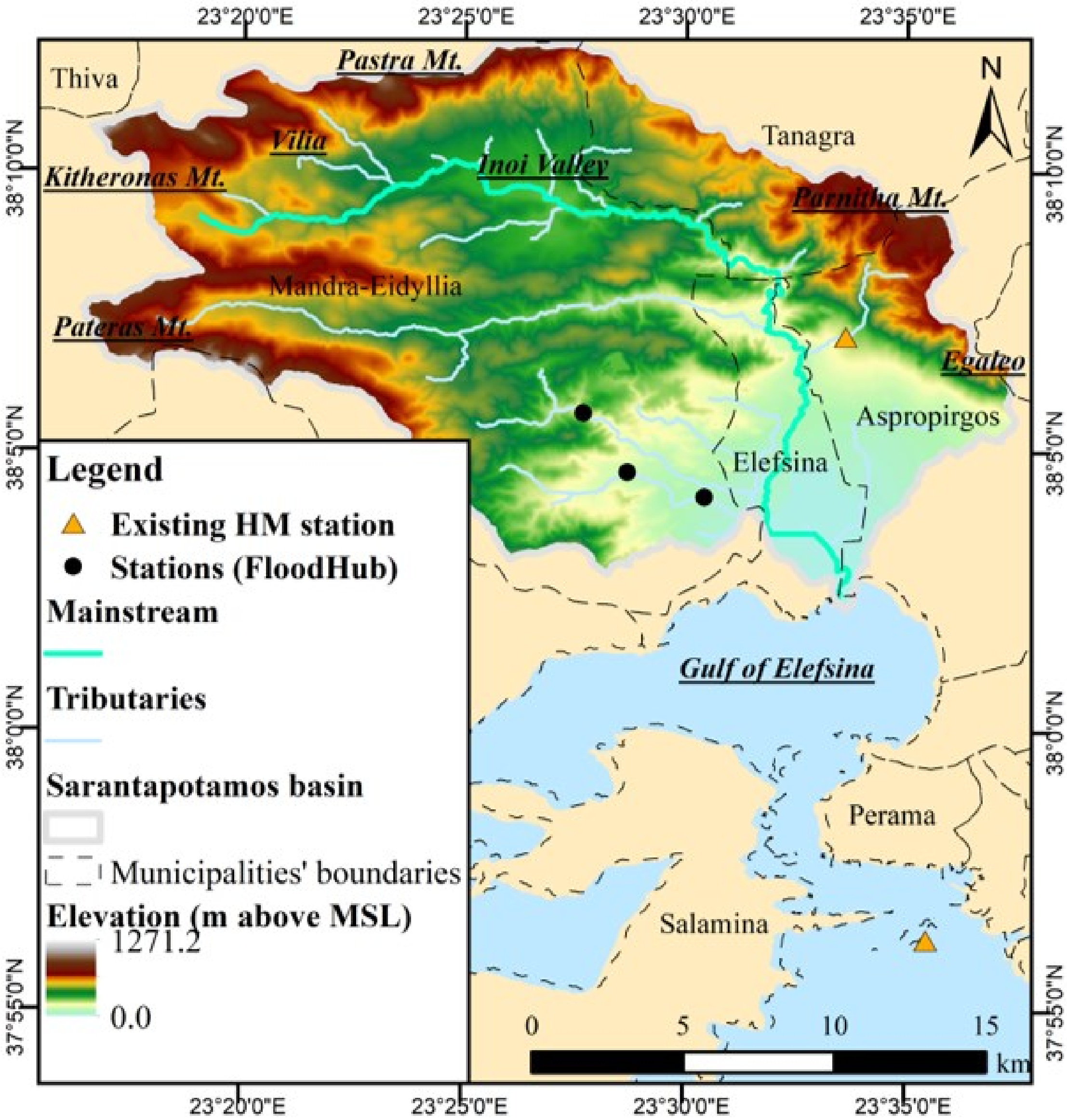


Figure 2-4: Sarantapotamos River basin and existing hydrometeorological stations

Source: (Theochari et al. 2021)

The Sarantapotamos basin's climate and morphology present unique challenges, particularly in managing flood risks. The combination of intense rainfall events and the basin's varied topography frequently results in significant flooding, posing threats to life, property, and infrastructure. This hydrological complexity necessitates a comprehensive understanding and approach to water resource management, emphasising sustainable practices to mitigate flood risks and protect the region's valuable ecological and water resources.

2.1.3 Historical flood events

Western Attica has witnessed several catastrophic flood events over the years. These incidents have shaped the region's environmental management strategies and highlighted the urgent need for advanced planning and infrastructure reinforcement to mitigate future disasters. Here's an expanded overview of the significant flood events:

- Flood Event on January 27, 1996, in Mandra: Despite the low amount of rainfall, totalling 17.30mm, the hydrological event led to an unusually high level of destruction. This occurrence resulted in the tragic loss of two lives, highlighting the potential for catastrophic consequences from even small amounts of rainfall. The event predominantly affected the Thriasio Plain, including Elefsina, Mandra, Magoula, and Megara, causing substantial damage to agro-industrial resources and infrastructures. A major contributing factor was the runoff from the slopes of the Geraneia Mountains, which had been affected by wildfires. This highlights the increased risk associated with changes in flood dynamics following wildfires in the landscape (Kopsida 2019).
- Flood Incident on May 24, 2007, in Fyli: The Fyli municipality, particularly the Zefyri area, experienced a devastating flood following heavy rainfall. Remarkably, the nearest weather station in Tatoi recorded an unprecedented 57.3 mm of rainfall, significantly exceeding records from nearby stations. This event led to widespread damage to properties, flooding of streets, and significant interruptions to vehicular movement, highlighting the region's susceptibility to severe meteorological phenomena (Tsergas 2021).
- Other Significant Historical Floods in the municipality of Fyli: Notably, two other significant floods occurred on January 16, 2013, and October 22, 2013, further emphasising the area's exposure to flood risks and the essential need for strategic flood management practices.
- November 11, 2013, in Fyli: On November 11, 2013, Attica faced significant rainfall, leading to disruptions and damages, especially within its basin, predominantly on the western side. Kamatero, notably along Fyli Avenue between the streets of D. Gounari and Kamatero, experienced considerable damage with road subsidence, causing a halt in traffic. The Fire Brigade was mobilised extensively to rescue individuals from stuck vehicles. The flooding incidents were mainly concentrated in the western regions, near the Agios Georgios stream, with the municipality of Fyli experiencing the highest frequency of these events, representing 36% of the occurrences (Tsergas 2021).
- Severe Rainfall on October 24, 2014, in Mandra and Aspropyrgos: This date marks another intense rainfall event, with the meteorological station in Mandra recording 67mm of rainfall. The deluge led to severe water accumulation on major highways

around Mandra, causing significant traffic issues and highlighting the need for better water management and infrastructure planning.

- Historic Flood on February 27, 2015, in Mandra and Elefsina: This event is remembered for the catastrophic night-time flood that caused significant damage to residential and commercial properties. Unfortunately, the streams surrounding the Kiapha and Agia Aikaterini areas couldn't handle the pressure, leading to water overflowing onto the streets and beginning to traverse the city. The force of the floodwaters was so powerful that it moved vehicles and caused widespread material losses. The community's response included a significant emergency operation focusing on vulnerable individuals and managing the flood's aftermath, which included prolonged power outages. Nearly all recorded incidents (80%) were concentrated in the municipality of Mandra, with a small percentage (12%) in Elefsina. According to the Meteo website (www.meteo.gr), rainfall in Mandra on that specific date reached 26.8 mm.
- November 2017 Floods in Mandra-Eidyllia, Elefsina, and Megara: Over three days, from November 15 to 18, a series of storms triggered by high atmospheric instability caused unprecedented flooding across the region. The storms hit the Mandra area early on November 15th. Meteorological and satellite data analysis revealed that the storms were concentrated around Mount Pateras, causing significant rainfall in the early hours and into the afternoon of that day. This event is particularly noteworthy for the flash floods that affected the hydrological basins of Nea Peramos and Mandra, leading to 25 fatalities. The storm, known for its short duration and highly localised heavy rainfall, is characteristic of Mediterranean flash floods. NASA's IMERG data captured the spatial and temporal aspects of the storm well, indicating that the Mandra area received about 150 mm of rainfall within approximately 7 hours on November 15th, 2017. This amount represents roughly 40% of the area's annual rainfall. The floods resulted in 25 fatalities and extensive material damage, marking it as the third deadliest flood in Attica based on the number of deaths. Approximately 49% of the recorded incidents were in Mandra-Eidyllia, with 27% in the Megara municipality and 7% in Eleusina (Tsergas 2021). Radar measurements from the NOA showed that the "Soures" basin accumulated 194 mm of rainfall, while the "Agia Aikaterini" basin received 153 mm. This phenomenon was so extreme that it suggests a return period of over 500 years (Diakakis et al. 2019). The construction of residential areas and infrastructure along natural water paths significantly exacerbated the flooding, marking this event as a tragic reminder of the critical need for strategic urban planning in flood-prone areas.
- June 26-27, 2018, Floods in Mandra-Eidyllia, Elefsina, and Megara: Just months after the devastating 2017 floods, the area was again hit by intense rainfall, causing significant flooding in Mandra and Nea Peramos. The event prompted over 83 calls for emergency

water pumping, with some areas reporting water levels of up to 2 m. Regarding the distribution of flood incidents across the municipalities of Attica, Mandra-Eidyllia accounted for 68% of the total incidents. Significant percentages were also recorded in the municipalities of Eleusina and Megara, located in western Attica, with 20% and 6%, respectively. As for the rainfall amounts recorded during this flood event, the closest meteorological station in Eleusina measured a total rainfall of 45.8 mm (Tsergas 2021). The repeated occurrence of such floods within a short period emphasises Western Attica's ongoing challenges in flood management and the urgent need for comprehensive, sustainable solutions to reduce future risks.

These historical flood events in Western Attica serve as critical case studies for enhanced environmental management, urban planning, and disaster preparedness strategies. They highlight the region's vulnerability to climatic anomalies and the profound impacts of such events on human life and property, emphasising the urgent need for FRM. The Greek Ministry of Environment, Energy and Climate Change website (http://floods.ypeka.gr) hosts a compilation of historical flood events, where significant flooding incidents in Western Attica are spatially mapped out. According to the information provided by the Ministry of Environment and Energy in Figure 2-5, these pivotal floods are represented, showcasing their geographical distribution across the region.

Figure 2-5: Historical flood events in Western Attica

2.2 Data Used

2.2.1 Unit hydrographs and drainage basin boundaries

This section emphasises collecting and preparing hydrological data essential for constructing GUHs. Specifically, the research utilised a set of individuals UH procured from the Greek PPC. These hydrographs represent a crucial dataset for the study, providing a foundation for analysing and modelling hydrological behaviours in ungauged basins across the Greek landscape.

A total of 14 UH were initially acquired from the PPC, covering a range of durations, including half-hour, one-hour, and two-hour intervals. The variability in the formats of these hydrographs presented a unique challenge; some were available in formats with ready coordinates, while others required digitisation from hard copies. This necessitated a meticulous approach to data conversion, employing GIS technology to digitise watershed basin boundaries supplied by the PPC. This conversion process was vital for digitally representing the basins, ensuring the hydrographs' geographical context and basin characteristics were well-defined and reliable for subsequent analysis.

Out of the original 14 hydrographs, data from 8 basins were deemed complete and usable for the research objectives. These selected basins were subject to a rigorous analysis, where their hydrographs were standardised based on basin size criteria; smaller basins under 40 km^2 were assigned half-hour hydrographs, while larger basins received one-hour hydrographs. This standardisation was critical for ensuring a uniform analytical framework across all basins, facilitating the accurate development of GUH models. Figure 2-6 illustrates the 8 UHs utilised in the development of the GUH. Chapter 3.3 of the dissertation thoroughly presents the detailed process of data preprocessing, essential for constructing and analysing GUHs from the collected hydrological data. Furthermore, the boundaries of catchment areas across Greece were acquired from the flood management plans developed for the country. These boundaries were georeferenced and digitised in a GIS environment, enabling their use in the development of the GUH.

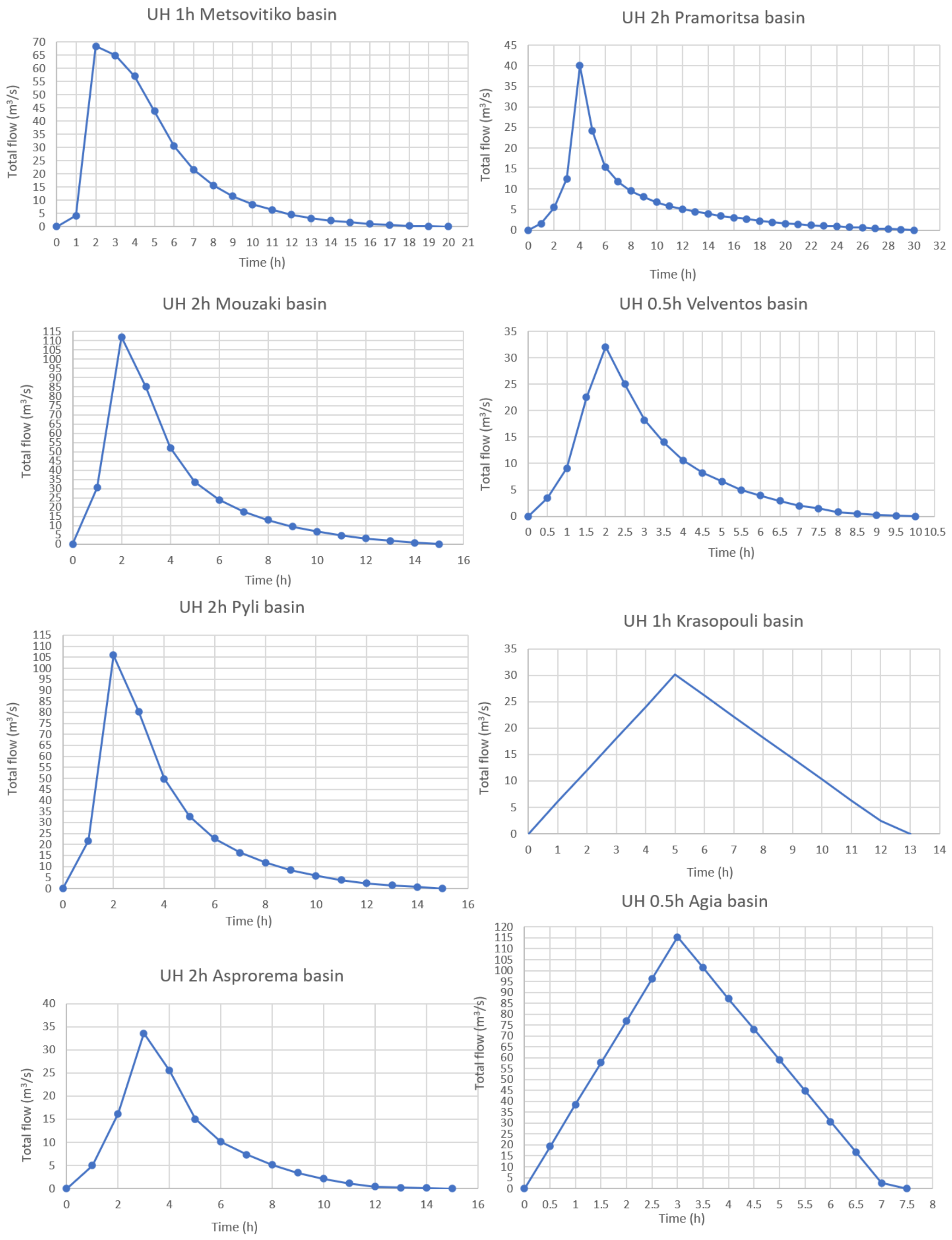


Figure 2-6: Unit Hydrographs (UHs) obtained from PPC

2.2.2 Roughness coefficient data

Another critical component discussed is the determination of the roughness coefficient, which is essential for accurately calculating velocities within hydrological modelling. This coefficient plays a crucial role in integrating various velocities—overland and within channels—offering a holistic perspective on the movement of water across the landscape. Overland velocities are computed by incorporating land cover and topographical slope data, whereas channel velocities consider the stream order.

For this research, the values for the roughness coefficient were meticulously chosen from established literature, drawing on tables proposed by Haan et al. 1994 and McCuen 1997. These tables provide a range of roughness coefficient values, crucial for determining overland flow velocity considering soil cover and slope information. This emphasis on the roughness coefficient underscores the thorough preparation and analysis of data pivotal for enhancing the precision of the GUHs developed in the research.

2.2.3 Rain gauge datasets

This dataset focuses on the hyetographs employed to calculate the design storm in the drainage basin upstream of the Magoula settlement. The design precipitation hyetographs are computed using the Alternating Block Method, informed by the Intensity-Duration-Frequency (IDF) curves specific to the Mandra hydrometeorological station.

The revised IDF curves are not just applied, but they are the key, updated from Kourtis et al. 2023, to model design storms across four climate scenarios: current, mean, upper, and lower, maintaining a return period of 100 years for consistency. These adjustments are not just important, they are crucial for predicting future flood hydrographs and assessing the efficacy of NBS under varying climate conditions. The IDF data in this research is derived from the FRMPs for Greece by the Ministry of Environment, Energy and Climate Change. The IDF evaluation utilised a Log Pearson Type III distribution, a 5-parameter GEV model, which comprehensively assesses the rainfall intensities expected for the 100-year return period.

Table 2-1 Presents the specific parameters for the station and the calculated accumulative rainfall height, H, rainfall instensity, i, time of concentration, t_c, through Giandotti's formula, for the selected duration for each scenario and return period of 100 years. This detailed preparation of IDF data under different climate scenarios is critical for estimating the design of storm hyetograph, providing a foundation for the hydrological analysis and modelling efforts that follow in this dissertation.

Table 2-1: IDF parameters of Mandra station and calculated rainfall characteristics

Station	Mandra			
ID	292			
Elevation	258			
IDF Parameters	η		0.622	
	κ		0.125	
	λ		213.4	
	ψ		0.641	
	θ		0.124	
Scenario	**Current**	**Mean**	**Upper**	**Lower**
$t_c(h)$	6.5	6.5	6.5	6.5
$d(h)$	24	24	24	24
$T(y)$	100	100	100	100
$i(mm/h)$	9.15	13.54	40.09	6.43
H (mm)	219.53	325.02	962.27	154.23

2.2.4 GIS datasets

In complement to the hydrological measurements integral to this research, a detailed suite of GIS datasets was curated to enrich the analysis, offering a multi-dimensional perspective on the study area's environment, infrastructure, and socio-economic landscape. These datasets, outlined below, were pivotal in delineating the geographical and physical contours of FRM, facilitating a detailed understanding of the interaction between natural and human-made systems:

- Digital Elevation Model (DEM): Sourced from the National Cadastre & Mapping Agency S.A., this high-resolution DEM provided the foundational layer for all spatial analyses. With a spatial resolution of 5 m x 5 m, it offered precise elevation data crucial for watershed delineation and surface water flow modelling. The DEM's accuracy is characterised by a Root Mean Square Error (RMSE) of ≤ 2.00 m and an absolute accuracy of less than 3.92 m at a 95% confidence level. The data is formatted in ERDAS Imaging (IMG) and aligned with the Hellenic Geodetic Reference System 1987 (GGRS87 or EPSG:2100), ensuring high fidelity in elevation data for the study area.
- CORINE Land Cover (CLC, 2018): To capture the land cover diversity within the European context, the CLC 2018 dataset was employed, detailing land cover across 44 distinct European classes. This granular land cover mapping, enriched with data from Sentinel-2 and Landsat-8 satellites, covering the period between 2017-2018, and achieved a geometric precision of under 10 meters, thanks to the high-resolution images from Sentinel-2, enhancing the final product's accuracy to better than 100 meters. It provided a vital layer for assessing how variations in land cover influence hydrological processes and, by extension, flood dynamics. Initiated in 1990 and updated every six years from 2000 onwards, the CLC's latest release is from 2018. It

specifies a minimum mapping unit (MMU) of 25 hectares for area features and 100 meters for linear features. The dataset's improved geometric accuracy, courtesy of the high-resolution satellite imagery, significantly enhanced the precision of land cover analysis.

- Road Network Data: Comprehensive road network information, sourced from the OpenStreetMap (OSM) project, accessible through the Geofabrik website (https://www.geofabrik.de/data/), was integrated into the analysis. This dataset was indispensable in hydrometric-hydrometeorological network design.
- Borehole data layer: was developed using information from the National Register of Water Intake Points, available on the website of the Greek Ministry of Environment, Energy and Climate Change (http://lmt.ypeka.gr/public_view.html). This resource facilitated the creation of a detailed map of boreholes, reflecting the distribution and characteristics of water intake points throughout the study area.
- Historical Flood Event Records: An archive of historical flood events was compiled from the Ministry of Environment and Energy website (http://floods.ypeka.gr). This website serves as a repository for a collection of historical flood events, spatially documenting significant flooding occurrences in Greece.
- Flood-vulnerable areas: First, it is essential to identify flood-prone zones to establish criteria for station installations upstream from areas vulnerable to flooding. To this end, information was derived from the outcomes of a GIS-based MCDM analysis focused on flood vulnerability assessment within the Attica region, encompassing the Sarantapotamos basin. This comprehensive study, conducted by Feloni et al. (2020), provides critical insights into the spatial distribution of flood vulnerability, informing the strategic placement of monitoring stations to effectively enhance FRM and mitigation efforts.
- Municipal Boundaries: Administrative boundaries, derived from open-access GIS resources like the geodata.gov.gr website, facilitated a localised analysis of flood risks and management policies.
- Geological information: This information was sourced from the official website of the Hellenic Geological Survey (EAGME) at https://www.eagme.gr/site/services. This website provides comprehensive geological datasets, including detailed maps and regional geological features, essential for analysing the study area's soil composition, rock formations, and structural geology.
- IDF stations: An inventory of IDF stations along with their corresponding fitted parameters, as developed during the formulation of the FRMPs for Greece by the Ministry of Environment, Energy and Climate Change (SSW-MEECC 2017), is available in a shapefile (.shp) format.

3. Methodological Framework

3.1 General Overview

Acknowledging the urgency for innovative FRM strategies due to the growing challenges of climate change, this dissertation introduces a novel, comprehensive methodological framework. This is designed to tackle the complexities of FRM cohesively and systematically, mainly focusing on the Sarantapotamos River basin in West Attica. This region has historically faced significant flooding challenges. The core of this framework is most effectively conveyed through a detailed flowchart (Figure 3-1), illustrating the sequential and interconnected stages of the methodology and their overall impact on enhancing FRM.

The process begins with a novel methodology for strategically placing hydrometric and hydrometeorological stations. Using a GIS-based multicriteria decision analysis, optimal locations within the Sarantapotamos River basin are identified for these stations. The selection process, guided by criteria detailed in Theochari et al. 2019, 2021, considers factors such as flood susceptibility, residential density, and environmental significance. This initial step is critical as it lays the groundwork for all subsequent analyses, ensuring that the data collection is targeted and relevant to the flood-prone areas of interest, especially in regions like Mandra that are highly susceptible to flooding. The criteria for site selection are comprehensive, ensuring that the subsequent data supports not only immediate flood warning needs but also long-term hydrological studies and environmental monitoring. Establishing these stations is pivotal, as it lays the foundational data infrastructure necessary for the subsequent phases of the framework.

Following the establishment of these monitoring stations, building on the data gathered from the strategically placed stations, the second stage focuses on developing GUH tailored for ungauged basins. This innovative approach utilises geomorphological metrics to establish relationships between rainfall and runoff, specifically designed for the Greek landscape's unique characteristics. The collected hydrometric data are pivotal to calibrating and validating the GUH models at this stage. This ensures that the hydrological models developed are accurate and reflective of the real-world conditions of the Sarantapotamos

River basin. This development marks a significant advancement in hydrological modelling, offering a precise tool for flood prediction in areas where traditional data might be lacking. The final step in this methodological framework involves the implementation of NBS, such as land cover changes and the construction of retention ponds. This stage evaluates the effectiveness of NBS in mitigating flood risks. The hydrological analysis required for this phase relies on the data collected from the hydrometeorological stations and the refined GUHs. By transforming rainfall data into runoff models, this stage generates flood hydrographs that are instrumental in understanding and managing flood risks. The implementation of NBS is closely linked to the initial site assessment and hydrological modelling, as the effectiveness of these solutions is predicated on the accuracy and depth of the foundational data and models.

Finally, this methodological framework represents a holistic approach to FRM, emphasising the seamless integration of data collection, hydrological modelling, and the application of sustainable flood mitigation strategies. By establishing a data-driven foundation through the strategic placement of monitoring stations, the framework enables the development of advanced hydrological models that can predict flood events with greater precision. The subsequent application of NBS, informed by accurate data and models, offers a sustainable approach to reducing flood risks, ultimately contributing to safer, more resilient communities. Through this comprehensive approach, the research aims to bridge the gap between traditional flood management practices and the need for innovative, adaptable solutions in the face of climate change. Utilising technological advancements, hydrological modelling, and environmental sustainability practices, the framework provides a scalable and effective strategy for managing flood risks tailored to the unique challenges of vulnerable regions like the Sarantapotamos River basin.

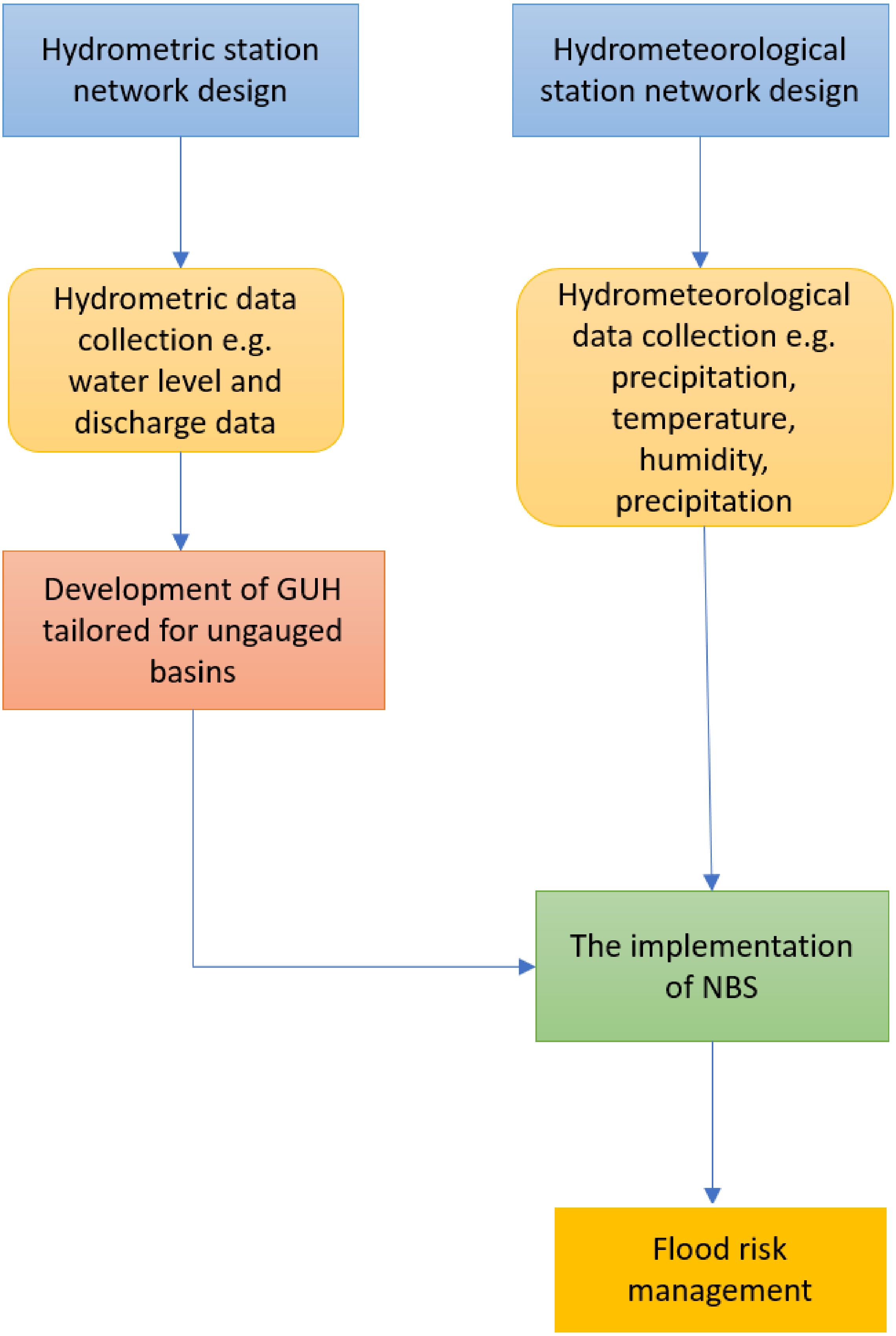


Figure 3-1: Flowchart of the methodological framework towards FRM

3.2 Hydrometric-Hydrometeorological Station Network Design

3.2.1 Multi-Criteria decision making (MCDM) analysis

The purpose of this phase of the methodological framework is to introduce a methodology for assessing potential sites for installing hydrometric and hydrometeorological stations by employing a GIS-based multicriteria decision analysis approach, considering various purposes such as water resources management and flood warning systems, as described in Theochari et al. 2019, 2021. The methodology is illustrated through a case study focusing on the Sarantapotamos River basin in West Attica. This area is selected due to its high susceptibility to flooding, especially in residential areas. The Mandra settlement, in particular, has a history of severe floods, often caused by intense rainfall events occurring over short periods. These events, coupled with its location at the confluence of two small watersheds and urban infrastructure in low-lying areas, contribute to its vulnerability. In recent years, the region has experienced significant floods, including a devastating event on November 15, 2017, which resulted in the loss of 25 lives. Establishing a stream flow data collection system in this basin is crucial for issuing timely flood warnings, which is essential for public health and socioeconomic well-being. Additionally, it will help build a comprehensive database for monitoring and safeguarding available water resources and the ecosystem.

The primary objectives are to utilise a GIS-based MCDM approach to design an optimal hydrometric-hydrometeorological network and evaluate location scores, addressing a spatial decision problem. As outlined by Malczewski 1999, 2004, decision problems incorporating geographic data are termed geographic or spatial decision problems. These typically entail evaluating various alternatives against multiple criteria. Consequently, integrating MCDA and GIS tools can address many real-world spatial challenges. In this context, decision-makers, such as station network designers, utilise MCDA analysis, which establishes standardised procedures for problem-solving by integrating factors such as geomorphological, technical, spatial, and flood control considerations. Additionally, the aim is to investigate how the formulation of selected design criteria and the choice of weighting method influence the identification of appropriate locations for hydrometric-hydrometeorological gauge installation. MCDA is a process that transforms geographic data inputs into a resulting decision output, representing a defined relationship between input and output maps. Geographic information is data referenced to specific locations and processed in a manner meaningful to users. Within a GIS, data is typically organised into thematic layers.

The initial step of decision-makers involves identifying the overarching problem and individual objectives, followed by selecting criteria and alternatives. Criteria encompass factors and constraints pertinent to the problem under examination. Subsequently, criteria values are standardised, and any enforced constraints are determined. Decision-makers then select the method for combining criteria and determining relevant weights to generate final results and potential alternatives. Ultimately, proposed solutions are derived from evaluating alternative options, as Drobne and Lisec (2009) emphasised. The critical steps of the analysis involve selecting criteria for network design, standardising their values, and calculating criterion weights using the Analytic Hierarchy Process (AHP) method proposed by Saaty 1977. AHP is chosen due to its application in various studies involving MCDM for site selection and its ability to estimate weights by establishing a hierarchy among criteria.

More specifically, three weighting scenarios are explored using AHP for the hydrometric station network, as detailed in Theochari et al. 2019. Additionally, weights are estimated using the Fuzzy Analytic Hierarchy Process (FAHP) proposed by Chang in 1996. This method demonstrates how the choice of weighting technique can significantly impact the results, incorporating fuzzy logic to enhance decision-making precision. In the design of the hydrometeorological station network, equal weights are allocated to criteria. The design criteria are formulated within the GIS environment as described in Theochari et al. 2019, 2021. GIS is crucial in managing spatial data from diverse sources and executing commands to solve spatial decision-making problems. The criteria are then combined using the weighted linear combination (WLC) technique to produce suitability maps for the network. The GIS-based MCDM identifies several suitable locations, from which those with the highest final score (FS) are selected for network establishment. Figure 3-2 provides an overview of the MCDA application process.

Previous studies' limitations include the analysis scale and limited description of criteria handling in GIS, whereas this analysis operates at a river basin scale, incorporates numerous spatial criteria, and discusses various aspects of the methodology.

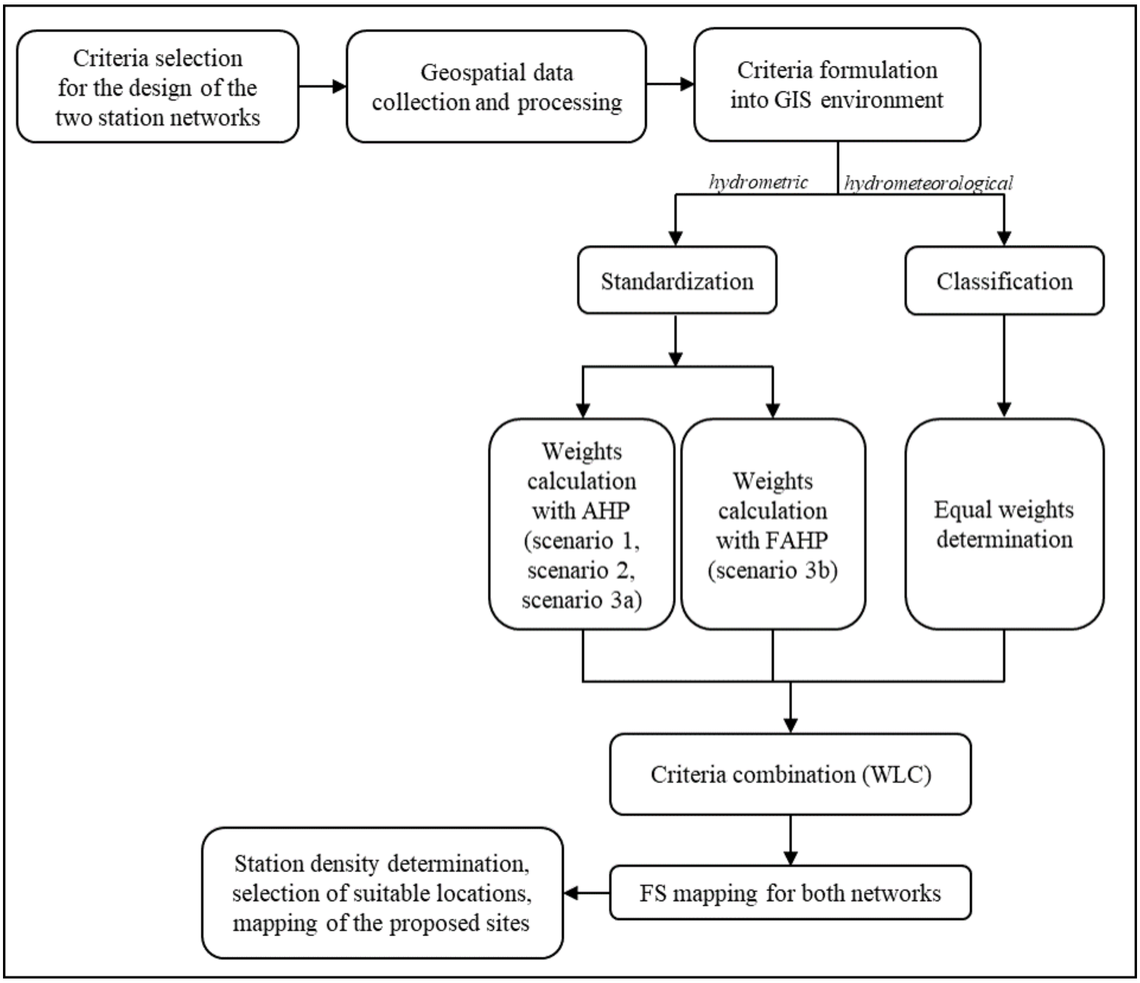


Figure 3-2: Methodology flowchart for assessing suitable locations for hydrometric-hydrometeorological gauges installation using a GIS-Based Approach
Source: (Theochari et al. 2021)

3.2.2 Standardization and classification of criteria

Standardisation is a crucial step within MCDM, as it aligns criteria onto a unified grading scale, typically ranging between 0 and 1. This process simplifies comparison by ensuring consistency, with the simplest method involving linear transformation as depicted in Equation (3.1) when the maximum criterion value represents the best-case scenario, and Equation (3.2) when it describes the worst-case scenario, a determination dependent on the MCDM problem at hand (Voogd 1983).

$$x_i = \frac{(FV_i - FV_{min})}{(FV_{max} - FV_{min})} \cdot SR \tag{3.1}$$

$$x_i = 1 - \frac{(FV_i - FV_{min})}{(FV_{max} - FV_{min})} \cdot SR \tag{3.2}$$

where FV_{min} and FV_{max} denote the minimum and maximum criterion values, respectively, FV_i represents the value of each raster cell standardised to xi, and SR indicates the standardised range (0–1).

The ArcGIS software (ESRI 2010) executes the standardisation process using the Raster Calculator and Map Algebra expressions.
Additionally, classification is utilised alongside standardisation in the current analysis for all criteria involved in hydrometeorological station design. Regarding hydrometric stations, the topographic slope criterion is classified into five classes. This classification utilised the Jenks natural breaks classification method (Jenks 1967) within the spatial analyst tool of ArcGIS (ESRI 2004). The Jenks method optimally arranges values into different classes by minimising each class's average deviation from its while maximising deviation from the means of other classes. This approach aims to reduce variance within classes while maximising variance between them.

3.2.3 Selection and formulation of criteria for hydrometric station network design

The criteria guiding the suitability of locations for hydrometric station installation can be divided into two main categories: general criteria, often represented in raster datasets (e.g., proximity, density), and special criteria based on technical standards outlined in ISO 1100-1 (WMO-No. 1044 2010). As described by Hong et al. 2016, these technical standards specify that a stream gauge should be situated where the river's course is predominantly straight for approximately ten times the stream width, both upstream and downstream. Additionally, it should be positioned sufficiently far from confluences with other streams to avoid potential influences and from areas vulnerable to tidal effects. Ideal sites should ensure that the total flow remains confined to a single channel at all stages without bypassing subsurface flow. Moreover, the streambed should be relatively free of aquatic vegetation, while the banks should be stable and of adequate height to withstand flood events and free from brush. According to WMO 2010, a "pool" should form upstream of the station location to ensure accurate stage recording even during extremely low flow conditions and to prevent high velocities at the stream ward end of recording instruments during high flow periods. Furthermore, the chosen installation site must remain unaffected by intense scour and fill. This is achieved by maintaining a consistent slope upstream and downstream of the site, particularly in regions where the course is sufficiently straight; locations with very low stream slopes are preferred.
As evident, many of the criteria outlined necessitate on-site evaluation, emphasising the importance of implementing a GIS-based methodology for site selection. This process within a GIS environment can suggest potential station locations by considering various criteria, thus minimising the fieldwork required for site selection. The proposed methodology incorporates seven criteria, five of which can be effectively expressed using GIS techniques according to Theochari et al. 2021: slopes (C1), distance from road networks

(C2), distance from confluences with other streams (C3), distance from settlements (C4), and distance from flood-prone areas (C5) as shown in Table 3-1.

Table 3-1: Criteria for optimal site selection of hydrometric stations, as cited in Theochari et al. 2019

Criteria	*Description*
C1	Topographic slopes
C2	Distance from the road network
C3	Distance from confluence with another stream
C4	Distance from settlements
C5	Distance from the flood-prone area

The first criterion, "station density", aligns with recommendations from WMO 2010, which prescribe the density of hydrometric station networks based on the geographic area type, such as "plain." The density of stream flow stations plays a significant role in data collection within a basin, necessitating careful site selection to align with data demand and installation budget constraints. The recommended density of a stream gauging network, as illustrated in Table 3-2 It is provided by WMO 2010. Although the required number of stream gauges is typically one, two locations are ultimately proposed to ensure comprehensive data collection, particularly for early flood warning purposes.

Table 3-2: Stream flow station density based on surface characteristics: Data adopted by WMO 2010, as cited in Theochari et al. 2019, 2021

Type	**Density**
Coastal	1 station per 2750km^2
Mountainous	1 station per 1000km^2
Hilly	1 station per 1875km^2
Plains	1 station per 1875km^2
Small island (area<500km^2)	1 station per 1985km^2
Polar, arid	1 station per 20000km^2

Consistent with WMO recommendations, the "slope" criterion advocates for station placement on gently sloping terrain, with lower slopes receiving higher scores. To create the slope criterion, slopes are calculated for the watershed and classified into five classes, each standardised according to Equation (3.2). This specific equation is used because the best slope values for locating hydrological stations are those with the lowest value. As a result, five classes with values from 0 to 1 are derived, and then these five raster files are merged into one raster to create the topographic slope criterion.

The criterion "distance from the confluence with another stream" aims to ensure that stream gauges are positioned sufficiently far from stream junctions to prevent interference from adjacent streams during flow recording. For this purpose, nodes are identified at the junction points and digitised. Subsequently, a 250-meter buffer zone is generated around these points. A Boolean map is then created, with zero values denoting the area within the buffer zone that should be avoided. This zone is where it would not be advisable to install a hydrological station to ensure that recordings are not affected by the actions of other streams. Subsequently, Euclidean distances are calculated from the outer perimeter of the buffer zones of the confluences. The resulting dataset is standardised in the subsequent step of the methodology, yielding a raster dataset with zero values within the buffer zones and standardised distance values from the nodes across the remaining part of the mainstream using Equation (3.2).

The criterion "distance from road network" relates to the location's accessibility. The road network utilised is extracted from the OpenStreet Maps geospatial database, including thematic layers up to the second order of rural roads (grade 2 track road), i.e., roads with asphalt or coarse gravel pavement, to ensure access at all times by conventional vehicles. Positions within a total distance of up to 50 m from the road network are selected as proposed sites by calculating Euclidean distances within this zone and along the main watercourse. Finally, these values are standardised based on Equation (3.2).

Introducing the criterion "distance from settlements" is crucial as the proximity of stations to settlements is significant for flood early warning systems and facilitates accessibility to the recording site. For this purpose, the boundaries of settlements are initially determined based on the CLC dataset 2018, which classifies land cover into 44 categories. Specifically, the urban fabric category corresponding to code 112 (discontinuous urban fabric) is selected, and digitisation of smaller settlements not included in the dataset due to a limited extent is performed. Then, a file for the adjacency of each settlement to the main watercourse is created, and, similar to the previous criterion, Euclidean distances are calculated for each point. Then, the ArcGIS geoprocessing tool “Times” compares the upstream Euclidean distance and the upstream mainstream part of each neighbouring settlement to isolate the Euclidean values along each upstream segment of the main watercourse. These Euclidean distances are standardised according to Equation (3.2). Finally, these standardised files are merged to produce the final standardised criterion for distance from settlements, as shown in Figure 3-3.

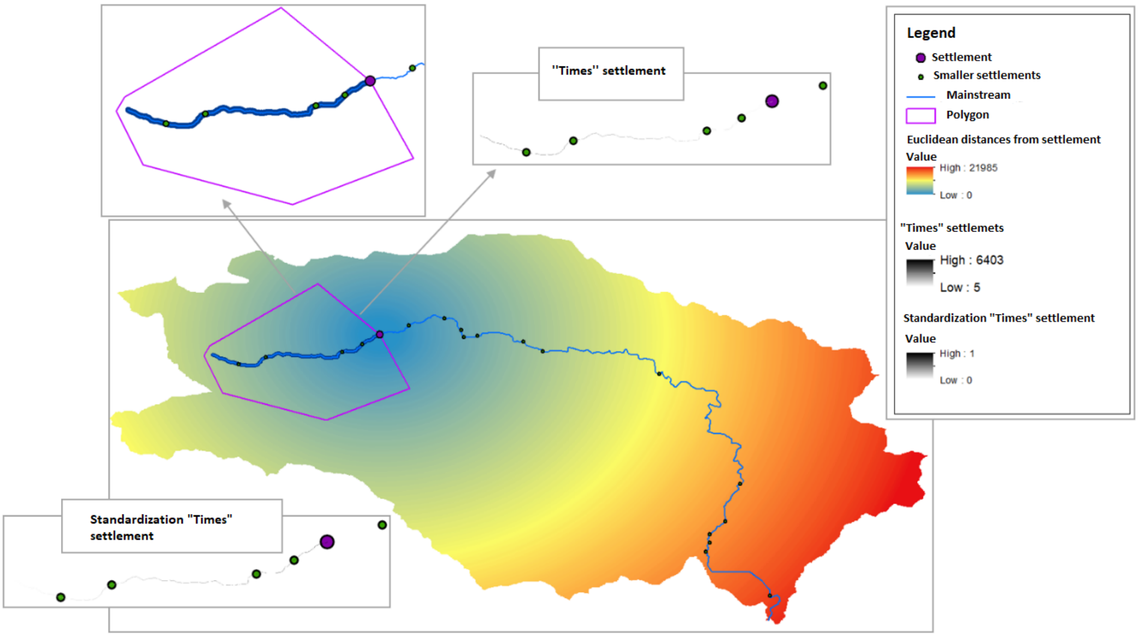


Figure 3-3: Representation of the 'Distance from Settlements' criterion in ArcGIS environment

The criterion "distance from flood-prone areas" ensures that the network can function operationally within the early warning framework besides monitoring the river's hydrology. Therefore, knowledge of flood history is required for siting hydrometric stations when they are placed for flood warning purposes, and positions near areas more affected by floods and upstream of vulnerable areas are preferred. This involves a GIS process to derive standardised values along the mainstream and upstream of flood-prone areas. The highest value is attributed to the outer margin of the vulnerable area, which is gradually decreasing upstream. This criterion utilises flood susceptibility zones defined in a Feloni et al. 2020 study. This aimed to find the optimal technique for determining flood-vulnerable areas, with a case study of the Attica region and, by extension, the watershed under consideration. The analysis of Feloni et al. 2020 includes the evaluation of individual scenarios, where the urban flood events dataset was utilised for this purpose. Through the evaluation, it was found that using the Fuzzy AHP method for weighting the criteria and the K-means algorithm for clustering these values (i.e., scenario "FAHP.3K") leads to the optimal result concerning the determination of the high and very high-risk zones, incorporating the highest number of recorded urban flood events. Therefore, for this specific siting criterion, the implementation of a process in ArcGIS that assigns normalised values along the watercourse and upstream of the flood-prone area is required. This is done so that the maximum value is given at the boundary of the flood-prone area and gradually decreases as the distance upstream increases. For this purpose, initially, the shapefile of the flood-vulnerable area is created based on the available scenario "FAHP.3K" to determine the position of the boundary on the main watercourse. Subsequently, the Euclidean distance upstream of this point and along the main watercourse is calculated. These values are then standardised according to Equation (3.2) to produce the flood-prone area criterion, as shown in Figure 3-4.

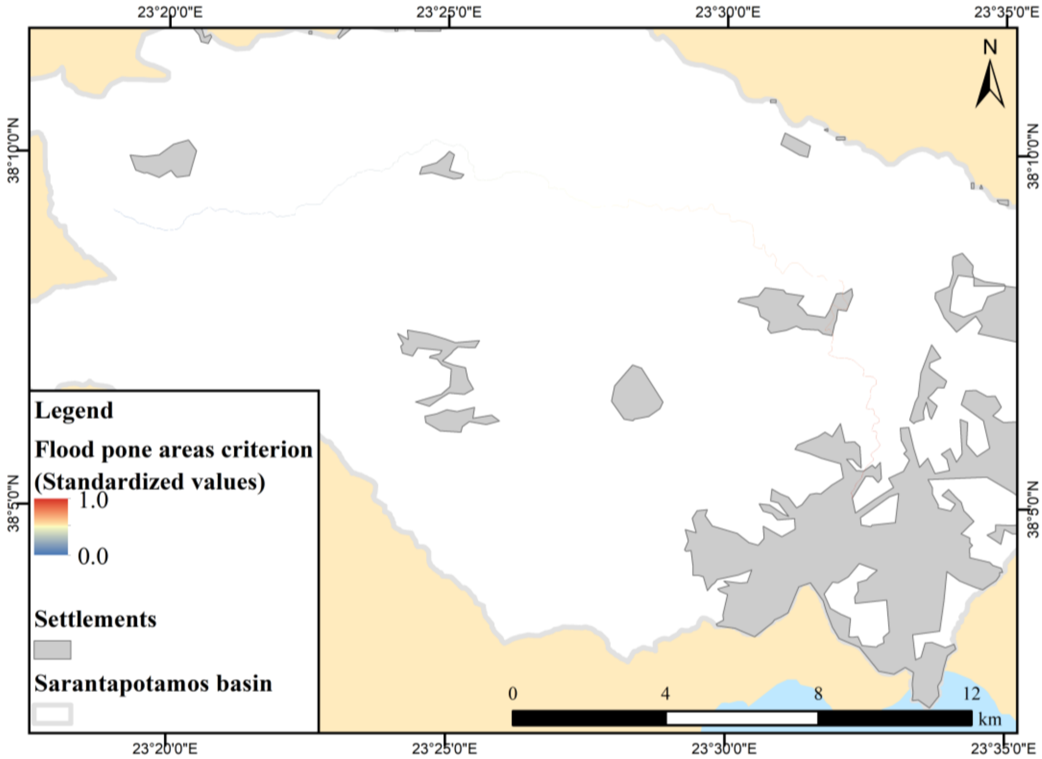


Figure 3-4: The criterion of distance "from flood-prone areas" for the design of hydrometric station networks. Source: (Theochari et al. 2021)

It is worth noting that the way criteria are formulated within a GIS environment may vary depending on the researcher's perspective and experience and the available data. Therefore, the final suitability map of site locations may differ regarding the final score. Specifically, two of the criteria mentioned above, namely "distance from settlements" and "distance from flood-prone areas," have been formulated differently in Theochari et al. 2019 and 2021.
Theochari et al. 2019 followed the following procedure for their formation:

The criterion "distance from settlements."

Installing hydrometric stations near settlements is particularly important for flood warning purposes. To identify settlements within the basins under consideration, the urban development category containing code 112 for continuous urban fabric and discontinuous urban fabric, respectively, is selected from the Corine 2018 dataset in ArcGIS. As a result, the settlements appeared as polygons, and subsequently, using the buffer command, a 500-meter zone was created around the perimeter of the settlements with a value of 0. This zone signifies areas where installing a hydrometric station would not be advisable, as a flood warning would not be meaningful. Therefore, this zone will be a constraint to exclude site placement. Next, Euclidean distances from the settlement buffers are calculated to apply the criterion that the hydrometric station should be located at the closest distance from the settlement polygons but outside the 500-meter zone created. These distances are then used to create a file where standardisation is performed through operations in the Raster Calculator using Equation (3.2). This ensures that the best sitting location has values closer to zero. Consequently, a standardised file with values (0,1) based on distances from settlements criterion is generated.

Subsequently, to define the upstream of the settlements and obtain the final standardised criterion containing the minimum distance and the upstream of the settlements, the following procedure is followed. Initially, the vector file of the main watercourses is selected, and a new field is created, where the value one is assigned using the Field Calculator. Using the Feature to Raster command, the vector file of the main watercourses, with the field set to have the value 1, is converted into a raster file with a value of 1. Therefore, using the two raster files of the basin and the main watercourse obtained, the "Mosaic to New Raster" command is utilised to merge them and create a unified mosaic containing the two files mentioned above. After making this unified file with values ranging from 0 to 1 is multiplied by the flow accumulation file. After the multiplication result, a condition is applied using the Raster Calculator command to isolate the main watercourse. Then, the result of the contraction is standardised according to Equation (3.2) so that the best siting location would have values closer to zero. Therefore, a standardised file with values (0,1) based on the upstream of settlements criterion is obtained. Consequently, after creating the two standardised criteria, with optimal values closer to zero, these two criteria are multiplied for the minimum distance from settlements and the minimum distance from the upstream of settlements.

The criterion "distance from flood-prone areas."

Knowledge of flood history is essential for siting hydrometric stations for flood warnings. According to historical data, positions near areas most affected by floods are preferred as locations opposite these areas. To apply the proximity criterion, the shapefile of historical floods is imported into ArcGIS as point data under study. Then, for these points, using the buffer command, a zone of 1000 m is created with a value of 0, where it would not be suitable to install a hydrometric station, as it would not make sense for flood warnings. Therefore, this zone will be used as a constraint for exclusion. Then, the Euclidean distances from the flood buffers are calculated to apply the upstream criterion so that the hydrometric station is located closest to the floods but also outside the 1000 m zone created. The exact process for the distance criterion from settlements is followed, and the final result of forming the criterion is derived.

The criteria mentioned above are integrated to produce a suitability map with varied scores across the mainstream of the Sarantapotamos River. This map, representing the output of the MCDM process for the network, incorporates site scoring data. The creation of the drainage line, river basin layers, and basin slopes utilises a DEM with the assistance of the Geospatial Hydrologic Modelling Extension (HEC-GeoHMS; HEC 2013), a software package compatible with ArcGIS (ESRI 2010).

Finally, in addition to the criteria mentioned above, the selection process is influenced by a seventh criterion concerning the presence of bridges perpendicular to the mainstream direction. It concerns the criterion for technical site adequacy. Hydrometric stations that monitor water level or flow velocity at a specific section are desirable, for technical reasons, to be placed on passing bridges with a vertical orientation to the watercourse. This arrangement technically facilitates the placement of equipment and also ensures accessibility to the site. The constraints considered in this analysis revolve around installing stream gauges along the main course of the river network and within a distance of less than 50 m from roads. Additionally, adherence to the density of stations outlined in the WMO 2010 guidelines is a crucial constraint.

3.2.4 Selection and formulation of criteria for hydrometeorological station network design

Various criteria, such as geomorphological, administrative, technical, and geometric factors, are considered in the design of hydrometeorological station networks, as documented in the detailed analysis by Baltas and Mimikou 2009. The optimal design depends on determining the appropriate number of stations and their specific locations. This optimisation ensures that hydrometeorological stations yield highly accurate and reliable data at minimal expense, as Feloni et al. (2018) outlined.

According to recommendations from the WMO in 2008b, station density can be estimated based on elevation classification and spatial distribution within administrative regions. Consequently, the primary criterion for density is tied to altitude categorisation, as per the specifications of the Soil and Terrain Digital Database SOTER (Dobos et al. 2005) of the United Nations Environment Programme (UNEP). Specifically, altitude categorisation includes five zones: A (0-200 m), B (200–500 m), C (500–800 m), D (800–1200 m), and E (1200–1900 m). Although this initial criterion is not integrated into the WLC, it is utilised in the final step of selecting suitable sites among those with high suitability factors.

The second criterion involves considering the terrain slope as a constraint, with guidelines specifying an optimal slope ranging from 0 to 5%, per the SOTER Service specifications. Areas with slopes up to 2% are classified as flat, while those between 2 and 5% are considered gently undulating. Accordingly, stations are positioned within these two categories to adhere to this constraint. A Boolean map is generated to facilitate this, assigning a value of "1" where the slope is less than 5% and "0" where the slope exceeds this threshold. Thus, the "slope" criterion is represented as a restriction through a Boolean map derived from reclassifying the "slope" layer created using the DEM mentioned earlier.

The third criterion for selecting hydrometeorological station sites pertains to land cover types, aiming to ensure the presence of at least one station within each main category. Utilising CLC data, four primary categories are identified, corresponding to the following land cover types: (1) Artificial surfaces; (2) Agricultural areas; (3) Forests and Semi-natural areas; and (4) Water surfaces - Water collections. In the study area, only three categories are observed (Figure 3-5). Notably, while there are typically four land cover type categories, in some instances, such as this area, the required number of stations (per the first criterion) may be lower than four.

Additionally, three criteria related to proximity—distance from settlements, distance from roads, and proximity to boreholes—are integrated into the design, recognised as technical criteria in the global literature (e.g., Baltas and Mimikou 2009; Feloni et al. 2018). The "distance from settlements" criterion aids in monitoring recording stations and controlling instruments, with optimal sites selected at distances of 1 km from large settlements and 500 m from small settlements. This criterion is formulated using settlement data obtained from the CLC 2018 dataset, focusing on areas classified as "Discontinuous urban fabric" and refined as needed using satellite imagery. Buffer zones are delineated, and the layer is converted into a Boolean map (raster format) to establish the criterion.

The "proximity of stations to the road network" is the fifth criterion, essential for assessing accessibility. The OSM layer provides relevant road network information, encompassing all thematic levels of roads. For analysis, only roads up to the second class of rural roads (grade 2: track road) are considered to ensure year-round accessibility via conventional vehicles. This criterion is represented as a Boolean map with a 200 m buffer zone from the road network, facilitating easy access on foot under various weather conditions.

The next criterion is the presence of "boreholes." To facilitate integrated water resource management, stations are recommended to be established where clusters of boreholes exist. The corresponding buffer zone from these clusters extends 500 m.

Finally, additional criteria denote the spatial extent of the analysis, such as conducting it within the river basin scale. The spatial distribution of stations across the study area is considered concerning the final selection of station positions based on suitability map results. This ensures that each station represents an almost equal percentage of the total area. Table 3-3 outlines the decision criteria for both networks and the method employed for standardising (S) or classifying (C) values.

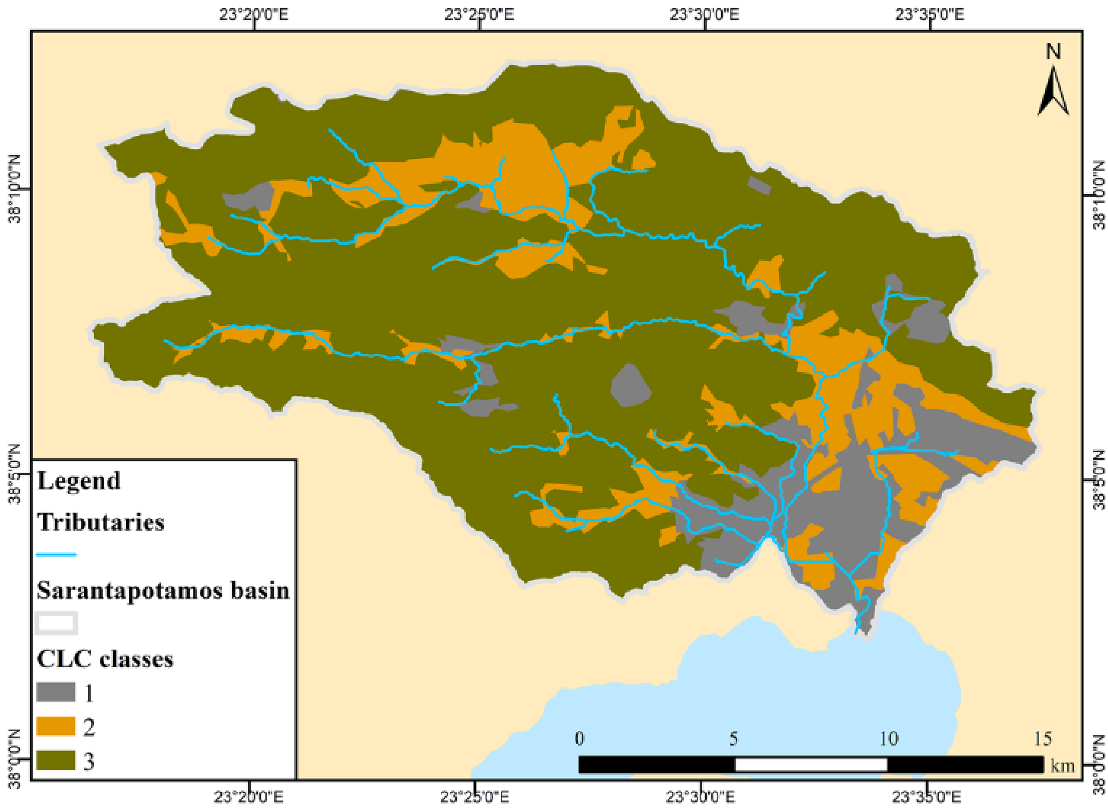


Figure 3-5: The three main CLC class categories utilised in the design of the hydrometeorological station network Source: (Theochari et al. 2021)

Table 3-3: Summary of decision criteria for designing the hydrometeorological (HM) and hydrometric (HY) station network Source: Theochari et al. 2021

Criterion	Standardisation/ Classification	Constraints	Remarks
(HM) Density	(C)Five (predefined) Elevation zones	-	Estimation of the required number of stations (density) per elevation zone. The criterion is applied to the suitability map for the final sites' selection.
(HM)Terrain slope	(C)Two (predefined) classes	Boolean Map "1" (≤5%); "0" (>5%)	Terrain slope calculation using the available DEM - Classification in two classes and Reclassification for the Boolean Map creation
(HM)CLC classes	(C)Four main categories	-	Classification of CLC in four categories. The criterion is applied to the suitability map for the final sites' selection.
(HM) Distance from settlements	(C)Two (predefined) classes	Boolean Map "1" (≤1 km from large settlements or ≤500 m from small settlements);	Buffer zones of two sizes depending on a settlement's categorisation - Boolean map creation ("1" for Buffer zones)

		"0" (>1 km or >500 m, respectively)	
(HM) Distance from the road network	(C)Two (predefined) classes	Boolean Map "1" (≤200 m from the road network); "0" (>200 m)	Road network classification to extract specific categories - Buffer zones of 200 m from the road network - Boolean map creation ("1" for Buffer zones)
(HM)The existence of clusters of boreholes	(C)Two (predefined) classes	Boolean Map "1" (≤500 m from boreholes); "0" (>500 m)	Buffer zones of 500 m from the boreholes - Boolean map creation ("1" for Buffer zones)
(HM)Administrative boundaries	The analysis is performed within the administrative boundaries of a Municipality or at a river basin scale.		
(HM)Spatial distribution of the stations	Each station may represent an almost equal percentage of the total area. The criterion is applied to the suitability map for the final sites' selection.		
(HY)River channel slope	(C)Two (predefined) classes and (S)with equation (3.2) in the class of low slopes	-	The slope is classified into two classes, and then values of the class of low slope (≤5%) are standardised using equation (2)
(HY) Distance from the road network	(S)with equation (3.2)	-	Euclidean distance from road network calculation (Con≤50) – "Times" ArcGIS geoprocessing tool to create a raster with values along the mainstream - Standardization using equation (2) - 'Mosaic to new raster' to combine the latter layer with that of the whole mainstream ("0")
(HY) Distance from confluence with another stream	(S)with equation (3.2)	Boolean Map "1" (>250m); "0" (d<250)	Creation of a feature class (type point) with the intersection of streams – "Mosaic to new raster" with "Euclidean distance" layer
(HY)Upstream distance from settlements	(S)with equation (3.2)	-	Upstream mainstream part determination when close to a settlement – "Euclidean distance" – "Times" between the upstream Euclidean distance and the upstream mainstream part of each neighbouring settlement - Standardization using equation (2) and "Mosaic to new raster" to combine the latter layer with that of the whole mainstream ("0")

(HY) Distance from flood-prone areas	(S)with equation (3.2)	-	"Euclidean distance" from flood-prone areas determination - Definition of the upstream mainstream for each vulnerable area – 'Times' between 'Euclidean distance' and 'upstream' – Standardization – "Mosaic to new raster" to combine the latter layer with that of the whole mainstream
(HY) Drainage line	-	Boolean Map "1" (along the mainstream), "0" (outside the mainstream)	To define the processing area
(HY) Density	Estimating the required number of stations (density) according to the area's categorisation. The criterion is applied to the suitability map for the final sites' selection.		

3.2.5 Determination of criteria weights using AHP and FAHP methods

The pivotal stage in the process involving MCDM on GIS is the selection of criteria and their expression, followed by their standardisation or classification to obtain design criteria scaled within (0,1) ultimately. This step is crucial for subsequent combinations to determine the FS. In MCDM analysis, decision criteria can be combined in various ways, including the WLC and its variants, necessitating aggregating weighted criteria. In this analysis, criteria weight estimation is conducted using the AHP method (Saaty 1977). In the present analysis, equal weights are allocated (i.e., 0.25) for each criterion for hydrometeorological station design. Conversely, for the hydrometric station network design, the relative importance of each factor influences the suitability (FS) of the positions. Each design scenario exhibits a range of values across the spectrum, reflecting the varying significance of individual factors.

To investigate this further, three factor weighting scenarios are explored, as detailed in Theochari et al. 2019. In the first scenario (scenario 1), greater emphasis is placed on technical criteria such as slopes, distance from the road network, and distance from confluence with another stream. In the second scenario (scenario 2), which prioritises flood protection, the criterion regarding distance from flood-prone areas holds significant importance. The third scenario (scenario 3a) strikes a moderate balance between technical and flood-related factors. In this scenario, neither technical nor flood protection criteria are prioritised exclusively; their importance is alternated in the hierarchy. For all scenarios, the topographic slope stands out as the most preferred criterion, as the feasibility of establishment is limited to areas with very low slopes.

AHP is an analytical technique employed to weigh criteria and organise the problem into a hierarchy, aiming to simplify complexity by breaking it down into subproblems. Furthermore, AHP is grounded on the principle that decision-makers experience and knowledge are as crucial as the available data. While this technique was initially developed with various analytical tools, the integration of GIS techniques was pioneered by Rao et al. 1991. This method has been extensively applied in numerous studies incorporating MCDM for various site selection issues (e.g., Sestak 1989; Chung and Lee 2009; Van Aken et al. 2014; Feloni et al. 2018; Deng and Deng 2019; Theochari et al. 2019; Ikram et al. 2020; Bertsiou et al. 2020; Matomela et al. 2020). The implementation of this method starts with decomposing the problem into a hierarchical model comprising its fundamental components, enabling pairwise comparisons using Saaty's 1977 fundamental scale as illustrated in Table 3-4Pairwise comparisons of different criteria are based on the researcher's subjective perspective (e.g., personal, empirical, bibliographic, field research, etc.). The relative significance is determined by comparing each criterion pair. In each comparison between two design criteria, relative significance is assigned a score ranging from 1 (equally significant) to 9 (absolutely more significant). At the same time, the other option in the pairing receives a rating equal to the reciprocal of this value.

Table 3-4: Scale for pairwise comparison Source: Saaty 1977

Numerical value	*Description of importance*
1	equal
2	equal to moderate
3	moderate
4	moderate to strong
5	strong
6	strong to very strong
7	very strong
8	very strong to extremely strong
9	extremely strong

In Saaty's 1977 technique, weights are derived through a series of operations on a matrix of comparable pairs among the criteria. These comparisons assess the relative importance of two criteria concerning the suitability for the intended objective. To evaluate the weight of each criterion, the following procedure is followed:

1. Assumption of column values for each matrix of comparable pairs.
2. Division of each matrix element by the sum of its corresponding column.
3. Calculation of the average of the data for each matrix sequence obtained in the previous step.

The resulting averages represent the criteria weights (Drobne and Lisec 2009). Saaty 1977 suggests that altering elements should reassess weights if the consistency ratio (CR) ≤ 0.10 limit is not met. The CR is calculated as follows:

$$CR = \frac{CI}{RI} \tag{3.3}$$

Where,

RI: Random Index, a consistency index of a randomly generated comparable pair matrix depending on the number of elements being compared,

CI: Consistency Index providing a measure of deviation from consistency. It is calculated by Equation (3.4):

$$CI = \frac{(\lambda - n)}{(n - 1)} \tag{3.4}$$

Where,

λ: Eigenvalue of the matrix,

n: Number of criteria.

Additionally, weights for the third scenario (scenario 3b) are estimated using the FAHP proposed by Chang 1996, demonstrating the influence of the chosen method on weight estimation in the resulting suitability map. Fuzzy logic is a flexible and straightforward approach that bridges quantitative and qualitative information (Pourmeidani et al., 2020). Specifically, the extended FAHP method (Chang 1996) utilises triangular fuzzy sets of numbers, aligning them with Saaty's 1977 crisp set of numbers and linguistic scale. Various linguistic transformation functions have been examined for fuzzy numbers (Bulut et al. 2012; Lee 2010). Here, the transformed linguistic scale of significance is applied to triangular fuzzy numbers (TFN), as depicted in Table 3-5. The correspondence of Table 3-5 It is directly utilised to convert the crisp set of pairwise comparison tables generated in the AHP process into TFN ones.

According to Chang 1996 and Junior et al. 2014 and Charilas 2012, the weighting process begins with computing the value of the fuzzy synthetic extent (Si). Subsequently, the vector of fuzzy numbers of weights Si is transformed into the corresponding real-number vector (V). Finally, the actual weight vector W is obtained by normalising the vector V such that its terms sum to 1. It is crucial to note that the CR should be at most 10% to consider the hierarchy and comparison between the primary factors and to accept the resulting weighting factors.

Table 3-5: Linguistic scale of significance convert Source: Data adopted by Zhou 2012 and Junior et al. 2014 with changes as cited in Theochari et al. 2019

	FAHP scale	
Linguistic Scale	*TFN scale*	*TFN reciprocal scale*
Equally Important	(1,1,1)	(1,1,1)
Intermediate 1	(1,2,3)	(1/3,1/2,1)
Moderately Important	(2,3,4)	(1/4,1/3,1/2)
Intermediate 2	(3,4,5)	(1/5,1/4,1/3)
Important	(4,5,6)	(1/6,1/5,1/4)
Intermediate 3	(5,6,7)	(1/7,1/6,1/5)
Very Important	(6,7,8)	(1/8,1/7,1/6)
Intermediate 4	(7,8,9)	(1/9,1/8,1/7)
Absolutely Important	(9,9,9)	(1/9,1/9,1/9)

3.2.6 Combination of criteria for suitability map

The final stage of the MCDM entails the production of a suitability map, which evaluates the appropriateness of various regions for the optimal placement of a hydrometric-hydrometeorological station network within the study area. In an MCDM analysis, decision criteria can be combined in multiple ways. The WLC method is integrated into the GIS environment using the Raster Calculator (Map Algebra Toolset). The FS is then calculated using Equation (3.5). If constraints are applicable, Equation (3.6) is used by multiplying the FS value with the constraint layer (ci). FS layers are generated for all alternatives based on factor weighting, and the most suitable sites are selected from positions with the highest FS.

$$FS = \sum w_i x_i \qquad (3.5)$$

$$FS = \Sigma w_i x_i * \Pi c_i \qquad (3.6)$$

Here, FS represents the final value for each cell, where w_i is the weight of criterion i calculated using the AHP method, and x_i is the standardised value of criterion i.

The WLC method is applied separately for each station network to determine the FS for site suitability, using the weights calculated according to the method mentioned above. Since all criteria are expressed using standardised values on the same scale, the resulting suitability map assigns scores ranging from zero to one.

3.3 Geomorphological Unit Hydrograph TB Development

3.3.1 Introduction

The objective of this phase in the methodological framework is to advance hydrological modelling in Greece by proposing an innovative approach centred on developing GUH, named GUHTB for ungauged basins. The aim is to establish relationships based on the geomorphological features of the basin and to provide a valuable tool for precise hydrological assessments in regions where data is sparse. This endeavour involves a statistical analysis that serves as a validation check for the UH computed through the detailed time-area diagram method, ensuring reliability for design purposes. Utilising readily computable indices enhances the practical utility of the approach for design applications. The time-area diagram method is implemented using ArcPy, a Python 2.7.3 scripting language module, to initiate this process. This method, which calculates hydrographs by distributing partial watershed areas contributing to runoff at the watershed outlet relative to travel time, is well-established in hydrological analysis (Theochari and Baltas 2022).

Recent advancements in GIS tools, DEMs, and ArcPy have opened up new possibilities in hydrological research. These tools enable precise determination of hydrological and watershed geomorphological metrics, providing us with a level of accuracy and detail that was previously unimaginable. ArcPy, in particular, proves invaluable in facilitating the processing and analysis of geospatial data, seamlessly integrating the time-area diagram method into a comprehensive and geographically accurate hydrological study. Additionally, GIS tools further enhance the development of SUH models by providing detailed hydrological and geomorphological parameters. GIS facilitates the integration of land cover data with topographic data, thereby enhancing model development.

Furthermore, hydrological data provided by the PPC of Greece mainly observed UH from various watersheds, which inform the determination of optimal channel velocity ranges in the time-area diagram method. System analysis is conducted to optimise the fitting of the time-area diagram model to observed UH, involving simulations at different channel velocity differentiation levels. Concurrently, ArcPy is employed to program geomorphological parameters, further enhancing the efficiency and functionality of the implementation.

This comprehensive approach enables precise hydrograph estimation, even in areas with limited traditional data sources. Morphometric analysis of watersheds assists in interpreting their shape and hydrological characteristics, enabling comparative analyses among different watersheds. Various geomorphological metrics are examined for each basin, and correlations are established with specific GIUH attributes. These empirical relationships establish relationships for each GIUH attribute through regression analysis for 70 drainage basins, shaping the GUH based on the geomorphological metrics of the respective basin. Subsequently, validation regression analysis is performed for 30 drainage basins using the derived equations to ensure the robustness and utility of the developed models in capturing diverse watershed hydrological behaviours.

This dissertation introduces an innovative GUH development method tailored for ungauged basins in Greece. It addresses the challenge of limited data in hydrological studies by offering a more precise alternative to traditional parameter determination. The model enhances GUH's applicability to regions without extensive data, ensuring wide accessibility with its user-friendly nature and basic GIS knowledge requirement. Integrating geomorphological characteristics enhances understanding of hydrological responses, particularly in data-scarce landscapes like Greece. The GIUH approach holds promise for flood management and hydrological predictions in regions with limited data.

3.3.2 Data preprocessing and analysis

The methodology employed in this PhD research involves detailed data preprocessing and analysis to enhance the hydrological modelling of GUHs for ungauged basins in Greece. The initial step in this process is the acquisition of 14 individual UHs from Greece's PPC. These hydrographs vary in duration, including half-hour, one-hour, and two-hour intervals, and are available in different formats. Some come with pre-defined coordinates, while others are only accessible as hard-copy diagrams. In addition to the hydrographs, the PPC provided the watershed basins' boundaries in hard copy form. This supplementary data is crucial for accurately defining the geographical context of each hydrograph and understanding the specific characteristics of the basins they represented. The process of digitising these basin boundaries is detailed, involving using GIS technology to scan and accurately convert the complex copy maps into digital format. This step is crucial to ensure that the digital models of the basins match their real-world counterparts, providing a solid foundation for subsequent hydrological analysis.

A two-pronged approach addresses the challenge of converting hard-copy hydrograph diagrams into a usable digital format. For diagrams without ready coordinates, a digitisation process is employed. This involves scanning the diagrams and using optical character recognition (OCR) technology, complemented by manual tracing of the hydrograph curves. This detailed process ensures the accurate capture of hydrograph data in digital format, which is then systematically entered into Excel for further analysis. The data is directly inputted into analytical tools for hydrographs that are provided with ready coordinates, streamlining the preprocessing phase.

The watershed basin maps provided in hard copy are digitised using GIS technology. This digitisation is critical for accurately representing the basin areas and boundaries within the GIS environment. It involves a careful georeferencing process, where the hard copy maps are aligned with digital maps using common reference points. This ensures that the digital representations of the basins are as accurate as possible, facilitating the precise assessment of basin characteristics and the development of GUHs.

From the initial set of 14 hydrographs, complete and usable data is obtained for eight basins. These selected basins undergo a detailed analysis process, where the hydrographs are standardised to durations corresponding to the size of the basin. Specifically, basins smaller than 40 km^2 are assigned half-hour hydrographs, while larger basins receive one-hour hydrographs. This standardisation process is crucial for creating a uniform basis for analysis and developing the GUH models. The data preprocessing and analysis phase lays the groundwork for an innovative hydrological modelling approach in Greece's ungauged basins. This phase ensures that the GUH models developed are based on accurate and reliable data by effectively converting varied data into a consistent and analysable digital format.

3.3.3 ArcPy Automation: Time-area diagram method

The development of time-area diagram methods aimed to distribute rainfall temporally into a runoff, necessitating data on soil roughness, terrain slope, and the distribution of flow directions and velocities across the watershed (Theochari and Baltas, 2022). A time-area histogram illustrates the portions of a watershed contributing to direct runoff within a specified timeframe. It is derived from a cumulative travel time map featuring isochrones connecting areas within the same travel time zone, reflecting hydrologic and hydraulic characteristics. Travel time is computed from flow velocity based on runoff volume, surface roughness, slope, and stream network (Her and Heatwole 2016).

This dissertation implements the time-area diagram method using ArcPy within ESRI ArcGIS 10.5. ArcPy, a Python site package, extends Python's capabilities, granting access to geoprocessing tools and functions for manipulating GIS data. Integrating Python scripts proves pivotal in significantly enhancing map production efficiency and data quality (Cho 2020). Through ArcPy, users can script and automate tasks encompassing data conversion, georeferencing, feature extraction, and more. It has become widely adopted for diverse general-purpose applications as a high-level programming language (Ryu et al. 2018). ArcPy sees extensive utilisation in developing GIS interfaces for various hydrology applications (Hu et al. 2016, Ali et al. 2019, Ramírez-Cuesta et al. 2020, Mello et al. 2022).

The ArcPy code outlined in this section performs thorough geospatial analysis within the ArcGIS environment, primarily emphasising hydrological parameters within a predefined study area. This area corresponds to the eight basins for which UHs are acquired via the PPC. The script begins by importing essential libraries, such as ArcPy for geospatial processing, NumPy for numerical operations, and others for geospatial processing, data manipulation, visualisation, configuring the environment, and specifying input and output paths. It then configures the script environment by enabling overwrite mode and defining paths for input and output folders and files. This setup ensures the script can update existing data without manual intervention and efficiently organises file storage. Paths to critical datasets, such as DEM and land cover, are specified. Acquiring a Spatial Analyst extension license is crucial for unlocking advanced spatial analysis capabilities. The subsequent step involves using the ExtractByMask tool to extract the DEM within the defined study area, serving as the foundation for subsequent analyses, including flow direction and accumulation calculations. Stream delineation follows, employing the Strahler method to determine stream order. Parameters for stream definition can be adjusted based on the characteristics of the basin. The slope and the square root of the slope are then computed for terrain characterisation. Beyond topographical analyses, land cover assessment utilises the CLC dataset. This process involves clipping the Corine Land Cover (CLC) vector data for Greece to match the extent of the study area and converting it into a raster format for compatibility with other geospatial analyses.

Calculating velocities, both overland and within the channel plays a pivotal role in hydrological modelling. Merging these velocities into a mosaic provides a comprehensive view of hydrological dynamics. Overland velocity integrates land cover and slope information, while channel velocity is determined based on stream order. Various empirical methods, including those linked to Manning's roughness coefficient, have been explored for computing overland velocity. For instance, equation (3.7) represents one such formula:

$$Voverland = k * \sqrt{J} \tag{3.7}$$

Where k is a roughness coefficient primarily associated with soil cover (m/s), and J denotes the mean slope of the watercourse (m/m).

The roughness coefficient is dependent on the physiographic characteristics of the study area, reflecting the inherent uncertainty in its determination. The literature often presents a wide range of values for this parameter in overland flow, indicating variability based on different environmental conditions. The values for the roughness coefficient are extracted from tables proposed by Haan et al., 1994, and McCuen, 1997.

A system analysis employing simulation methodology is conducted to analyse the impact of channel velocity on UH generation via the time-area diagram method. This approach allows for the differentiation of velocities within the range of 0.1-2.0 m/s to 0.1-6.0 m/s, while other parameters remain constant. The time-area diagram method is applied to the eight hydrographs, and the Nash-Sutcliffe Efficiency (NSE) is calculated to identify the channel velocity range that best fits these hydrographs. The simulation varies velocities incrementally, ranging from 0.1 m/s to 2.0 m/s and extending up to 0.1-6.0 m/s. This methodical variation helps to determine the optimal velocity settings for accurate hydrograph modelling precisely.

The selected channel velocity range is justified for Greek conditions based on hydraulic simulations conducted across various drainage basins in the country. Maximum velocities observed within Greek hydrographic networks have reached up to 6 m/s, particularly in mountainous basins with steep slopes, characteristic of Greece's topography. This comprehensive approach aims to capture the variability in velocity that aligns with observed hydrographs across diverse hydrological conditions in Greece, ensuring the model's relevance and accuracy in predicting water movement.

After calculating overland and channel velocities, the two sets are combined using the "Mosaic to New Raster" tool to generate a comprehensive velocity raster. This raster is then utilised in subsequent calculations. A weight raster, indicating the reciprocal of velocity, is produced to further refine the analysis by dividing 1.0 by each cell value in the velocity raster. This technique effectively inverses the velocity, facilitating calculations where slower velocities carry more weight, such as in the accumulation of flow or retention time assessments. This step is designed to facilitate flow accumulation calculations. The resulting weight raster holds values inversely proportional to velocity, effectively representing areas where flow is slower as having higher weight.

Utilising the FlowLength tool, flow length is then computed based on the downstream direction, incorporating the weight raster. This produces the accumulation raster, which indicates the accumulated distance travelled by flow from each cell. The flow accumulation values are converted from seconds to hours to introduce temporal considerations into the model. This conversion is crucial for rendering the data suitable for temporal analysis, allowing for a more nuanced understanding of how water flows and accumulates over time within the watershed. This process involves dividing each cell value by 3600 to convert the accumulation raster from meters to hours, ensuring the representation of flow duration rather than just distance. Reclassification of the accumulation raster then allows for dynamic adjustments based on the specific characteristics of different basins, tailoring the analysis to the unique hydrological behaviour of each area. Subsequent data processing and analysis include extracting values from a table or feature class, manipulating this data, and plotting a line graph to represent the findings visually. Additionally, a function calculates the NSE for each hydrograph, measuring model accuracy.

The script offers a systematic approach to hydrological analysis that is adaptable to a variety of scenarios. The results of this analysis contribute to the development of the GIUH for each basin. These steps prepare the data for comparative analysis, enhancing the potential for further insights and visualisations. In this process, the script includes a function to calculate the NSE, which is crucial for assessing hydrological models' predictive accuracy and reliability. This function takes two lists as inputs: 'observed', which contains measured values, specifically UH values for each of the eight drainage basins, and 'simulated', which represents predicted values based on the model. The function then calculates and returns the NSE, providing a quantitative measure of how well the simulated hydrographs match the observed data, thus validating the effectiveness of the hydrological models developed.

This comprehensive approach significantly enhances the script's functionality, enabling it to assess not only the spatial characteristics of the basins but also to correlate these findings with the corresponding hydrograph information.

By integrating spatial data with hydrological dynamics, the script facilitates a deeper understanding of how geographical features influence water flow and retention. This integration allows for more precise predictions and assessments, crucial for effective water resource management and planning in diverse hydrological environments. The NSE results are printed and can be utilised for further analysis, providing a quantitative basis to evaluate the performance of the hydrological models.

Figure 3-6 depicts the flowchart of the ArcPy code developed for the time-area diagram method. Careful attention to detail throughout the script ensures a comprehensive and systematic approach to hydrological analysis. In summary, this ArcPy script offers a step-by-step methodology for hydrological analysis, integrating diverse geospatial operations to derive meaningful insights from the landscape. Using conditional logic enhances the analysis's flexibility and reliability, enabling its applicability across various locations and scenarios. This approach not only facilitates accurate hydrological modelling but also adapts to the unique conditions of each study area, thus proving indispensable for effective water resource management.

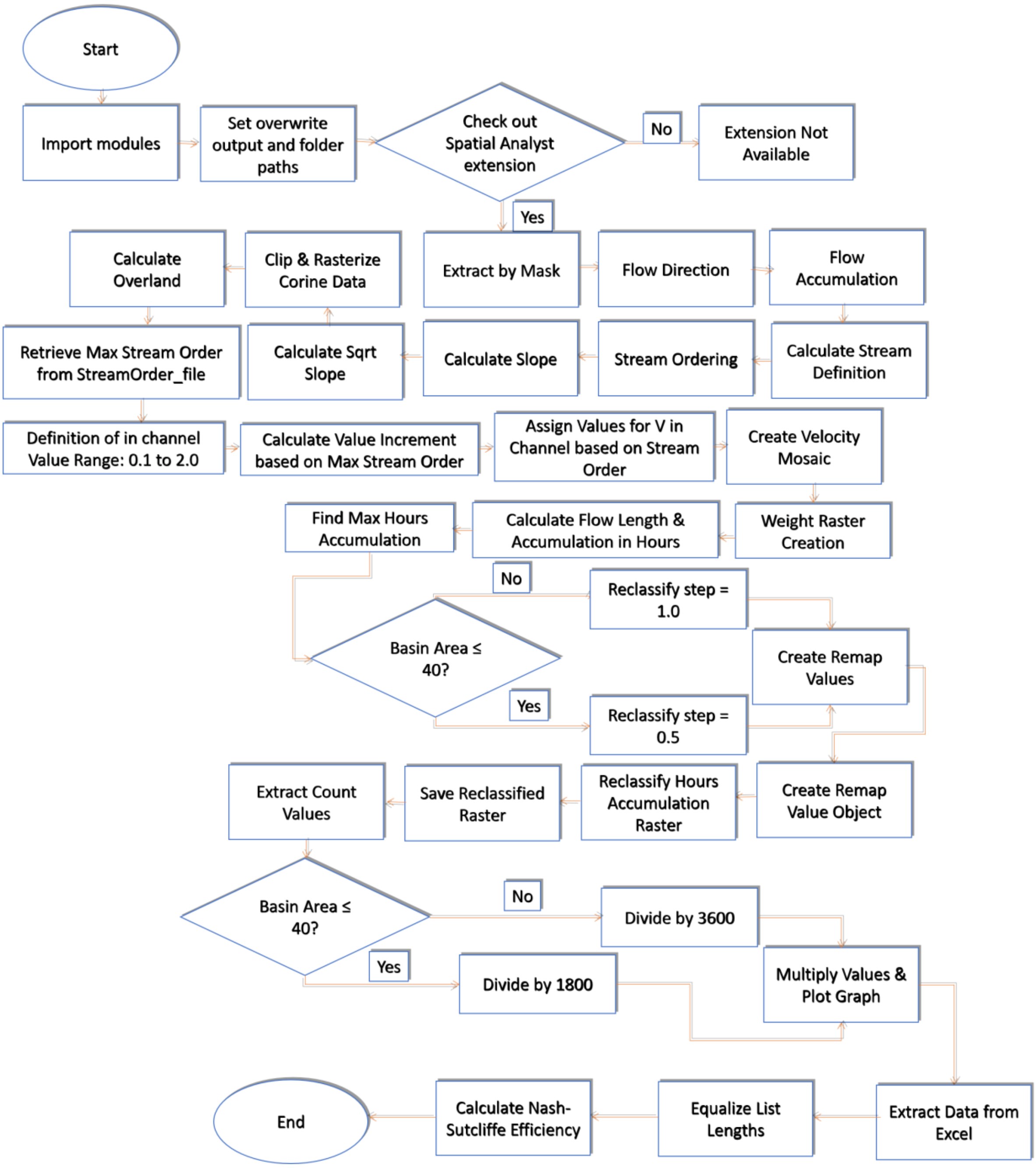


Figure 3-6: Flowchart illustrating the ArcPy code developed for the time-area diagram method.

3.3.4 Geomorphological metrics computation through ArcPy programming

A fundamental aspect of this phase of the methodological framework involves the detailed calculation of GIUH attributes. These measurements are determined through complex calculations that rely on the geomorphological metrics characterising the specific basin under consideration. Morphometry measures and mathematically analyses the configuration, shape, and dimensions of the Earth's surface and landforms. Morphometric analysis includes the assessment of linear, areal, and relief aspects of a basin, as well as contributions from slope (Rudraiah et al. 2008).

This dissertation investigates seven key geomorphological metrics to provide a comprehensive understanding of basin characteristics. ArcPy programming is crucial for performing these detailed calculations and establishing a robust and efficient framework for computing geomorphological metrics essential for hydrological modelling. Leveraging ArcPy's capabilities can automate complex spatial analyses, streamline data processing tasks, and enhance the accuracy and reproducibility of the resulting hydrological models. Integrating advanced programming within the GIS environment facilitates a more dynamic and precise approach to understanding watershed behaviour under various hydrological conditions.

One such metric, elongation ratio (Re), quantifies the relationship between the diameter of a circle with the same area as the drainage basin and the maximum length of the basin. In the context of subbasins, elongation ratio values typically range from 0.45 to 1.12. These values exhibit variation between 0.6 and 1.0 across diverse climatic and geological types (Rudraiah et al. 2008).

Another metric, drainage density (DD), influenced by climate, rock type, relief, infiltration, vegetation, surface roughness, and runoff intensity, represents the total stream length per drainage area. Surface roughness shows no significant correlation with DD (Rudraiah et al., 2008). DD varies based on factors such as soil resistance, vegetation density, and relief. Smith 1950 categorised drainage density into five texture classes: very coarse (< 2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8), and very fine (> 8).

Regarding drainage texture (T), according to Horton 1945, it represents the total number of stream segments of all orders per perimeter of a specific area. Horton also emphasises the crucial role of infiltration capacity in affecting T, incorporating DD and stream frequency (FS). Smith 1950 further classifies drainage texture into five categories based on drainage density, with values less than 2 indicating very coarse texture, 2 to 4 as coarse, 4 to 6 as moderate, 6 to 8 as acceptable, and values greater than 8 signifying very fine drainage texture. As defined by Horton 1932, FS refers to the total number of stream segments of all stream orders per unit area. There is optimism that basins sharing the same drainage density may exhibit differences in stream frequency, and basins with identical stream frequency could display variations in drainage density (Rudraiah et al., 2008).

Circularity Ratio (Rc), defined by Miller in 1953, represents the ratio of the watershed area to the area of a circle with an equivalent perimeter. The Rc typically ranges from 0.2 to 0.8 or ≤ 1. Values above 0.5 indicate increased circularity and homogeneity in geological material. In contrast, values below 0.5 suggest an elongated watershed shape (Malik et al. 2019). Form factor (FF), defined as the ratio of the basin area to the square of the basin length, was introduced by Horton in 1932. The FF, which consistently exceeds 0.78 for a perfectly circular basin, indicates that a smaller FF value corresponds to a more elongated basin shape (Rudraiah et al., 2008). Finally, the compactness coefficient (Cc), introduced by Strahler 1964, represents the ratio of a watershed's perimeter to that of its equivalent circular area. Cc consistently exceeds 1, indicating the presence of more compact sub-watersheds when its value is greater than 1 (Malik et al. 2019).

3.3.5 Geomorphological unit hydrograph derivation

In the current dissertation, the time-area diagram method is applied to analyse the hydrograph attributes, as mentioned earlier, of 70 drainage basins within the selected study area, comprising a total of 100 basins as depicted in Figure 3-7. The primary objective is to compute the UH for each basin. This method involves correlating various hydrograph attributes with corresponding geomorphological metrics for each basin. Such correlations establish relationships between hydrograph attributes and morphometric metrics, essential for defining the GUH for each basin.

The relationships derived from these correlations are then used to formulate equations that express each hydrograph attribute in terms of the associated morphometric parameter. Subsequently, a validation regression analysis is conducted using the remaining 30 basins out of the total 100. This analysis aims to identify the most suitable regression equation for each hydrograph attribute based on calculated statistical measures, including Coefficient of Determination (R^2), Mean Absolute Error (MAE), and RMSE. These indices are crucial for assessing the regression models' accuracy and effectiveness, aiding in identifying the most reliable equations for predicting hydrograph behaviour within the studied watershed.

Combining the time-area diagram method with validation regression analysis, this integrated approach provides a comprehensive understanding of hydrograph characteristics and their relationship with geomorphological metrics. It contributes valuable insights to watershed management and hydrological modelling endeavours, enhancing the capability to effectively predict and manage hydrological responses in various basins. This methodology not only aids in the direct application within the study area but also serves as a model for similar hydrological studies in other regions.

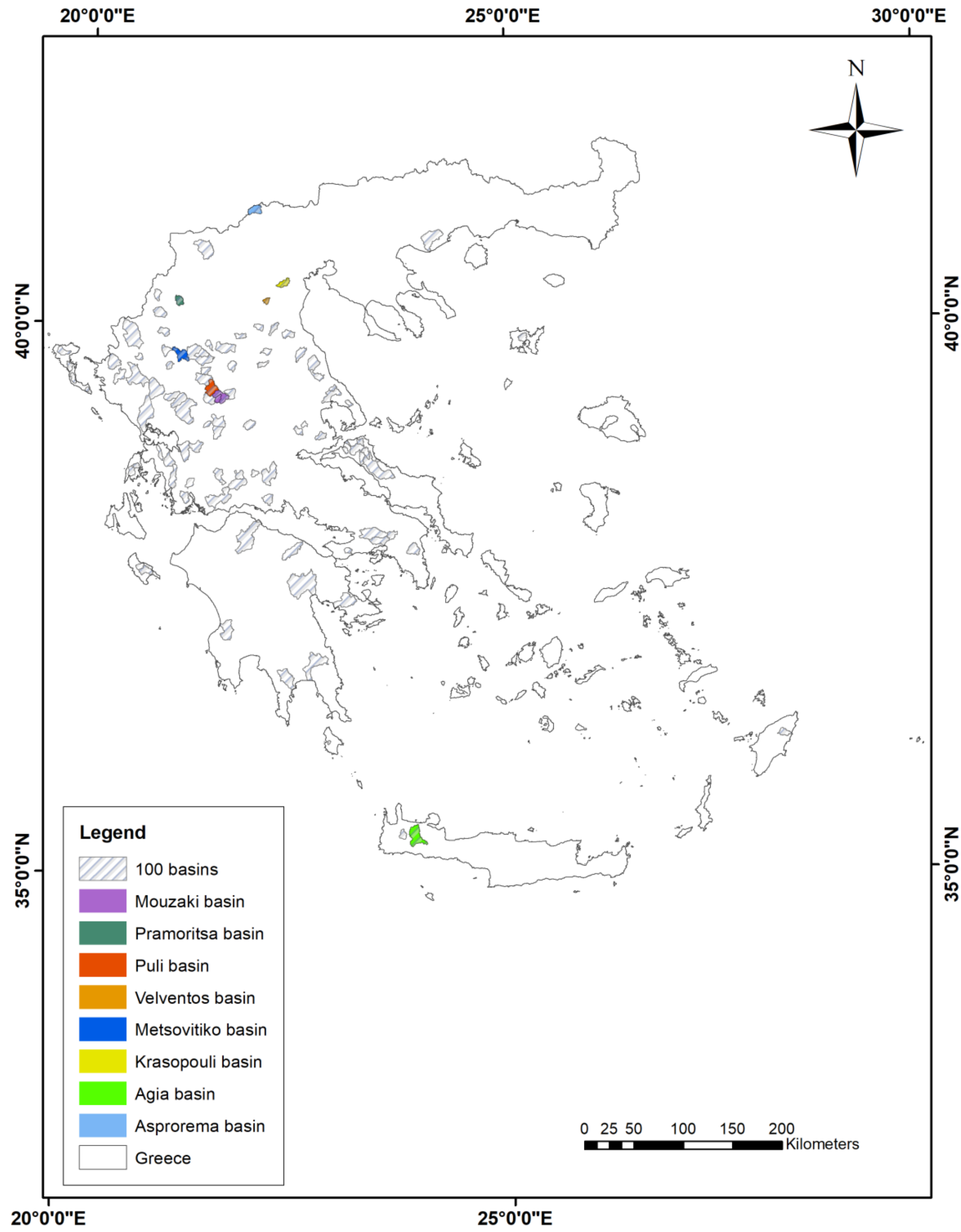


Figure 3-7: The selected basins for GUH development. Source: (Theochari and Baltas 2024 b)

3.4 Nature -Based Solutions Analysis

3.4.1 Introduction

The aim of this stage within the methodological framework is to introduce the implementation of two NBS—specifically, land cover change and the construction of retention ponds, as well as a combination of the two—within the Sarantapotamos river basin upstream of the Magoula settlement in Greece. Furthermore, the efficiency of these NBS is evaluated by analysing flood hydrographs at the basin outlet through detailed hydrological analysis. This stage investigates both pre- and post-NBS conditions under current climate scenarios and anticipates the implications of future climate change scenarios. By doing so, it assesses the potential modifications in hydrograph characteristics such as peak discharge, volume, and time to peak discharge, providing a comprehensive understanding of how these interventions could mitigate flood risks. The evaluation focuses on immediate hydrological responses and integrates long-term climate resilience into the planning and implementation of NBS, ensuring sustainable water management practices that align with environmental conservation and flood risk reduction objectives. The scenario before the implementation of NBS serves as a baseline for comparison, encompassing current and projected future climate conditions.

IDF curve equations, crucial for projecting future design precipitations, are adapted from Kourtis et al. 2023. This adaptation allows for assessing NBS within the context of both average and worst-case climate scenarios. The hydrological analysis employs the User-Specified (US) Unit Hydrograph (UH) method as a rainfall-to-runoff transformation technique, utilising Hydrologic Modeling System (HEC-HMS) software to compare different scenarios. This analysis is pivotal in evaluating the performance, efficiency, resilience, and adaptability of the NBS under various climatic conditions.

The study area is chosen due to its susceptibility to floods and significant flood history, with recurrent flooding events posing considerable hazards to the local population and environment. The innovation is valuable to the growing knowledge of NBS, particularly in how they enhance flood resilience and safeguard settlements downstream of a basin outlet. In this context, this dissertation outlines a practical methodology for NBS implementation and extensively assesses resulting flood hydrographs under current and future climate conditions. Such evaluations are essential for determining the effectiveness of NBS in FRM, providing valuable insights for environmental agencies, policymakers, and local communities in developing and refining flood mitigation strategies.

3.4.2 Hydrological analysis

Flood hydrograph computation before and after NBS

A hydrological analysis uses the HEC-HMS software to compute the flood hydrographs at the basin outlet and compare them before and after implementing NBS. This analysis involves several components for simulation, including a basin model, a meteorological model, control specifications, and a time-series data manager (USACE 2018). Each component employs specific methods to calculate runoff volume, direct runoff, channel flow, and base flow. Specifically, the US UH method converts rainfall into runoff, requiring a UH input in HEC-HMS. Furthermore, the time-area diagram method is implemented within a GIS environment, where a sequence of commands computes the UH, considering the basin's physical attributes like the DEM and the vector CLC file. The core concept of this approach is depicted by the time-area diagram histogram, illustrating the distribution of partial watershed areas contributing to runoff at the watershed outlet based on travel time (Theochari and Baltas, 2022).

For the HEC-HMS simulation, rainfall data is a crucial input where a precipitation design corresponding to a specific return period of 100 years is determined. To ascertain the rainfall intensity for this return period, a rainfall duration of 24 hours is considered. The process involves computing the distribution of rainfall depths and the design of the precipitation hyetograph using the Alternating Block Method, which utilises the IDF curve from the Mandra hydrometeorological station. This method applies the IDF curve to establish the temporal distribution of rainfall, strategically placing the rainfall peak at the centre. Following the Mononobe model discussed by Na and Yoo 2018, significant rainfall intensities are alternately positioned to the right and left of the peak.

Furthermore, the SCS CN method is selected to estimate losses in hydrological modelling using HEC-HMS. This method involves assigning CN values based on the types of land cover and geology present within the basin. To facilitate this, a spatially distributed vector file of the CN is created within a GIS environment, adhering to the methodology outlined by Wanielista et al. 1996. The CN value ranges from 0 to 100, indicating the runoff potential of specific land cover and soil types. Lower CN values signify a higher infiltration capacity, reflecting less potential for runoff and more for absorption (Viji et al. 2015). An average CN value of 67 is calculated based on the basin's composite land cover and soil characteristics and is then input as a parameter into HEC-HMS. This CN value plays a critical role in the model, significantly influencing the estimation of runoff volumes from rainfall events.

Subsequently, the flood hydrograph is computed by integrating this loss estimation with the rainfall input and other hydrological processes modelled in HEC-HMS. This comprehensive approach allows for a nuanced analysis of how different land covers and soil types within the basin contribute to flood dynamics, providing valuable insights for flood risk management and mitigation strategies. Once the NBS for implementation has been determined, the hydrological analysis is repeated using HEC-HMS to assess the effectiveness of these interventions. Specifically, to compute the post-land cover change flood hydrograph, a new Curve Number (CN) value is calculated to reflect changes in land cover within the basin's polygons. These changes result in varied CN values, as illustrated in Figure 3-8. Due to the alterations in land cover polygons, a new average CN value of 62 is computed and then input into HEC-HMS, while all other data remains unchanged. This updated CN value is crucial because it directly affects the runoff calculation, reflecting the increased infiltration and reduced runoff potential due to the implemented land cover changes.

The new flood hydrographs are then compared with those from the pre-NBS scenarios. This comparison is instrumental in evaluating the effectiveness of the NBS by observing the reduction in peak discharge and overall runoff volumes. Such insights are valuable for understanding the potential flood risks and the effectiveness of the implemented measures in mitigating those risks, contributing to a more resilient and sustainable management of the watershed. This process highlights the importance of adaptive management strategies in flood risk reduction and underscores the role of strategic land cover management in enhancing hydrological responses to rain events.

In the case of implementing NBS, such as the construction of retention ponds, the initial hydrological analysis plays a crucial role. This analysis, conducted before the installation of retention ponds, indicates that it's necessary to decrease the volume of the initial flood hydrograph by approximately 75% of the ascending limb's volume to manage flood risks effectively. The design of the retention ponds is then formulated based on the surplus volume determined above the expected peak discharge, as identified through the hydrological analysis. By achieving a 75% reduction in the ascending limb of the flood hydrograph via NBS implementation, the peak discharge is kept at a manageable level and remains within safe limits. This protects the local infrastructure and communities from the immediate dangers of flooding and contributes to the long-term sustainability and resilience of the watershed.

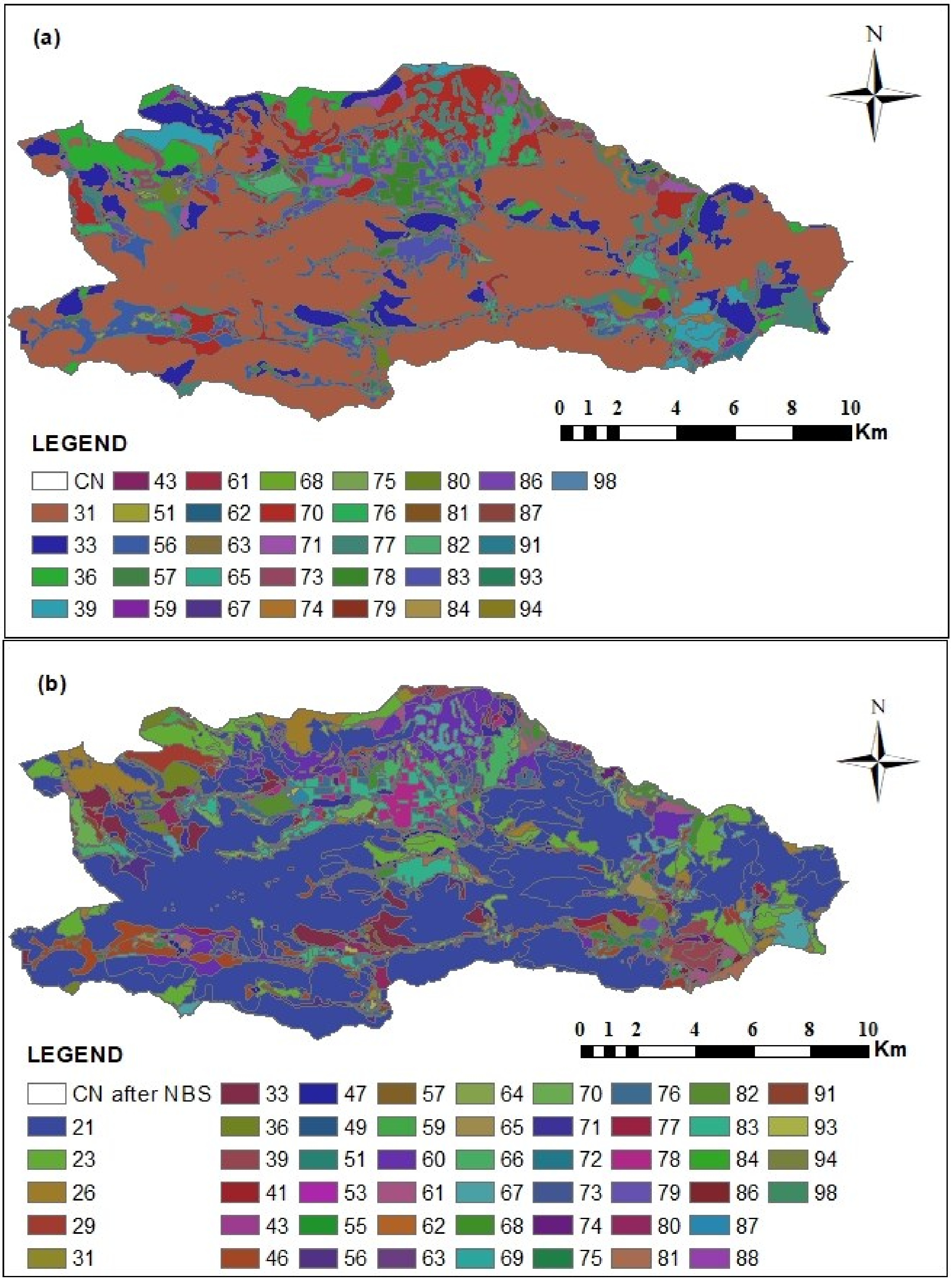


Figure 3-8: Comparison of Distributed Curve Number (CN) Values, a) Before and b) After Land Cover Changes. Source: (Theochari and Baltas 2024 a)

Flood hydrograph computation under climate changes

Following the previous hydrological analysis outlined, an additional examination is conducted to account for the effects of climate change. This analysis is crucial as it aims to predict the flood hydrograph for various future scenarios and assesses the efficacy of NBS under both mean and extreme climate conditions. Consequently, to accurately model these future conditions, necessary adjustments are made to the design precipitation inputs and the IDF curves traditionally used. The updated IDF curves are derived from the work of Kourtis et al. 2023. This research updated the IDF curves based on rainfall data collected from the Thissio meteorological station. Kourtis and colleagues employed bias-corrected and temporally disaggregated climate projections, utilising an empirical model initially proposed by Sherman in 1931. Specifically, they used the Generalized Extreme Value (GEV) distribution method without scaling to analyse the 1-hour annual maxima series, providing a refined tool for understanding and predicting rainfall intensities under future climate scenarios.

The development of future IDF curves by Kourtis et al. 2023 is a comprehensive approach designed to accommodate the projected climate changes spanning the hydrological years from 2021-2022 to 2099-2100. These curves are crucial for updating the understanding of rainfall patterns under changing climatic conditions with an acceptable spatial resolution of 0.11° and a daily temporal resolution. Three distinct future IDF curves have been produced to capture the breadth of climate variability and potential future scenarios. Each curve corresponds to different climate scenarios, encapsulating a broad uncertainty spectrum. This is achieved through the use of bootstraps for all climate models, including General Circulation Models (GCMs) and Regional Climate Models (RCMs), as well as for various climate scenarios, mainly focusing on Representative Concentration Pathways (RCPs) 4.5 and 8.5. Additionally, various bias correction methods are employed for spatial downscaling and bias correction to ensure the reliability and applicability of the projected data. Kourtis et al. 2023 have thoroughly examined the climatic aspects involved in developing these IDF curves. Their methodology incorporated two general circulation models, four regional climate models, two representative concentration pathways, five bias correction techniques, two temporal disaggregation approaches, and two probability distributions.

This extensive range of models and methodologies underlines the complexity and variability inherent in climate modelling and emphasises the need for robust techniques to predict future climate scenarios accurately. Using these future IDF curves is critical for assessing the impact of climate change on hydrological patterns and for updating current infrastructure and planning practices to better handle anticipated changes in precipitation intensity and frequency. The reliance on projections from GCMs is pivotal, as these models provide the fundamental data necessary for simulating the interactions of the atmosphere, oceans, land surface, and ice. These models are essential for understanding global climate dynamics and making regional predictions that inform local climate adaptation strategies.

Recognising the limitations of GCMs, particularly their coarse spatiotemporal resolution, there is a recognised need for refinement through dynamic and/or statistical downscaling techniques. This refinement is crucial as it addresses the scale mismatch between global projections provided by GCMs and the regional or local scales required for practical climate impact assessments.

As detailed by Kourtis et al. 2023, dynamic downscaling involves using RCMs driven by GCM outputs under various climate scenarios, including RCPs or the earlier Special Report on Emissions Scenarios (SRES). This method provides a more detailed and regionally specific understanding of climate phenomena by enhancing the resolution of the climate data. In their study, Kourtis et al. 2023 utilised empirical bootstrapping methods to handle the uncertainty inherent in climate modelling. This involves generating an ensemble mean representing the future mean intensity, calculated across multiple model runs and scenarios. Furthermore, upper and lower intensity bounds have been established at ± 95% confidence intervals to capture the range of possible outcomes, also derived using the bootstrapping approach. This methodology provides a mean estimate and quantifies the uncertainty around this mean, presenting a more comprehensive view of potential future climate conditions.

Integrating dynamic downscaling with bootstrapping techniques allows for a robust analysis that can accommodate the variability and uncertainty of climate projections. This approach is instrumental in translating the coarse-scale information provided by GCMs into actionable insights at a regional level, thereby enhancing the reliability and applicability of climate data for planning and decision-making in the context of climate adaptation and risk management.

Integrating future IDF curves into the hydrological analysis enhances understanding of potential changes in rainfall patterns and intensities due to climate change, providing a comprehensive view of the future hydrological responses within the study area. The choice to use IDF data from Thissio station instead of the closer Mandras station is justified by several reasons. Thissio station offers a long-spanning, comprehensive dataset crucial for historical data analysis and the development of rainfall models within the Attica region, unlike Mandras station which has limited recent data. Additionally, the similarity in elevation and climate conditions between Thissio and the study area ensures the applicability of the data; the proximity in elevations supports that rainfall patterns observed at Thissio station accurately represent those in the study area. Furthermore, the spatial resolution of Thissio station’s rainfall data at 12 km effectively covers the region of interest, providing a reasonable representation of rainfall patterns and variations in the study area.

Following the updated hydrological analysis, three flood hydrographs are calculated for future upper, mean, and lower intensities based on design precipitations from mean and worst-case climate scenarios. This new hydrological analysis evaluates the effectiveness of NBS. The NBS measures are aimed at reducing peak discharge and mitigating flood impacts. The analysis offers valuable insights into flood risk mitigation by applying NBS to the hydrological model and comparing the resulting flood hydrographs with the baseline scenario. This comprehensive approach informs decision-makers on selecting and implementing suitable NBS measures to reduce future flood impacts effectively.

3.4.3 Implementation of NBS

Land cover changes

Following the hydrological analysis, the appropriate NBS are chosen and integrated into the basin. A systematic methodology is employed to implement NBS related to land cover change. Initially, a thorough analysis of land cover patterns within the basin is conducted using the CLC dataset 2018. The advanced spatial analysis capabilities of the ArcGIS (ESRI 2010) environment are used to comprehensively assess the distribution and characteristics of various land cover types. Identifying areas suitable for land cover modification involves examining regions with low human utilisation or those deemed non-essential for human survival. Special attention is also given to areas with limited capacity to absorb runoff water effectively. This typically includes transitional woodland/shrub, sparsely vegetated areas, and regions affected by burns. Such areas are considered prime candidates for land cover change due to their low ecological functionality and high potential for improvement.

A strategic decision is made to replace these less effective land cover types with broad-leaved forests. This choice is based on the multiple benefits that broad-leaved forests bring to flood management and ecological enhancement. Broad-leaved forests are known for their exceptional water retention capabilities, which can significantly mitigate flood risks by reducing runoff and increasing water infiltration. Additionally, these forests enhance biodiversity, providing habitat for various wildlife species and supporting overall ecosystem health and resilience. This approach not only aims to reduce the immediate and direct impacts of floods but also contributes to the long-term sustainability and resilience of the watershed. By enhancing the natural landscape through strategic land cover changes, the implemented NBS foster a more balanced and healthier watershed that can better withstand climatic variations and extreme weather events.

Once suitable areas are identified within the basin, detailed attention is given to selecting appropriate broad-leaved forest species and sourcing suitable plant material. This process involves assessing the species' adaptability to local weather, soil conditions, and water patterns, ensuring they are well-suited for successful growth. In the study area, oak and plane tree forests are recommended as the preferred broad-leaved species.

A significant landscape transformation occurs by converting 61 km² to broad-leaved forest, marking a notable change in land cover. Specifically, this includes replacing 59.4 km² of transitional woodland/shrub, 1.5 km² of sparsely vegetated areas, and 0.25 km² of burnt areas with broad-leaved forest. This strategic selection of species and regions enhances the basin's resilience and sustainability, contributing to better flood management and ecosystem stability. Figure 3-9 illustrates the land cover before and after the change, with intervention areas highlighted in fuchsia pink to depict the extent of this transformation.

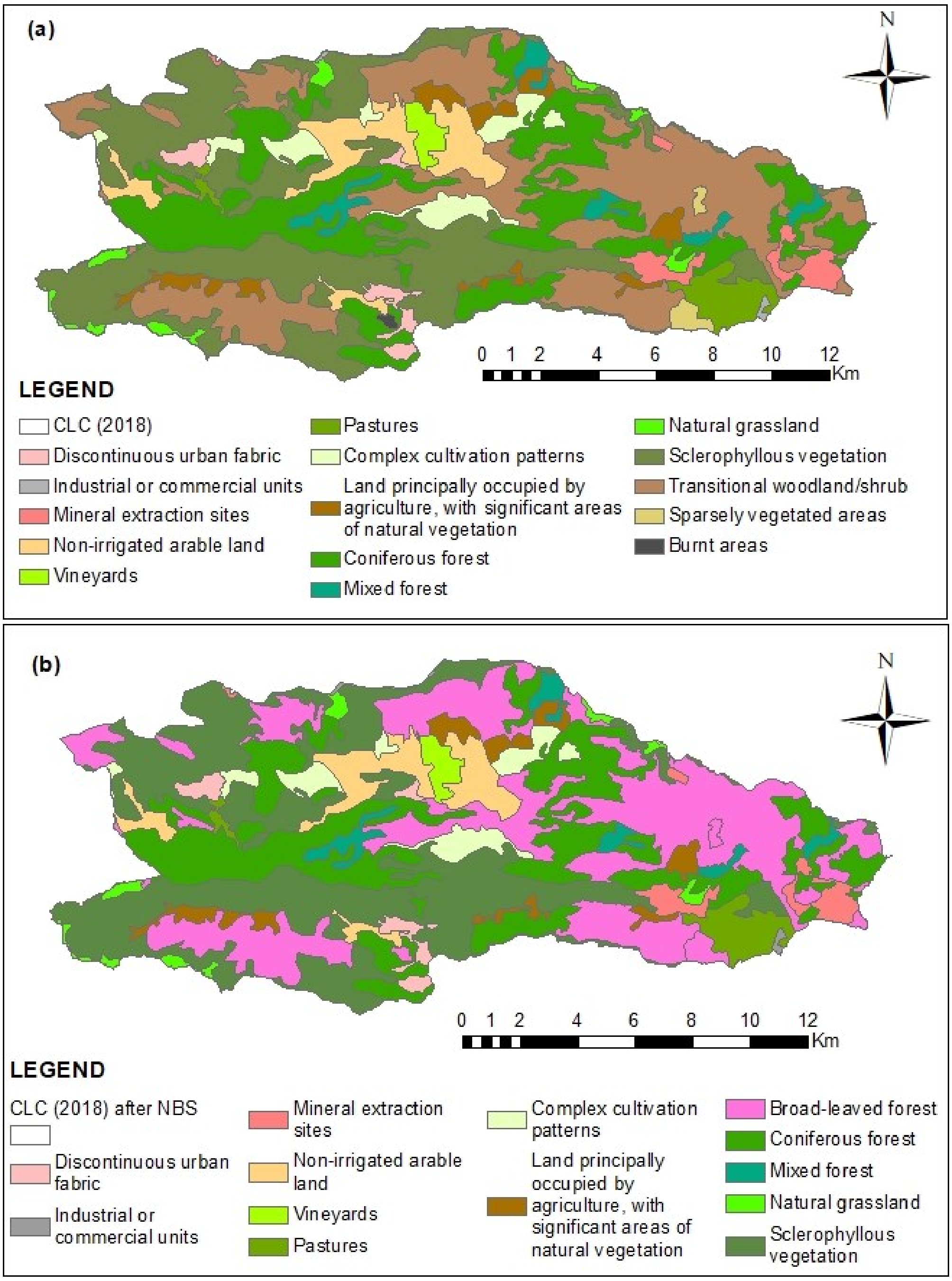


Figure 3-9: Corine Land Cover (CLC), a) before and b) after the implementation of Nature-Based Solutions (NBS) Source: (Theochari and Baltas 2024 a)

Additionally, the study extends its investigation to the particular case of land use changes in the fire-affected regions of Northern Evia following the catastrophic blaze of August 2021. This inclusion aims to assess the efficacy of NBS tailored for areas devastated by wildfires, marking a significant expansion of the project's scope. This broader approach addresses the immediate needs of flood prevention and ecological enhancement. It explores the potential for NBS to contribute to long-term recovery and resilience in areas impacted by severe environmental disturbances.

Retention ponds construction

Retention ponds significantly enhance the resilience of residential areas by mitigating the impacts of extreme weather events, such as heavy rainfall and increased flood risks, exacerbated by climate change. These ponds serve as natural buffers, absorbing and retaining excess water and thus reducing communities' vulnerability to flooding. Typically constructed alongside flood-prone rivers, retention ponds redirect and retain excess river discharge during high flows, utilising low-lying river areas as adequate storage spaces (Chan et al., 2020).

Various methods are employed to establish retention ponds. These include utilising pre-existing natural depressions in the landscape, excavating new depressions, or constructing embankments to create the necessary storage space for excess water (European Commission 2013). Each method is chosen based on the area's specific environmental and geographical conditions, aiming to maximise the efficiency and sustainability of the water management system.

In this stage of methodological framework, an extensive review of existing literature (e.g., Mardjono et al. 2022; Munfarida and Rizal 2022; Ferk et al. 2020; Staccione et al. 2021; Collentine and Futter 2018) is conducted to gather insights and evaluate the effectiveness of retention ponds in flood risk management. However, the author ultimately determines the design criteria for retention ponds based on the region's topography, the slopes, the river network's density, and the cross-section study. While the number of ponds directly influences the overall cost of the integrated design, this analysis primarily focuses on assessing the effectiveness of the number of retention ponds in managing flood risks. The central concept of designing these retention ponds involves establishing a system of ponds along the mainstream on both sides, strategically using non-exploitable land areas. Given their shallow depth and placement on relatively flat terrains, the construction of these retention ponds primarily requires small-scale earthworks, distinguishing them from more intensive "grey" infrastructure projects. The soil excavated during the pond construction is repurposed for perimeter reinforcement, often forming earthen embankments that help contain the water.

Based on the hydrological analysis conducted before implementing NBS and assuming a targeted 75% reduction in the volume of the initial flood hydrograph, the peak discharge post-NBS implementation is anticipated to decrease substantially. This reduction aims to maintain the peak discharge at approximately 75% of the ascending limb's volume, roughly 383 m^3, following a horizontal line. This 75% value is an indicative maximum flow rate to reduce the flow dictated by the necessary technical work based on the hydrograph shape derived from a small catchment. Consequently, the volume encompassed by the initial flood hydrograph above the horizontal line representing the desired new peak discharge corresponds to the total volume targeted for the design of the retention ponds, calculated to be 3.3 hm^3 according to the diagram. This volume represents the excess water above the desired peak discharge, effectively managed by the constructed ponds. The shape of the retention ponds is selected to be elliptical, with a major axis of 80 m, a minor axis of 20 m, and a depth of 2 m, based on sound engineering principles aimed at avoiding excessive earthworks that would incur ecological and economic costs. The distance between the ponds is deemed suitable and designed to be 10 m. Additionally, it is assumed that each retention pond will have an area of 5024 m^2, resulting in a volume of 13.397 m^3. Considering all these factors, it is concluded that the total number of ponds to be designed is 245. These ponds will be strategically positioned on both sides of the river in areas covered with sclerophyllous vegetation, coniferous forest, and mixed forest, which are not exploitable for other human uses.

The detailed pond designs are created using AutoCAD Civil 3D 2023, as depicted in Figure 3-10. However, implementing this NBS involves specific challenges, particularly concerning maintenance costs. As the ponds are designed to receive surface water runoff, sediment accumulation at the bottom is inevitable. Regular maintenance is required to ensure effective operation, including removing accumulated materials. Additionally, preventive measures can be implemented upstream of the ponds to serve as sediment retention works, further enhancing their functionality and reducing maintenance needs. This comprehensive approach not only mitigates flood risks but also incorporates considerations for long-term sustainability and cost-effectiveness.

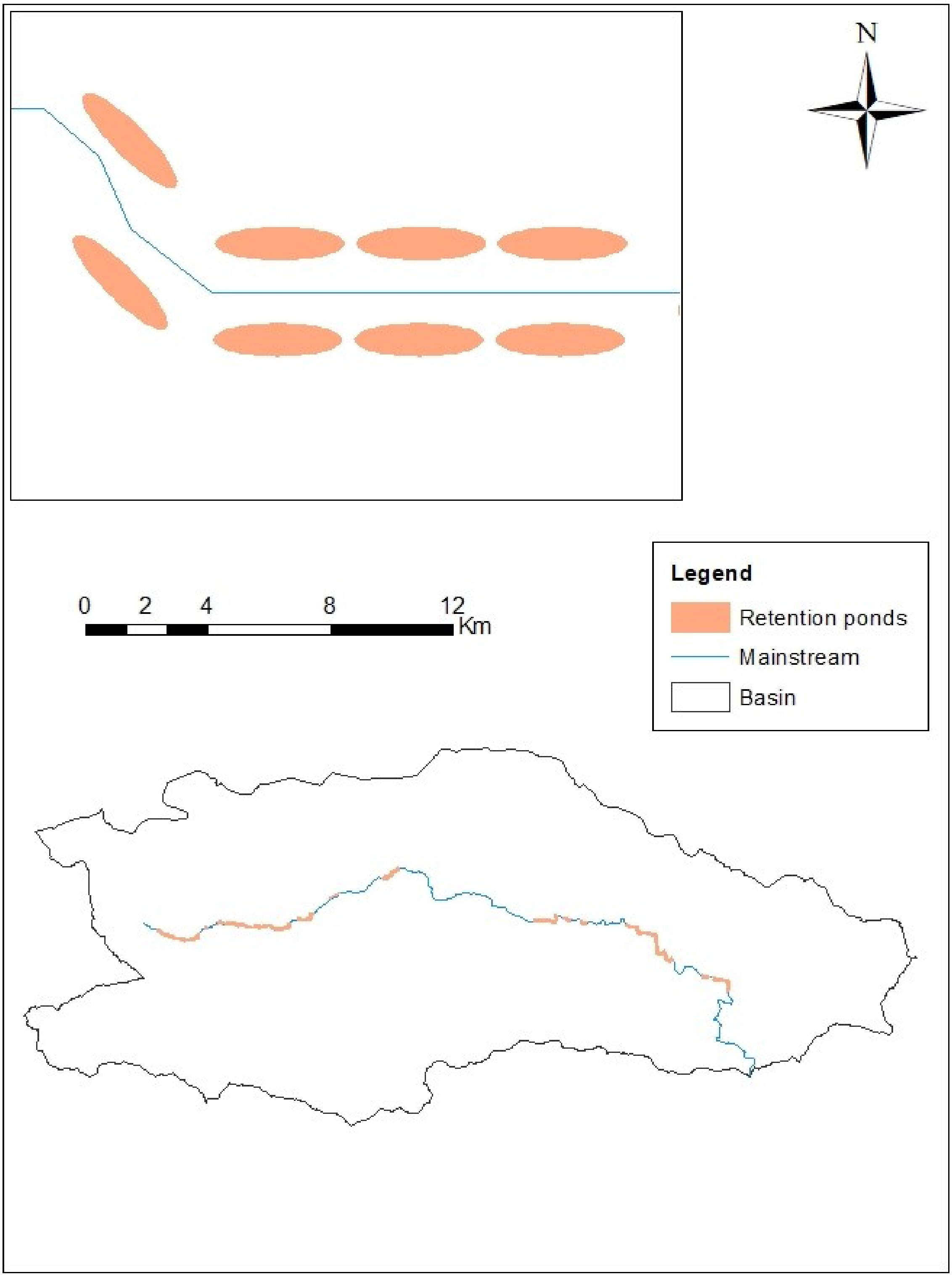


Figure 3-10: The retention ponds along the mainstream
Source: (Theochari and Baltas 2024 a)

4. Results and Discussion

4.1 Optimal Hydrometric-Hydrometeorological Station Network Design

4.1.1 Optimal hydrometric station network design

According to the methodology outlined in Section 3.2, two methods are employed for GIS-based MCDM in station network design. The first method concentrates on hydrometric stations and adopts an integrated approach considering various criteria with differing weights. The second method, applied to hydrometeorological stations, uses equally weighted criteria as constraints.

Concerning the hydrometric station network, The AHP method determines the criteria weights. Specifically, as depicted in Table 4-1(a), pairwise comparison matrices are constructed for each scenario by assessing the relative importance of each pair of criteria using Saaty's pairwise comparison scale 1977. Acknowledging the potential subjectivity in these comparisons, an additional scenario is presented where weighting values are obtained from an FAHP approach, as shown in Table 4-1(b). Consequently, "Scenario 3" is denoted as "3a" under the AHP method and "3b" under the FAHP approach. The pairwise comparison using FAHP also incorporates the TFN for each comparison. Fuzzy pairwise comparisons suggest that if a criterion is significantly less critical than others, its weight is practically zero. This means that even if a criterion is included in the decision-making process, it holds no importance relative to others and is assigned a zero weight.

In contrast, the AHP method does not allow for criteria to have zero weights due to its deterministic nature, but weights for less important criteria are close to zero (Özdağoğlu and Özdağoğlu 2007). Fuzzy logic employs linguistic values to describe the relative significance of criteria, reducing subjectivity and potentially leading to less risky decisions. However, for the specific MCDM problem of stream-gauging network design, FAHP might be less suitable. This is because reducing the number of criteria assumed in FAHP leads to a high number of suggested locations, which is impractical and requires extensive fieldwork.

Table 4-2 delineates the calculated criteria weights across different scenarios, providing critical insight into prioritising criteria for the optimal placement of hydrometric stations.

This table, derived from data from Theochari et al. (2019), lays the groundwork for a comprehensive understanding of the varied factors influencing hydrometric station placement, each shaped by the specific objectives of the respective scenarios. This detailed analysis is crucial for tailoring station deployment to meet precise environmental monitoring needs. In every scenario assessed, the weight of topographic slopes (W_{C1}) emerges as paramount, confirming the universal significance of terrain in influencing water movement and measurement. The consistency observed across scenarios highlights the significant impact of terrain on the accuracy of hydrological data, underscoring the critical importance of understanding water flow dynamics in diverse landscapes.

Table 4-1: Pairwise comparison matrix for each scenario as cited in Theochari et al. 2019

a)			*Scenario 1*					*Scenario 2*					*Scenario 3 (3a)*		
	C1	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C1**	**C2**	**C3**	**C4**	**C5**
C1	**1**	5	9	7	5	**1**	7	9	5	3	**1**	5	7	9	3
C2	1/5	**1**	3	3	3	1/7	**1**	1	1/7	1/9	1/5	**1**	3	5	1/5
C3	1/9	1/3	**1**	3	3	1/9	1	**1**	1/7	1/9	1/7	1/3	**1**	3	1/7
C4	1/7	1/3	1/3	**1**	1	1/5	7	7	**1**	1/3	1/9	1/5	1/3	**1**	1/9
C5	1/5	1/3	1/3	1	**1**	1/3	9	9	3	**1**	1/3	5	7	9	**1**
b)								*Scenario 3 (3b)*							
		C1			**C2**			**C3**			**C4**			**C5**	
C1	1	**1**	1	4	5	6	6	7	8	9	9	9	2	3	4
C2	1/6	1/5	1/4	1	**1**	1	2	3	4	4	5	6	1/6	1/5	1/4
C3	1/8	1/7	1/6	1/4	1/3	1/2	1	**1**	1	2	3	4	1/8	1/7	1/6
C4	1/9	1/9	1/9	1/6	1/5	1/4	1/4	1/3	1/2	1	**1**	1	1/9	1/9	1/9
C5	1/4	1/3	1/2	4	5	6	6	7	8	9	9	9	1	**1**	1

In Scenario 1, the weight assigned to topographical slopes (W_{C1}) is the highest, indicating that the land's inclination is the most critical factor in the network's design for this scenario. This emphasis on slope consideration likely stems from the need to ensure accurate runoff measurement, which heavily depends on slope gradients. Steep slopes can cause rapid surface runoff, potentially increasing flood risk, whereas gentle slopes might lead to a more gradual flow, significantly influencing the hydrological data collected. This differentiation is essential for designing precise and effective hydrometric stations tailored to specific environmental conditions.

In Scenario 2, which is aimed at flood protection, slopes (WC1) are slightly less important; however, they remain the most critical criterion. Given its substantial weighting, the significance of the distance from flood-prone areas (WC5) is emphasised. This adjustment highlights a shift in focus towards mitigating the impacts of floods and prioritising locations that can provide predictive data for flood events, underscoring the need for strategic station placement to enhance flood management capabilities.

Scenario 3a demonstrates that the weight for slopes (C1) is closely aligned with Scenario 1, reinforcing the importance of topographic factors in a balanced approach that integrates various considerations. However, the weight for the distance from settlements (C4) decreases from Scenario 1's weight of 0.060, contrary to an initial assessment. This indicates that, although still considered, the proximity to settlements carries less weight under the AHP approach than the initial technical scenario, suggesting a shift in priority within the assessment criteria.

Scenario 3b, approached via FAHP, presents an intriguing contrast. Similar to Scenario 1, the topographic slopes (WC1) continue to hold the highest weight, reinforcing the crucial role of physical geography in station placement. However, it completely removes the weight for the distance from road networks (W_{C2}), confluences (W_{C3}), and settlements (W_{C4}), assigning them zero weights. This underscores a methodological inclination to concentrate solely on natural hydrological characteristics and flood-prone areas (W_{C5}) in the decision-making process.

These comparative perspectives show that while topographic slopes universally retain the highest weight, emphasising their unquestionable importance, the treatment of the distance from settlements varies. This variability indicates a methodological difference in prioritising factors related to human settlements. Such analysis underscores the customised prioritisation within each scenario, showcasing the multifaceted nature of decision-making in station network design. It also highlights the intricate considerations that must be balanced to optimise the network for diverse objectives, reflecting a complex interplay of environmental and anthropogenic factors.

Table 4-2: Criteria weights for each scenario as cited in Theochari et al. 2019

	Scenario 1	*Scenario 2*	*Scenario 3a*	*Scenario 3b*
W_{C1}	0.566	0.474	0.476	0.565
W_{C2}	0.183	0.039	0.118	0.000
W_{C3}	0.124	0.036	0.061	0.000
W_{C4}	0.060	0.166	0.032	0.000
W_{C5}	0.067	0.284	0.312	0.435

To further clarify the hydrometric station network design process, the WLC method is crucial, incorporating the weights obtained from AHP and FAHP to integrate multiple criteria into a single suitability score. This approach allows for a comprehensive evaluation of various factors, ensuring that the placement of stations optimally reflects the diverse needs and conditions specific to each scenario. The process involves a detailed standardisation of criteria, each normalised on a scale from 0 to 1, which allows for direct comparison and combination. Employing GIS tools enables the practical application of Map Algebra, which facilitates the detailed overlay and synthesis of raster datasets representing each criterion. For the station network design in the Sarantapotamos basin, station locations are recommended along the mainstream only. Therefore, the suitability assessment is conducted exclusively for the mainstream. This focused assessment ensures that the selection of stations aligns with the primary hydrological flow of the basin, thereby enhancing the network's capacity to capture comprehensive water resource data. The FS, ranging from 0 to 1, allows various thresholds to focus on optimal results. Two clusters are created according to Theochari et al. 2019, as depicted in Figure 4-1: black dots represent FS lower than either 0.90 (Figure 4-1(a)) or 0.95 (Figure 4-1(b)), while white circles indicate sites with higher FS. The demarcation into two clusters based on FS thresholds—a common practice in suitability studies—allows for a clear visual and quantitative distinction between highly suitable locations and those with lower suitability scores.

The number of eligible locations varies significantly with different FS cluster thresholds, with the second scenario resulting in the fewest potentially eligible locations: only four sites in the 90%–100% FS cluster. A spatial comparison between the two FS clusters is shown in Figure 4-1(a) and Figure 4-1(b), where grey rectangles highlight areas with reduced optimal locations among the two FS clusters (above 0.90 and 0.95 for Figure 4-1(a) and Figure 4-1(b), respectively). Regarding the AHP application, results indicate that Scenario 1 yields the most significant number of eligible locations, followed by Scenario 3. Moreover, Scenario 1 identifies at least four sites with FS over 98%, while Scenario 3 only identifies two sites within the same range. The fuzzy approach of AHP results in an increased number of suitable locations, as only two criteria are ultimately used to identify eligible locations, imposing fewer restrictions (e.g., proximity is not considered in WLC). All suggested locations, according to FAHP, achieve an FS in the range of 95%–100%, leading to identical results for Scenario 3b in both cases (Figure 4-1(a) and Figure 4-1(b)). The histogram depicted in Figure 4-2 offers a visual representation of the distribution of station locations across FS classes, providing a detailed view of the frequency distribution that forms the basis of station suitability. Each histogram corresponds to one scenario and displays the relative frequency of station locations across various FS classes (≤ 50%, 50%–60%, 60%–70%, 70%–80%, 80%–90%, 90%–95%, > 95%). According to the MCDM results, among the three scenarios of AHP, there are numerous locations with a score close to 80%, with the relative frequency decreasing as FS values increase (e.g., 80%–90%). In contrast, Scenario 3b, resulting from FAHP, exhibits an increased number of suitable stations with FS between 80% and 90%. The absence of frequency in this scenario's 90%–95% class is attributed to the number of criteria (only two criteria assumed) and particularly to the transformation of C1 to a 0–1 scale as classified value. Especially for this last scenario, the absolute number of suitable locations differs, as criteria that act as restrictions (e.g., C2) are not considered.

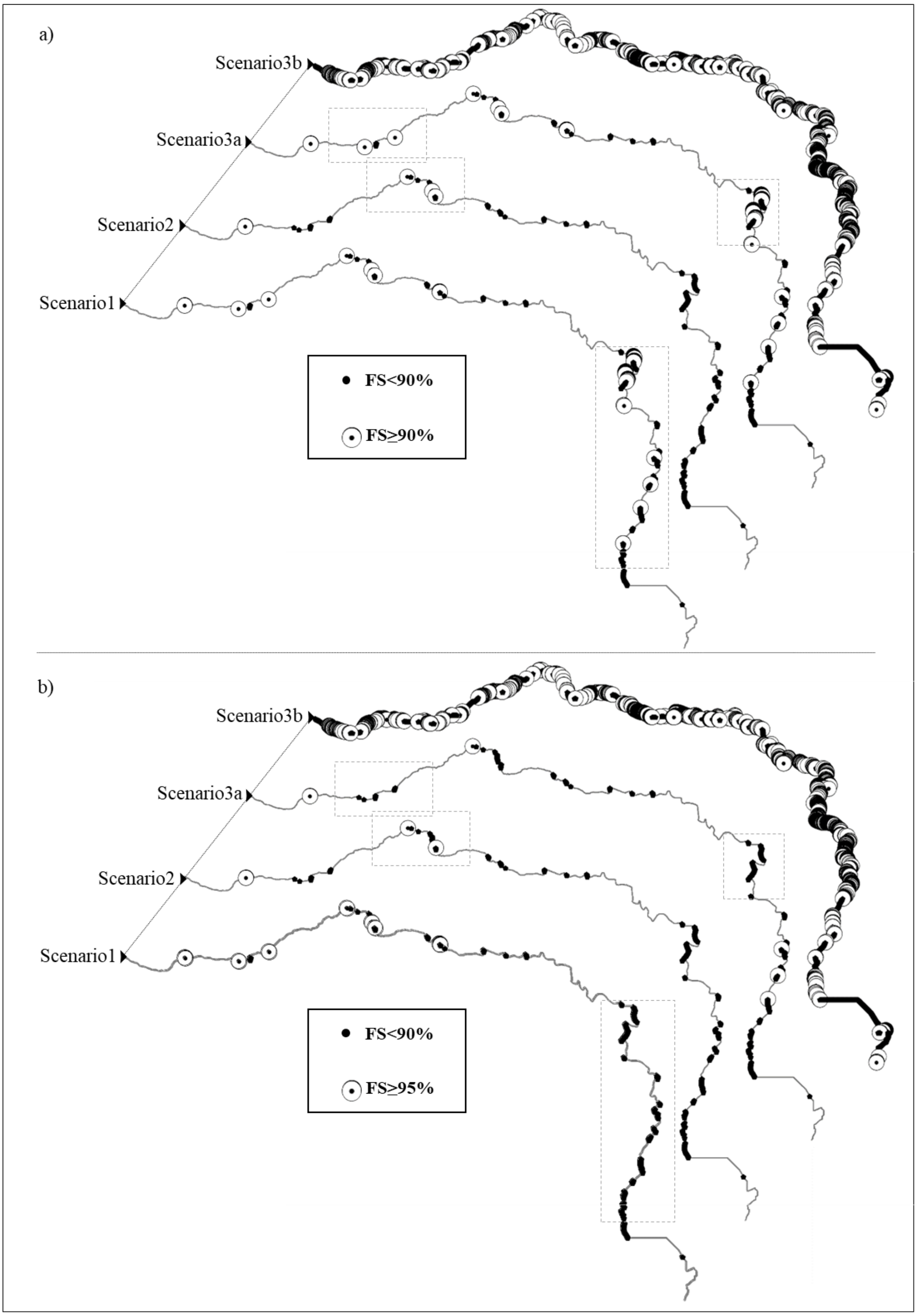


Figure 4-1: FS across the mainstream depicted in two clusters of (a) (0.0–0.9) ≥ FS ≥ (0.9–1.0) (b) (0.0–0.95) ≥ FS ≥ (0.95–1.0). Source: (Theochari et al. 2019)

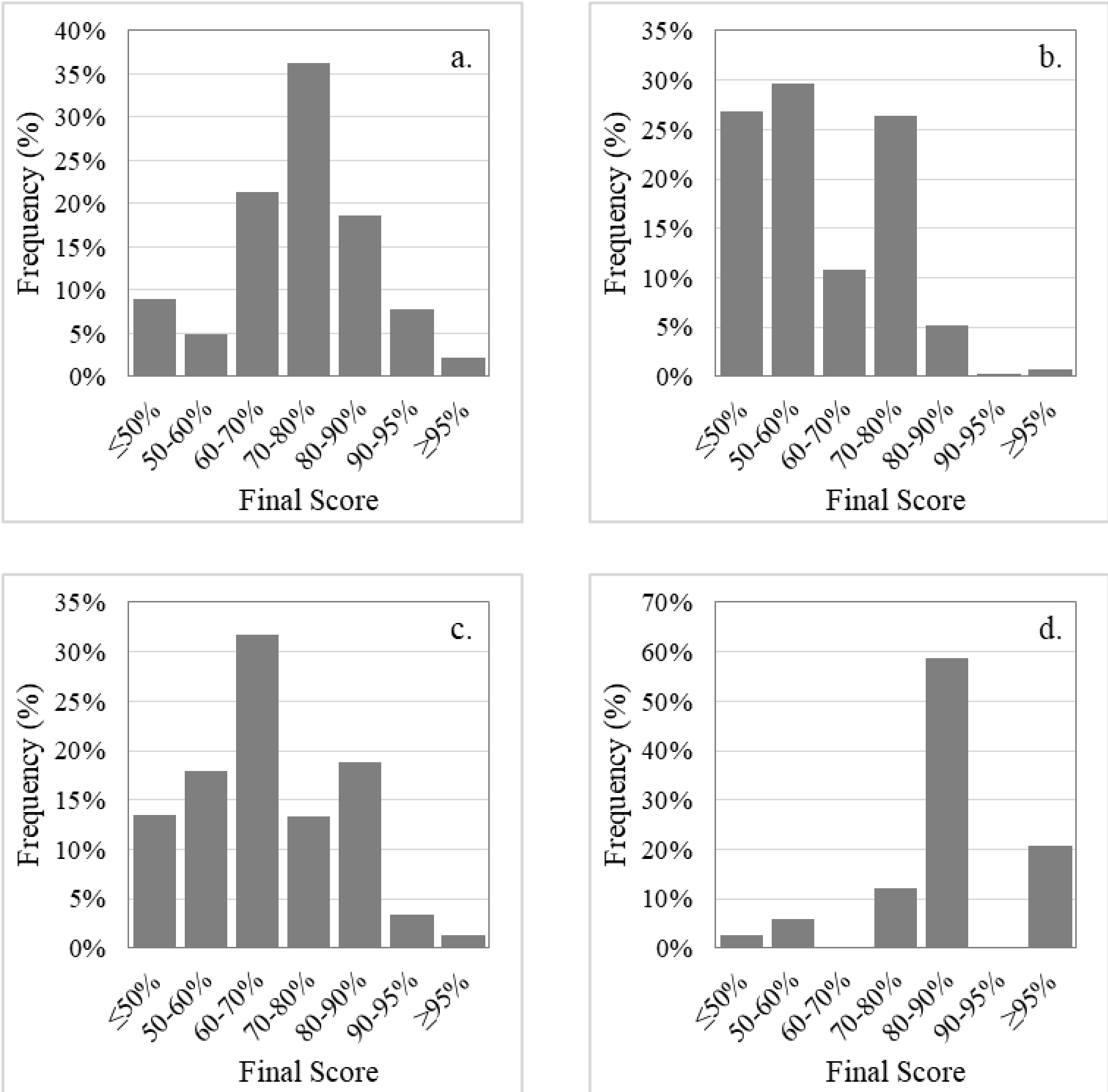


Figure 4-2: Relative frequency (%) of locations for various FS classes for a. Scenario 1; b. Scenario 2; c. Scenario 3a; d. Scenario 3b. Source: (Theochari et al. 2019)

Additionally, two FS clusters are delineated according to Theochari et al. 2021 (Figure 4-3): The first comprises small black dots representing FS values below 0.90, while the second consists of large red circles indicating sites with higher FS. When comparing the three scenarios based on weighting, it becomes apparent that the "slopes" criterion holds the highest significance across all scenarios. Conversely, the criterion "distance from settlements" ranks the least important in the first and third scenarios. However, in the second scenario, the criterion "distance from the confluence with another stream" emerges as the least significant. Notably, the "distance from settlements" criterion is deemed highly important when the design objective involves developing a flood early warning system. For FS values exceeding 90%, all scenarios recommend the same optimal sites, with the highest FS and the second-best case typically situated in the southern part of the river.

In Scenario 3a (Figure 4-3c), where weights are determined using AHP, there are 59 positions with high FS, whereas in Scenario 3b (Figure 4-3d) utilising FAHP, the resulting map indicates 437 potentially suitable positions. This increase in appropriate locations is attributed to the FAHP approach, which considers only two criteria to identify optimal sites, resulting in fewer constraints. This observation aligns with the findings of Theochari et al. 2019. In all scenarios except the first one, suitable locations with FS > 90% are predominantly observed in the southern part of the river (lowlands), closer to settlements and flood-prone areas. In contrast, the first scenario suggests suitable locations across the entire length of the mainstream. The distinct feature of the first scenario is its emphasis on low slopes, proximity to the road network, and avoiding junctions to minimise the influence of other streams during flow recording. Hence, this scenario is preferable when decision-makers prioritise this hierarchy of criteria.

The design criteria are established along the entire mainstream length and then combined to derive the distribution of optimal locations. When considering findings from related research by Theochari et al. 2019, it becomes apparent that the distribution of suggested positions for identical scenarios within the same study area, criteria, and criteria weighting may vary. This discrepancy can be attributed to differences in the datasets utilised and the formulation of criteria between the two approaches.

It is important to note that the distribution of optimal locations, although based on the same criteria and weights, may differ due to variations in the datasets and the formulation of criteria between different studies. This underscores the significance of the GIS environmental setup and dataset selection, which are integral to the station network design process. Therefore, the detailed delineation of criteria within a GIS framework and the thoughtful selection of datasets for analysis represent additional variables that can significantly influence decision-making in station network design.

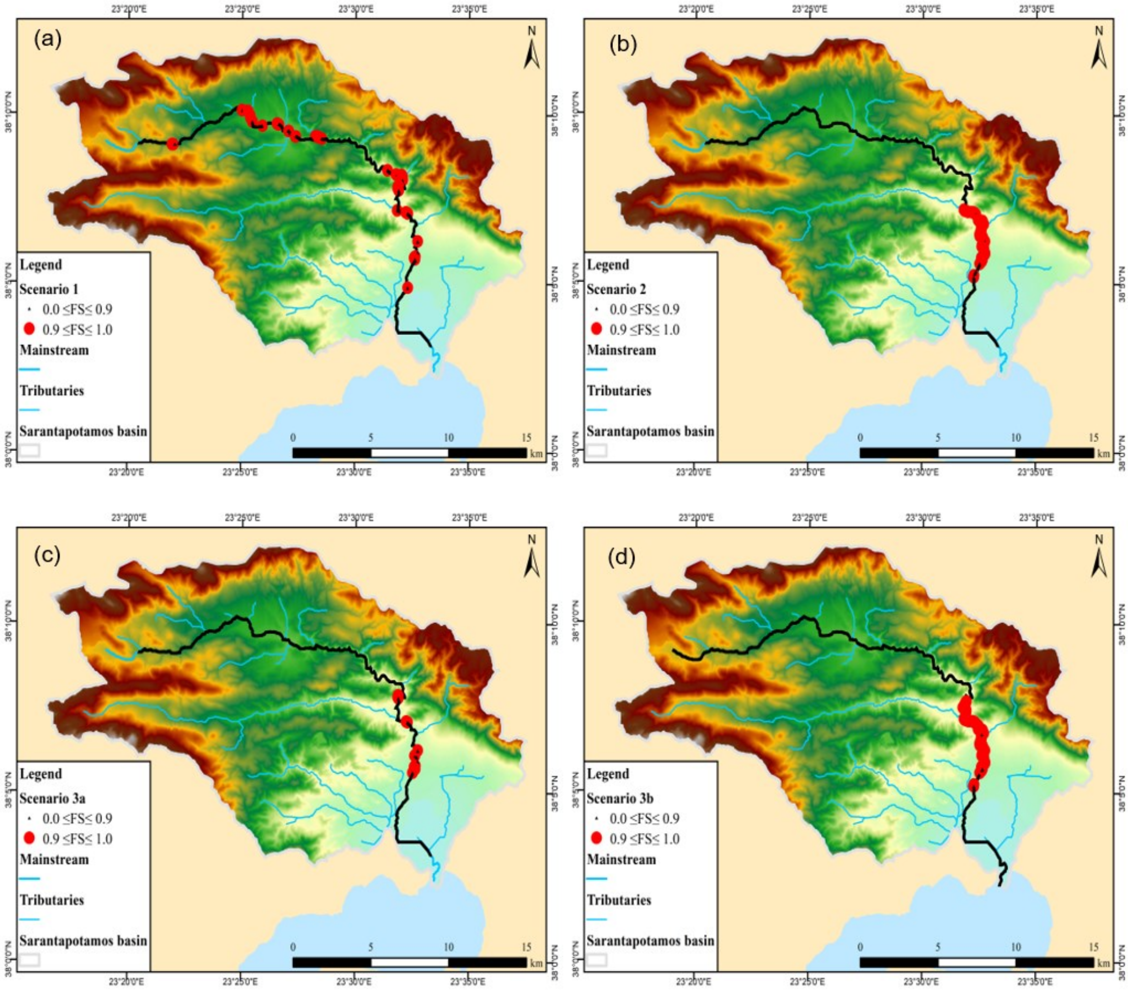


Figure 4-3: FS across the mainstream depicted in two clusters of (0.0≤ FS ≤0.9, 0.9≤ FS ≤1.0)

Source: (Theochari et al. 2021)

4.1.2 Optimal hydrometeorological station network design

The criteria selected for hydrometeorological station network design within the Sarantapotamos basin function as pivotal constraints that delineate the spatial domain of suitable and unsuitable locations for station placement. This rigorous approach ensures that only areas meeting all predetermined criteria are considered, optimising the network's effectiveness and relevance. Combining these criteria ultimately determines the suitable locations, with all design criteria being met when the FS reaches one. This methodological precision guarantees that each station is strategically placed to provide accurate and valuable data for comprehensive hydrological analysis. Boolean maps, as depicted in Figure 4-4, serve as a foundational tool in this process, providing a clear binary visual representation of the suitability of each location.

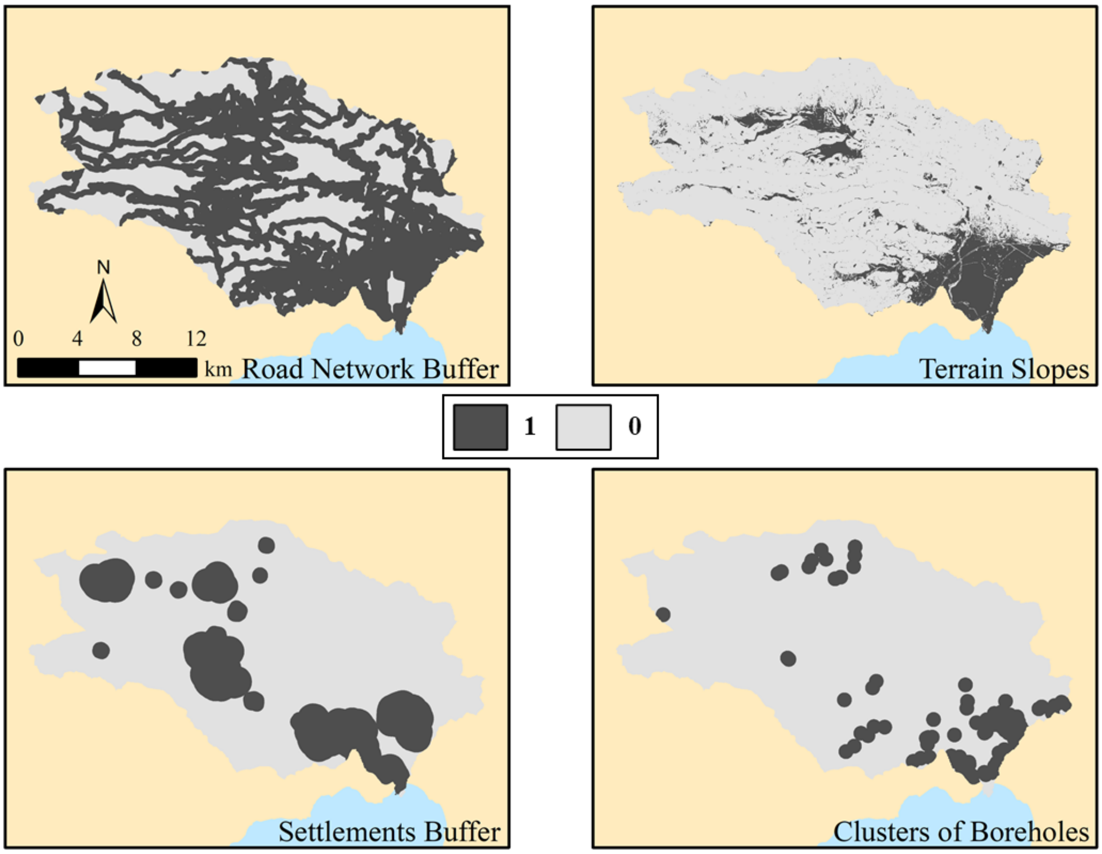


Figure 4-4: Boolean maps of criteria for hydrometeorological station network design Source: (Theochari et al. 2021)

These maps are fundamental in eliminating unsuitable locations, ensuring that any location deemed fit for a station is optimal according to all specified criteria. In these maps, cells with a value of "1" indicate potential suitability, while those with a value of "0" are flagged as unsuitable and are visually demarcated in light grey. This effectively illustrates areas that do not meet the design constraints and are thus excluded from further consideration, streamlining the selection process.

Formulating the criteria as constraints regulates the WLC results by ensuring their exclusion during WLC application, culminating in the suitability map shown in Figure 4-5. To visualise the spatial distribution of FS more effectively, five equal classes are created, representing possible values between "0" and "1": "0", "0.25", "0.50", "0.75", and "1.00". The first class (FS = 0) covers 34% of the river basin's total area, indicating areas where hydrometeorological stations are not permitted. The second class (FS = 0.25) encompasses 39% of the area, FS = 0.50 covers 16%, FS = 0.75 covers 7% and only 4% of the basin reaches the highest score, FS = 1.0. Candidate positions that achieve the pinnacle of suitability, FS = 1, are prominently displayed in dark green on the suitability map (Figure 4-5), drawing immediate attention to these prime locations.

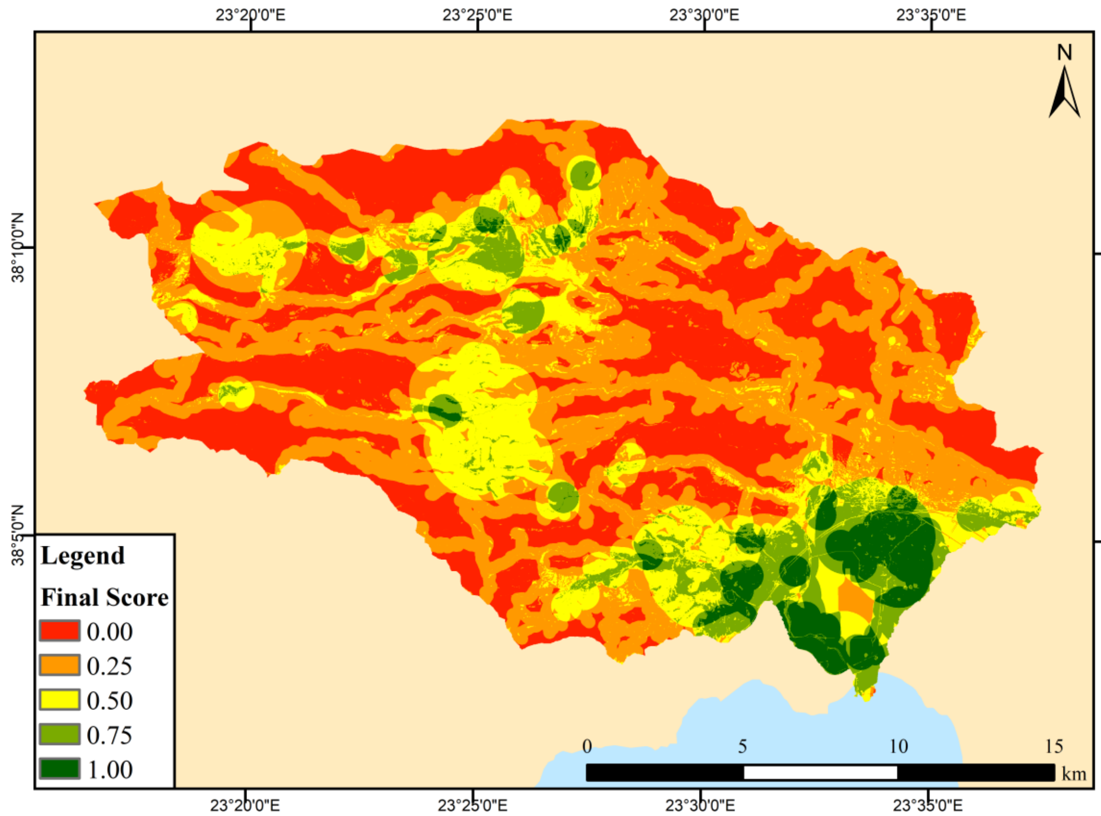


Figure 4-5: WLC among criteria for hydrometeorological station network design Source: (Theochari et al. 2021)

These are the areas where the hydrometeorological stations could be most effective and where their installation is most justified, given the multifaceted constraints of the design criteria. This thorough classification establishes a solid foundation for decision-making and captures the complexity of identifying optimal sites for hydrometeorological stations in a diverse and dynamic river basin environment. Such detailed visualisation of FS classes underscores the importance of rigorous criteria selection and spatial analysis in designing a station network that is both efficient and reliable, ensuring that each station contributes effectively to the overall monitoring objectives.

The final step in determining the placement of hydrometeorological stations within the Sarantapotamos basin involves assessing how many stations are located at different elevations across the terrain. This method ensures that the spatial coverage of the network is scientifically valid and cost-effective, striking a delicate balance between geographical requirements and resource efficiency. The density criterion, intricately connected to elevation as demonstrated in Figure 4-6, offers a systematic approach to determine the minimum number of stations needed to monitor each elevation zone within the basin effectively. This approach enables thorough coverage and follows an economical approach to minimising redundant data collection points. The calculation of the minimum necessary number of stations for each elevation zone is outlined in Table 4-3. Zone B, spanning the largest area of 163 km², necessitates the installation of two stations to ensure representative data sampling, considering its size and anticipated hydrological variability, whereas one station suffices for Zone C.

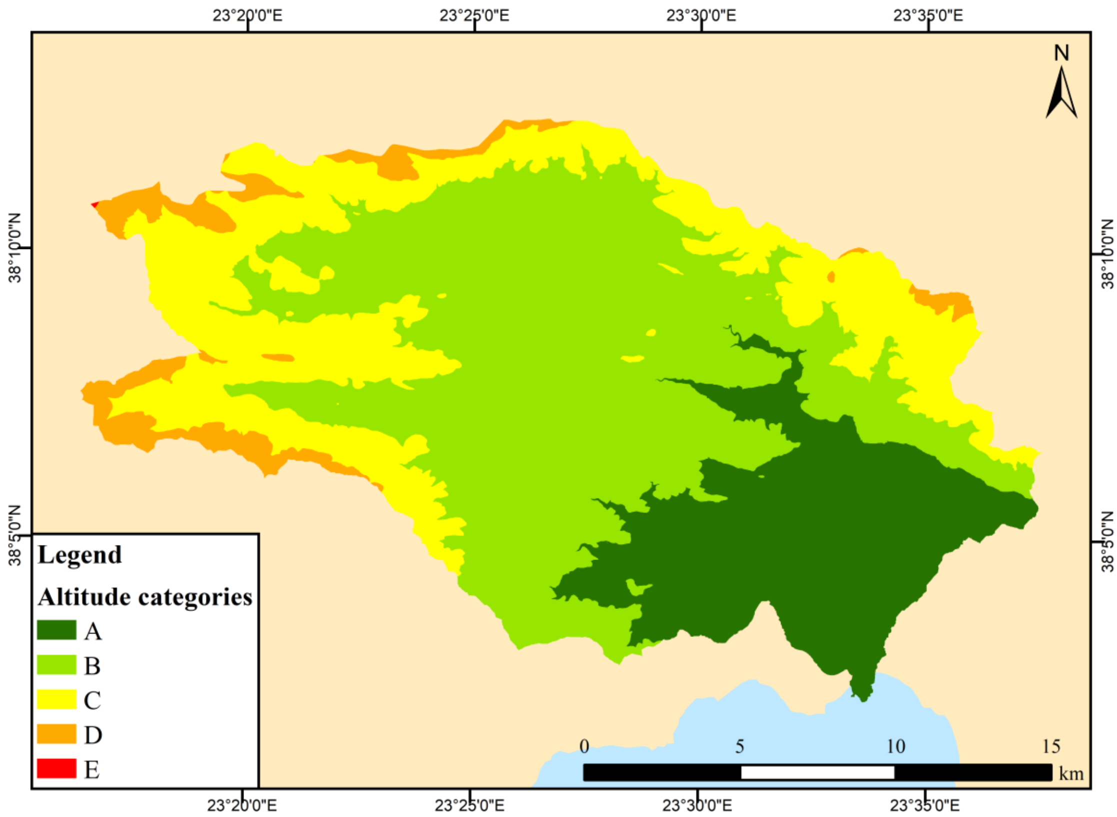


Figure 4-6: Altitude categorisation for the Sarantapotamos river basin.
Source: (Theochari et al. 2021)

Table 4-3: Grouping altitudes and calculating the desired number of hydrometeorological stations as cited in Theochari et al. 2019

Zone	Altitudes (m)	Station density	Area (km²)	Density	Final stations
A	0-200	600	71	0.1	0
B	200-500	100	163	1.6	2
C	500-800	75	90	1.2	1
D	800-1,200	50	17	0.3	0
E	1,200-1,900	50	0	0.0	0
Total	-	-	341	-	3

Consequently, based on the station density criterion, the optimal number of stations is determined to be three. The chosen locations represent the intersection of multiple decision-making factors, including suitability assessments, Boolean constraints, and the aforementioned elevation-related density criterion. Significantly, the methodology employed reflects a practical approach adopted by decision-makers to limit the number of stations. This approach is mainly justified by recognising that areas lacking station coverage due to elevation considerations represent a relatively small portion of the total area. In cases where decision-making on the number of stations might lead to fractional results, the Ceiling method offers a clear guideline: round up to guarantee coverage, thereby prioritising caution to prevent data gaps. Implicit in this strategy is the understanding that the ideal distribution of stations should be thorough yet reasonable and comprehensive enough to capture the hydrometeorological dynamics across the elevation gradient of the river basin. This judicious strategy underscores the critical role of elevation in informing the density and distribution of monitoring stations, ultimately guiding a network design that is robust, representative, and attuned to the basin's topographic and environmental intricacies.

4.1.3 The location of optimal hydrometric-hydrometeorological stations

The mapping in Figure 4-7 carefully outlines the distribution of hydrometric-hydrometeorological stations, which are essential for thoroughly understanding the Sarantapotamos basin's hydrological patterns. The proposed network comprises three hydrometeorological stations, coupled with the strategic placement of one primary and one additional hydrometric station. This design is intended to provide a robust assessment of the basin's hydrological response, ensuring comprehensive coverage and detailed insights into water dynamics across different basin sections. This strategic configuration optimises gathering crucial data, facilitating effective management and monitoring of the basin's hydrological environment.

The placement of hydrometeorological stations follows a systematic approach based on specific criteria, aiming to achieve an optimal density and spatial distribution across the entire basin. By adhering to these international standards, the proposed locations for these stations are strategically positioned to capture a diverse range of meteorological data essential for precise weather forecasting, climate analysis, and water resource management. In the hydrometric station network design context, the selection of positions is rooted in technical precision and the basin's flood management needs. The northern proposed hydrometric station site, situated along the bridge on the provincial road Oinois-Panaktou, is identified as optimal in Scenario 1. This location is deemed technically adequate because it can capture flow data unaffected by backwater effects or other anomalies that can impact the quality of hydrological measurements. Conversely, the southern location for the second hydrometric station consistently appears as a high-suitability site (FS > 0.9) across all examined scenarios, highlighting its reliability as a monitoring point. Its proximity to the provincial road Oinoi-Magoula and nearby settlements like Mandra and Magoula underscores its strategic importance. This station fulfils technical hydrological monitoring needs and is ideally positioned to enhance flood protection efforts. As a dual-purpose station, it can provide critical data to inform flood risk mitigation strategies and act as an early warning point to safeguard the surrounding communities.

By integrating density and spatial distribution criteria with the technical and functional needs of hydrometric and hydrometeorological monitoring, the proposed station network is positioned to deliver comprehensive data. This data will facilitate a thorough understanding of the Sarantapotamos basin's hydrology, leading to effective water management, reduction of flood risks, and the protection of ecosystems and human communities within and surrounding the basin.

Finally, one more observation from the above analysis is how criteria are expressed in a GIS environment and decision-makers' perspectives heavily influence the data utilised for the entire analysis. This influence is particularly pronounced in the design approach for hydrometric station networks, which tends to be more flexible in criteria formulation and hierarchy compared to hydrometeorological networks. When designing hydrometric station networks, there is more flexibility in how criteria are articulated and applied. Normalised values enable a more detailed and sophisticated data analysis, where variables can overlap and integrate in ways that capture the complexity and variability of the hydrological environment. This adaptability can be crucial when dealing with the dynamic flow of watercourses, as rigid binary conditions may not adequately capture the intricacies required for precise monitoring and assessment. On the other hand, the design of hydrometeorological networks often involves stricter constraints, possibly due to the broader range of variables that influence meteorological phenomena and the critical importance of capturing data that accurately reflects these variables. Boolean maps are especially effective in such cases as they offer clear, unmistakable distinctions between suitable and unsuitable locations. These binary maps are vital for ensuring that stations are only placed in areas that meet all necessary conditions for reliable data collection, given the significant impact that meteorological data can have on weather prediction, climate studies, and emergency planning.

The selection process for hydrometeorological station placement and its underlying criteria are not merely technical exercises but also reflections of strategic choices made by those responsible for designing these networks. These decisions have extensive implications for the capacity of the resulting infrastructure to provide the data essential for understanding and managing the basin's hydrological and meteorological processes. Decision-makers must

balance precision, flexibility, and practicality while also considering the long-term implications of their choices on resource management and disaster mitigation.
This intricate interplay among decision-maker perspectives, the expression of GIS criteria, and data selection highlight environmental monitoring network design's often complex and subjective nature. It underscores the necessity for a comprehensive understanding of both the technological tools available and the ecological phenomena under study. By ensuring that the resulting network is resilient, adaptable, and capable of facilitating informed decision-making, planners can effectively address the numerous challenges inherent in water resource management. This approach not only enhances the functionality of the network but also contributes to a more sustainable and effective management of environmental resources.

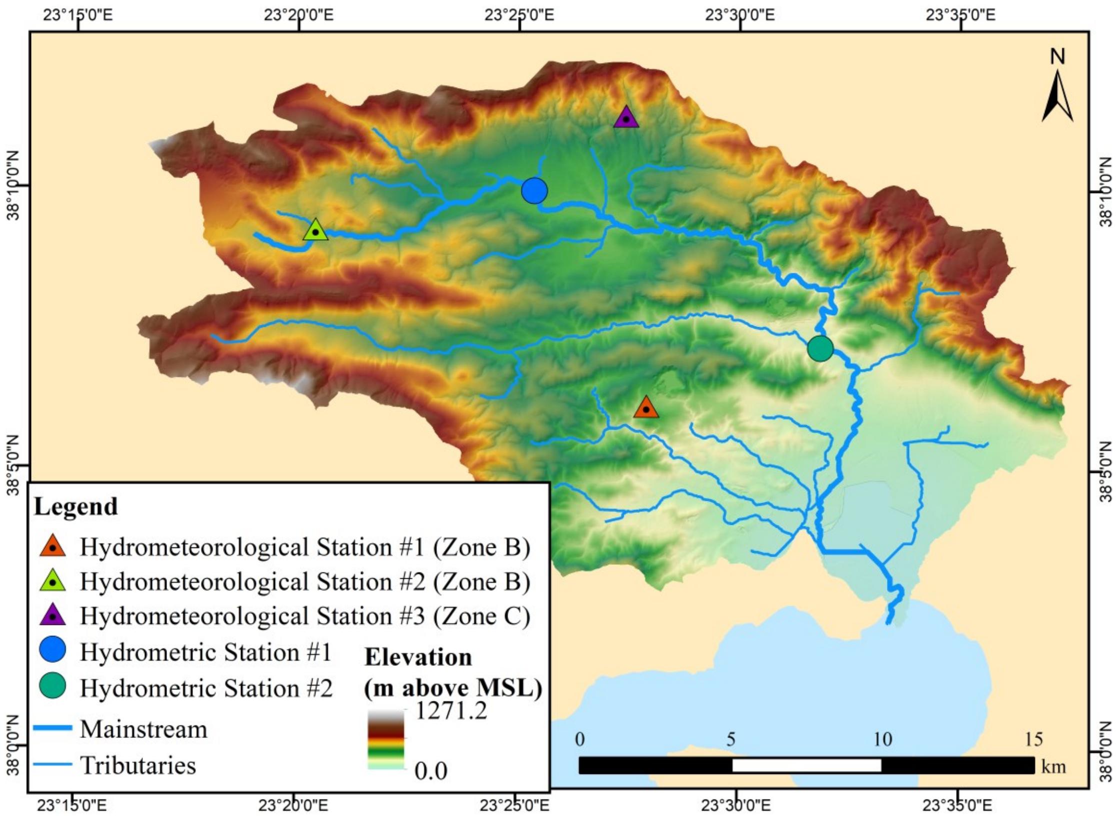


Figure 4-7: Hydrometeorological and hydrometric station network site selection.
Source: (Theochari et al. 2021)

4.2 Implementation of the Geomorphological Unit Hydrograph

4.2.1 System analysis of channel velocity

The system analysis delves into the impact of channel velocity on the UH by utilising the time-area diagram method. This approach involves a methodical examination through simulation, which allows for the differentiation of various velocities. Specifically, the simulation applies the time-area diagram method to generate eight distinct hydrographs. The primary aim is to evaluate the model's accuracy across different channel velocities and identify the velocity range that matches the closest to observed hydrographs.

The NSE, a widely accepted metric in hydrological modelling, is utilised to quantify the goodness-of-fit between the simulated and observed hydrographs. Figure 4-8 presents line graphs depicting NSE values across different velocity ranges, where the x-axis represents varying velocities (Vmax) and the y-axis likely indicates the NSE values. This visual representation helps assess how well the model performs under varying flow conditions and supports the identification of an optimal velocity range for accurate hydrological predictions.

In the Metsovitiko basin, the NSE values range from 0.293 to -1.647, providing insights into the model's performance. Positive values indicate a relatively good fit between simulated and observed hydrographs, while negative values suggest areas for improvement. Among these values, the NSE corresponding to a V_{max} of 2 m/s stands out with the highest value of 0.293, indicating relatively better model performance than other velocity ranges. This suggests the model performs better within the velocity range of 0.1-2 m/s, showing a closer alignment between observed and predicted values and a more precise capture of hydrological dynamics. Similarly, in the Pramoritsa basin, the model's performance varies with NSE values ranging from 0.37 to -0.234. Notably, the highest NSE value of 0.37 is observed for the velocity range of 0.1-2.0 m/s, indicating relatively better model performance than other velocity ranges.

Moving on to the Mouzaki basin, NSE values ranging from 0.73 to 0.641 suggest consistently good model performance, with a reliable fit between observed and predicted values across different channel velocity ranges. The optimal velocity range appears to be 0.1-4.0 m/s, although the 0.1-2.0 m/s velocity range demonstrates a high NSE, indicating its potential utility in hydrological modelling applications. In the Velventos basin, NSE values range from 0.599 to 0.243, indicating a good fit between simulated and observed hydrographs across various channel velocity ranges.

In the Pyli basin, NSE values ranging from 0.465 to 0.561 indicate a relatively good fit across various channel velocity ranges. The optimal range is 0.1-4.0, consistently showing positive NSE values. However, even the 0.1-2.0 range yields positive NSE values, suggesting its effectiveness for this basin. In the Krasopouli basin, NSE values exhibit variations across channel velocity ranges, ranging from 0.496 to -0.301. Positive values are observed at lower velocities, declining into negative values at higher velocities. Despite these variations, the 0.1-2.0 range consistently yields positive NSE values. Concerning the Asprorema basin, NSE values display variations across velocity ranges, ranging from 0.35 to -0.117. The model performs relatively better at lower velocity ranges but struggles as velocity increases. Nevertheless, the 0.1-2.0 range consistently yields positive NSE values, indicating its effectiveness for this basin.

In analysing the Agia basin, the NSE values range from 0.405 to -4.614. The highest NSE value is observed at the 0.1-2.0 m/s velocity range, which is 0.405. This positive NSE value indicates a reasonable fit between the simulated and observed hydrographs, suggesting the model captures the hydrological behaviour of the basin reasonably well at this lower velocity range. However, as the velocity increases from 3 to 6 m/s, the NSE values sharply decrease, moving into the negative range and reaching as low as -4.614. This negative trend signifies that the model's performance deteriorates significantly with higher velocities, indicating a less accurate representation of the hydrological processes occurring within the basin. This pattern of decreasing NSE with increasing V_{max} suggests that the model is more reliable for predicting slower flow scenarios. This is consistent with findings for the other basins, where lower velocities also correspond to higher NSE values.

Based on the analysis of the provided graphs and the understanding that a higher NSE indicates better model performance, with values closer to 1 being ideal, it is evident that the velocity range associated with the highest NSE should be selected. The top graph displays relatively consistent NSE values across different velocities, with a slight advantage observed for lower velocities, which generally have higher NSE scores across most variables. The bottom graph, providing a closer look at the lower velocity range, confirms this observation by demonstrating that the highest NSE values are typically found at the lower end of the velocity spectrum. Therefore, the velocity range of 0.1-2.0 is chosen as it consistently yields higher NSE values, indicating a more accurate model performance for most of the observed hydrographs. This decision aligns with achieving the highest possible model accuracy. The consistency of higher NSE values across datasets represented in the graphs further supports selecting this velocity range for subsequent stages of the research's procedures.

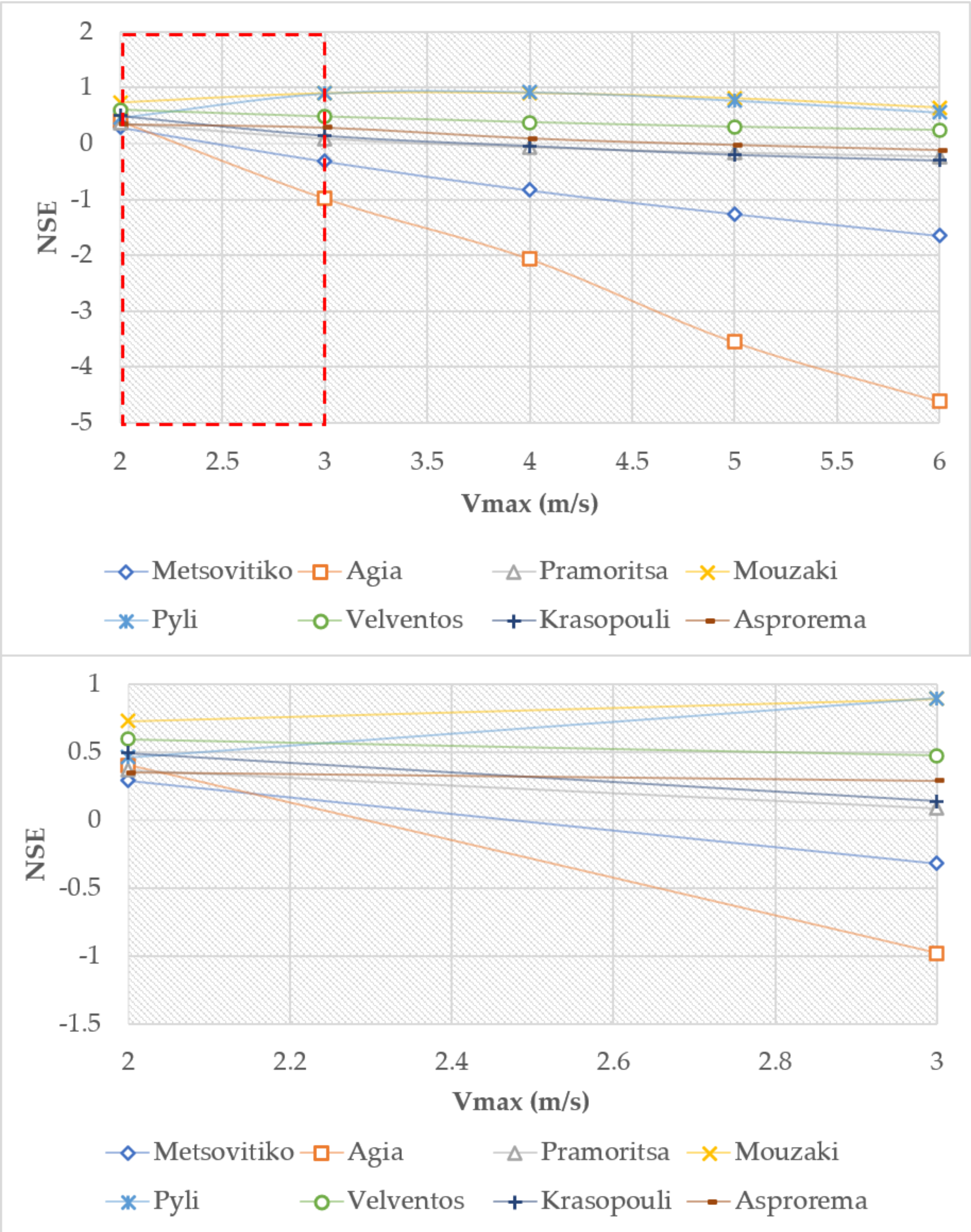


Figure 4-8: Analysis of Nash-Sutcliffe Efficiency (NSE) comparison across different velocity ranges.

4.2.2 Regression analysis

The investigation into the hydrological dynamics of 70 drainage basins, as part of a broader analysis encompassing 100 basins, marks a significant advance in understanding the interplay between geomorphological metrics and hydrograph attributes. Using the time-area diagram method as the primary analytical tool, this research carefully calculates UH for each basin, preparing for an in-depth look into the hydrological processes involved. This analysis aims to uncover the intricate relationships that determine how water moves through different types of terrain.

As the analysis progresses, it uses histograms to visually summarise how the basins' geomorphological metrics relate to the features of the resulting hydrographs. Figure 4-9 emerges as a pivotal visual aid, presenting these histograms in a structured grid format. This visual representation is instrumental in delineating the detailed coherence between UH attributes and the geomorphological metrics across the examined basins. Each histogram, by plotting the distribution of a specific y-axis variable against varied values of x-axis variables, offers a window into the intricate patterns and correlations embedded within the dataset. This method makes it easier to closely examine how various geomorphological traits affect hydrograph features, shedding light on the underlying patterns in the data. Each bar represents a specific value range in this visualisation, indicating correlation concentration within distinct intervals. Correlation strength is inferred from the distribution pattern: clear peaks denote stronger correlations, while flat or multi-peaked histograms suggest weaker or complex relationships. While histograms provide valuable insights into variable pair frequency and spread, it's important to note that they alone cannot definitively confirm correlations. They serve as a preliminary visualisation tool, necessitating further statistical or multivariate analysis to quantify and interpret the observed relationships accurately.

Looking closer at the histograms shows clear distribution patterns, which helps spot possible connections between different variables on the y-axis and their related variables on the x-axis. For example, the early examination of the maximum flow rate (Q_{max}) variable about various geomorphological metrics reveals various distribution patterns. Variables such as Rc and FF exhibit a dispersed nature, indicative of weak correlations, whereas other variables showcase a more concentrated distribution of histogram bars, hinting at moderate correlations. As the analysis transitioned towards examining the t_{Qmax} variable, a parallel pattern emerged with weak correlations observed in Rc and FF, where bars are scattered. Conversely, other variables present a more focused distribution, implying potential moderate correlations. This contrast highlights the variation in the landscape's physical traits and shows how these features affect hydrograph behaviour.

Going further, exploring the t_b variable more closely highlights the differences in how strongly it correlates with other factors. The noticeable spread in the histograms for Rc and FF variables indicates a weak connection to hydrograph attributes, suggesting that a broader range of factors influences these relationships. Conversely, the emergence of denser clustering among histogram bars for variables such as Cc signals the presence of more definitive, moderate correlations. This distribution pattern provides insight into the complex interaction between water movement and landscape features, hinting at underlying geomorphological processes that could significantly affect hydrological responses. The narrative continues as attention shifts to the t_{Q50L} and t_{Q50R} variables, where similar trends persist. The wide dispersion of histogram bars for Rc and FF indicates weak correlations, reflecting a complex interplay of factors that defy simple characterisation. Meanwhile, the tighter clusters observed in Cc and Re suggest potential moderate to solid correlations and pave the way for a deeper understanding of the mechanisms governing water flow dynamics.

The t_{Q75L} variable's histograms in Rc and FF are spread out, indicating weak correlations, while Cc and Re show concentrated bars, suggesting moderate correlations. Regarding the t_{Q75R} y-axis variable, histograms suggest a meaningful relationship with x-axis variables. In Rc, bars are spread, indicating a weak correlation. Moving to Cc, a slight concentration suggests a potential moderate correlation. The Re variable reveals a complex distribution with multiple peaks, possibly indicating a multimodal relationship or interactions with other variables not directly analysed. DD displays a reasonably uniform spread, suggesting a weak correlation.

The histogram analysis provides valuable insights into potential correlations between hydrograph behaviour and underlying geomorphological characteristics. By examining the distribution patterns across different variables, it becomes possible to infer the strength and nature of these connections. Further in-depth examination of the histograms will unveil crucial insights into the complex relationships influencing UH behaviour within the analysed drainage basins. This thorough analysis sheds light on the fundamental mechanisms that control hydrological processes and how they interact with geomorphological characteristics.

To explore these relationships further, a detailed regression analysis is performed. This statistical technique identifies specific equations summarising the relationships between hydrograph attributes and various geomorphological metrics. These regression equations and relevant statistical measures assessing model strength provide a quantitative understanding of the connections observed in the histogram analysis. Ultimately, the obtained regression equations serve as predictive tools, enabling the anticipation of hydrograph attributes based on selected geomorphological metric values. This predictive capability enhances understanding of hydrological processes and supports informed decision-making in water resource management and flood risk assessment.

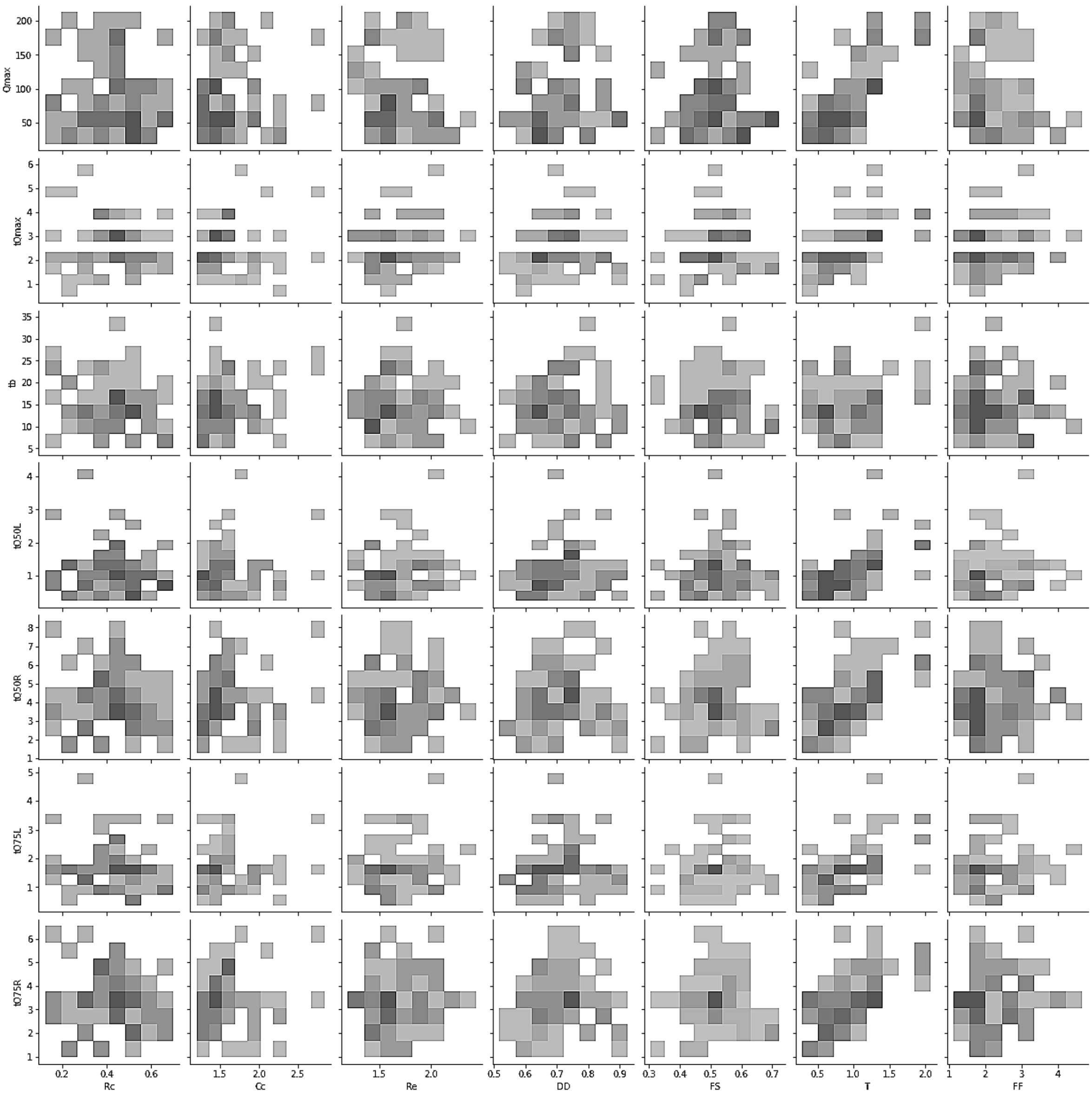
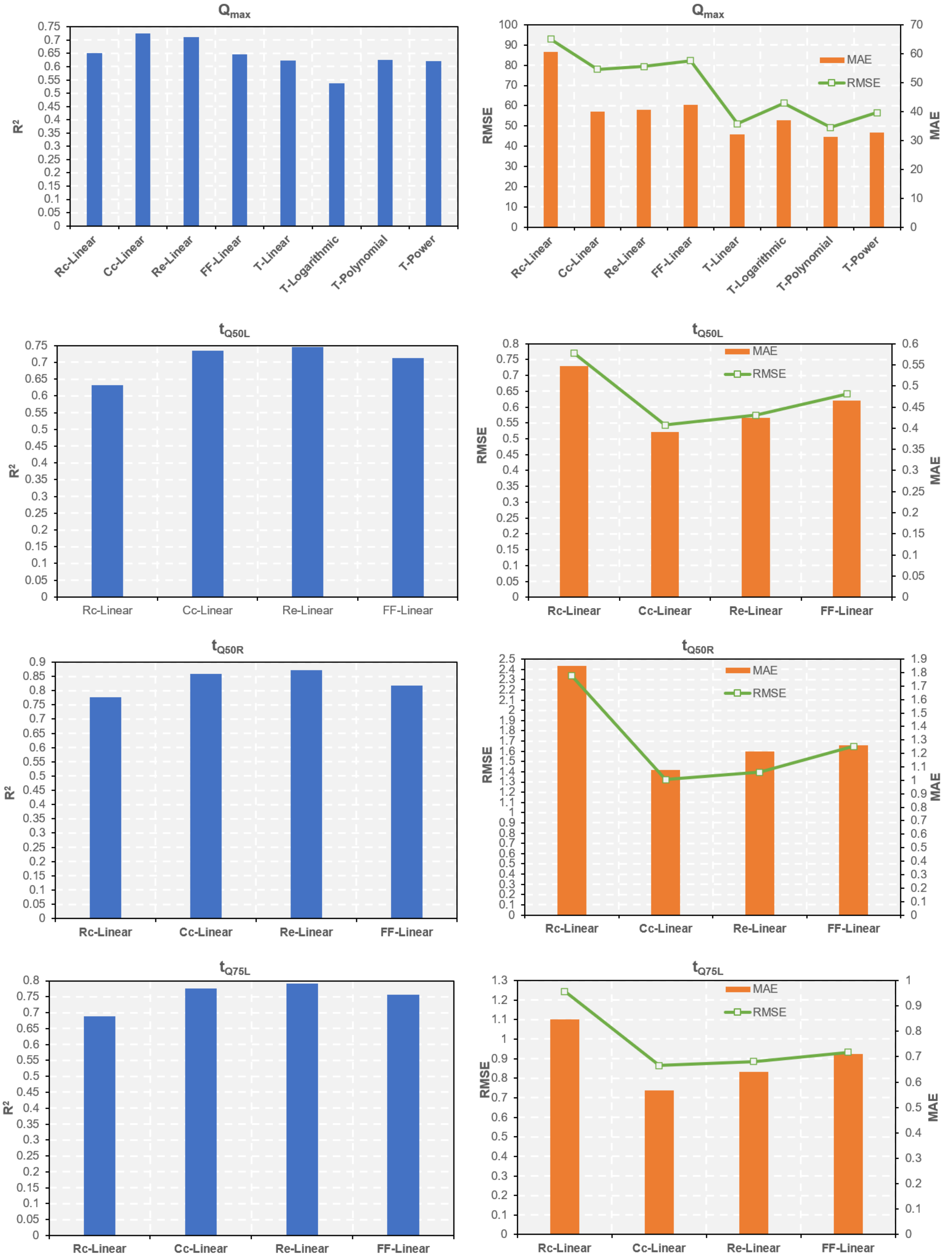


Figure 4-9: Histogram analysis of correlations between hydrograph attributes and geomorphological metrics.

4.2.3 Validation regression analysis

The validation regression analysis represents a critical phase in the study, aiming to identify the most appropriate regression equation for predicting each hydrograph attribute about geomorphological metrics. This analysis involves the remaining 30 basins from the total dataset of 100, providing a robust sample for statistical evaluation. Key statistical measures such as R^2, MAE, and RMSE serve as the litmus test for assessing the performance and reliability of each regression equation. The selection of optimal regression equations is paramount to ensure accurate prediction of hydrograph attributes across a diverse range of basin characteristics. Figure 4-10 visually depicts these relationships and provides an overview of the vital statistical metrics for model evaluation. Additionally, Table 4-4 presents detailed statistical measures for the entire set of examined UH attributes, offering a comprehensive understanding of the regression analysis results.



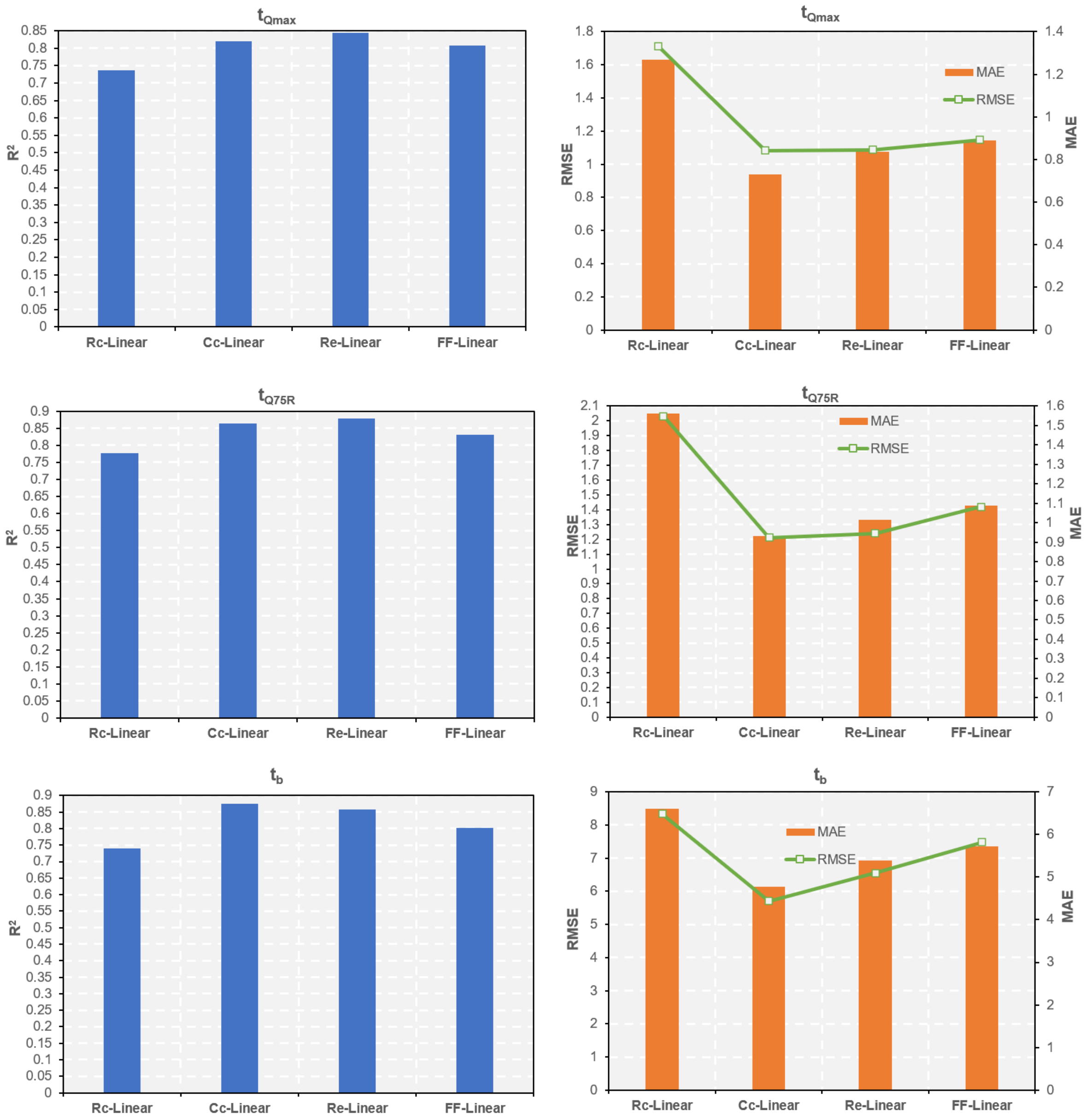


Figure 4-10: Visual representation of model evaluation metrics for selected UH attributes.

The first chart on the left in Figure 4-10 visually represents R^2 (R-squared) values for different types of equations corresponding to each hydrograph attribute. Higher R^2 values indicate a stronger fit of the model to the data, suggesting better predictive performance, which is crucial for reliable hydrograph analysis. Transitioning to the right side of Figure 4-10, the second chart combines a bar graph and a line graph to illustrate the relationship between RMSE, MAE, and the values of each hydrograph attribute across various equation types. The line graph, plotting RMSE values, is aligned with the left y-axis, providing insights into the model's prediction errors. Simultaneously, the bar graph represents MAE values, measured on the right y-axis, highlighting the average magnitude of the prediction errors. This dual-axis visualisation enables a comprehensive exploration of the relationships between hydrograph attributes, geomorphological metrics, and the accuracy of different equation types in capturing these connections. By presenting both error metrics alongside R^2 values, the visualisation effectively demonstrates how each model performs, facilitating a deeper understanding of which regression equations are most effective for predicting hydrograph characteristics in diverse basin conditions.

Table 4-4: Statistical measures for the evaluated Unit Hydrograph (UH) attributes

Geomorphological metrics	**Rc**	**Cc**	**Re**	**FF**	**T**	**T**	**T**	**T**
Equation	Linear	Linear	Linear	Linear	Linear	Logarithmic	Polynomial	Power
UH attribute	t_{Qmax}							
R^2	0.736	0.820	0.843	0.807	-	-	-	-
MAE	1.270	0.729	0.837	0.889	-	-	-	-
RMSE	1.713	1.082	1.088	1.148	-	-	-	-
UH attribute	t_{Q50L}							
R^2	0.631	0.734	0.745	0.713	-	-	-	-
MAE	0.547	0.391	0.424	0.466	-	-	-	-
RMSE	0.770	0.544	0.574	0.642	-	-	-	-
UH attribute	t_{Q50R}							
R^2	0.776	0.858	0.871	0.817	-	-	-	-
MAE	1.851	1.077	1.215	1.262	-	-	-	-
RMSE	2.337	1.322	1.396	1.646	-	-	-	-
UH attribute	t_{Q75R}							
R^2	0.778	0.864	0.878	0.831	-	-	-	-
MAE	1.561	0.931	1.015	1.088	-	-	-	-
RMSE	2.032	1.212	1.240	1.420	-	-	-	-
UH attribute	t_{Q75L}							
R^2	0.689	0.775	0.792	0.756	-	-	-	-
MAE	0.846	0.567	0.642	0.712	-	-	-	-
RMSE	1.245	0.865	0.886	0.933	-	-	-	-
UH attribute	t_b							
R^2	0.740	0.875	0.859	0.802	-	-	-	-
MAE	6.611	4.767	5.383	5.720	-	-	-	-
RMSE	8.330	5.708	6.547	7.477	-	-	-	-
UH attribute	Q_{max}							
R^2	0.650	0.725	0.712	0.646	0.624	0.538	0.625	0.622
MAE	60.559	39.988	40.645	42.264	32.000	36.888	31.205	32.648
RMSE	92.918	78.010	79.392	82.305	51.040	61.240	49.217	56.507

Concerning the Q_{max} attribute, the graph indicates that the T-Polynomial model exhibits the lowest MAE and RMSE values among the models presented. This suggests superior predictive performance with minimised prediction errors. The bar representing the T-Polynomial model is notably lower than others, indicating more minor errors on average and squared errors. Lower MAE and RMSE values are generally preferred as they signify a model that closely aligns with observed values, thus providing more accurate and reliable predictions. Despite the compelling R^2 value of 0.725 associated with the Cc-Linear equation, which traditionally would suggest a solid fit for the data by accounting for a significant proportion of the variance in Q_{max} values, the decision leaned towards the T-Polynomial model. This choice prioritises predictive accuracy and error minimisation over the variance explained. It underscores a detailed understanding that a model's ability to explain the variance, while important, is secondary to its precision and reliability in practical applications, particularly in hydrological forecasting, where the stakes of prediction errors can be high.

The T-Polynomial equation, chosen for its superior performance, is outlined below for reference. This equation accurately captures the complex, nonlinear relationships between the Qmax attribute and geomorphological metrics with its polynomial components. It offers a more sophisticated method for predicting hydrographs, outperforming linear models' accuracy and dependability. The precise coefficients and the formula's structure are meticulously designed to reflect the observed complex dynamics, ensuring its success in predicting water flow characteristics with reduced errors. This advanced approach enhances the equation's ability to provide precise forecasts, making it a strong foundation for advancing predictive hydrology and improving decision-making processes in water resource management. The formula for the T-Polynomial equation, chosen for its effectiveness in hydrological modelling, is illustrated below:

$$y = 8.6049x^2 + 78.275x + 6.3238 \tag{4.1}$$

where:

y= Q_{max} represents the peak discharge of the UH (m^3/s)

x= T is the geomorphological parameter associated with the drainage texture

For the t_{Q50L} hydrograph attribute, a nuanced analysis of the regression models reveals an exciting interplay between R^2, MAE, and RMSE values. The Re-Linear model stands out initially with the highest R^2 value of 0.745, suggesting a solid goodness of fit, indicating that this model can explain a substantial portion of the variance in t_{Q50L} values across the dataset. Typically, a higher R^2 value would be interpreted as a sign of a model's effectiveness in capturing the underlying pattern within the data. However, the analysis takes a turn when evaluating the model's predictive performance through the lenses of MAE and RMSE. Despite its high R^2 value, the Re-Linear model registers the highest values for both MAE and RMSE, indicating a less favourable predictive performance. This discrepancy underscores a critical insight: while R^2 measures the proportion of variance explained by the model, it may not always translate to the most accurate predictions, especially in the context of individual predictions. In contrast, the Cc-Linear model emerges as a more balanced and reliable predictor for the t_{Q50L} attribute. It boasts a high R^2 value of 0.7343, which, while slightly lower than that of the Re-Linear model, still indicates a robust ability to explain the variance within the t_{Q50L} data. More importantly, the Cc-Linear model demonstrates lower MAE and RMSE values than its Re-Linear counterpart. This combination of high R^2 with lower MAE and RMSE signifies intense goodness of fit and superior predictive accuracy, making the Cc-Linear model a preferred choice for forecasting t_{Q50L} values.

The distinction between R^2 and predictive errors (MAE and RMSE) is pivotal in this analysis. While R^2 gives a broad overview of the model's fit to the data, MAE and RMSE provide a more granular view of its predictive accuracy, with MAE offering an average magnitude of errors and RMSE amplifying the impact of more significant errors due to its squaring effect. MAE's lower sensitivity to outliers makes it a valuable metric for assessing model performance. The Cc-Linear equation, identified as the most reliable predictor for the t_{Q50L} dataset, is illustrated below. This equation captures the linear relationship between the t_{Q50L} attribute and the Cc geomorphological metric, embodying a refined tool that balances explanatory power and predictive precision. By leveraging the strengths of the Cc-Linear model, researchers and practitioners can achieve more accurate and reliable predictions for t_{Q50L}, enhancing the application of hydrological models in water resource management and planning. The Cc-Linear equation can be represented as follows:

$$y = 0.6835x \tag{4.2}$$

where:

y= t_{Q50L} represents the time to 50% of the rising limb of the hydrograph

x= Cc is the geomorphological parameter associated with the compactness coefficient

Specifically, concerning the t_{Q50R} hydrograph attribute, the Re-Linear model exhibits the highest R^2 value, indicating the best fit to the data among the considered models. However, despite the attractive high R^2 value of the Re-Linear model, examining its predictive accuracy with the RMSE offers a contrasting view. The Cc-Linear model distinguishes itself by registering the lowest RMSE, indicating more minor average squared errors. This suggests that, on average, the Cc-Linear model's predictions are closer to actual observed values, especially in minimising the impact of significant errors, which RMSE is particularly sensitive to. The analysis of MAE values corroborates this finding, mirroring the trend observed with RMSE. RMSE and MAE are critical in evaluating a model's predictive accuracy, offering insights into the average magnitude of errors in predictions (MAE) and the square root of the average of squared differences between predicted and observed values (RMSE). A model that exhibits low values for both these metrics is generally considered to provide reliable and accurate predictions. Despite the Re-Linear model's higher R^2 value, the Cc-Linear model emerges as the superior choice based on its lower RMSE and MAE values. It's essential to understand what these metrics mean properly. A high R^2 indicates a good fit of the model to past data, but it doesn't necessarily guarantee accurate predictions. This is where the significance of RMSE and MAE comes in, as they are essential for assessing predictive accuracy. For reference, below is the representation of the Cc-Linear equation.

$$y = 2.4892x \tag{4.3}$$

where:
y= t_{Q50R} represents the time to 50% of the falling limb of the hydrograph
x= Cc is the geomorphological parameter associated with the compactness coefficient

All four models show relatively high R^2 values for the t_{Q75R} hydrograph attribute, demonstrating a solid fit for the data across the board. However, the Re-Linear and Cc-Linear models slightly outperform the Rc-Linear and FF-Linear models with marginally higher R^2 values, suggesting a better fit. Notably, the Cc-Linear model has the lowest RMSE value, implying more minor average squared errors and suggesting its potential for more accurate predictions, particularly with fewer significant deviations. The MAE mirrors the RMSE trend, with the Cc-Linear model demonstrating the lowest MAE, indicating its predictions are, on average, closer to the actual values. A combination of a high R^2 and low RMSE and MAE typically signifies a model that fits well with historical data and accurately predicts new data with minimal errors. In this comparison, the Cc-Linear model balances a firm fit (high R^2) and accurate prediction (low RMSE and MAE) for the t_{Q75R} attribute. For reference, below is the representation of the Cc-Linear equation.

$$y = 2.0333x \tag{4.4}$$

where:
y= t_{Q75R} represents the time to 75% of the falling limb of the hydrograph
x= Cc is the geomorphological parameter associated with the compactness coefficient

For the t_{Q75L} hydrograph attribute, both the Re-Linear and Cc-Linear models demonstrate the highest R^2 values, indicating superior fits to the data compared to the Rc-Linear and FF-Linear models. Notably, the Cc-Linear model boasts the lowest RMSE, implying more minor average squared prediction errors than the other models. Furthermore, the Cc-Linear model exhibits the lowest MAE, suggesting its predictions are closer, on average, to the outputs of the time-area diagram model. Considering these metrics collectively, the Cc-Linear model appears to strike a balance between a firm fit (high R^2) and accurate prediction (low RMSE and MAE) for the tQ75L attribute. For reference, below is the representation of the Cc-Linear equation.

$$y = 0.9958x \tag{4.5}$$

where:
y= t_{Q75L} represents the time to 75% of the rising limb of the hydrograph
x= Cc is the geomorphological parameter associated with the compactness coefficient

When examining the tb hydrograph attribute, the Cc-Linear model is the most robust among the models assessed. It boasts the highest R^2 value and the lowest values for both RMSE and MAE. These characteristics indicate that the Cc-Linear model aligns closely with the output of the time-area diagram method and delivers precise predictions for tb with minimal errors. Below is the expression of the Cc-Linear equation:

$$y = 9.0156x \quad (4.6)$$

where:
y= t_b represents the base time of the hydrograph
x= Cc is the geomorphological parameter associated with the compactness coefficient

For the t_{Qmax} hydrograph attribute, the Re-Linear model boasts the highest R^2 value. However, this model also exhibits the highest RMSE and MAE, indicating inferior predictive performance. Considering both metrics, the charts suggest that the Cc-Linear model may offer the most dependable predictions for the t_{Qmax} dataset, as it achieves a high R^2 alongside low MAE and RMSE values. MAE and RMSE are more adept at capturing actual prediction errors, with MAE being less influenced by outliers than RMSE. The Cc-Linear equation is represented as follows:

$$y = 1.4738x \quad (4.7)$$

where:
y= t_{Qmax} represents the time to peak of the hydrograph
x= Cc is the geomorphological parameter associated with the compactness coefficient

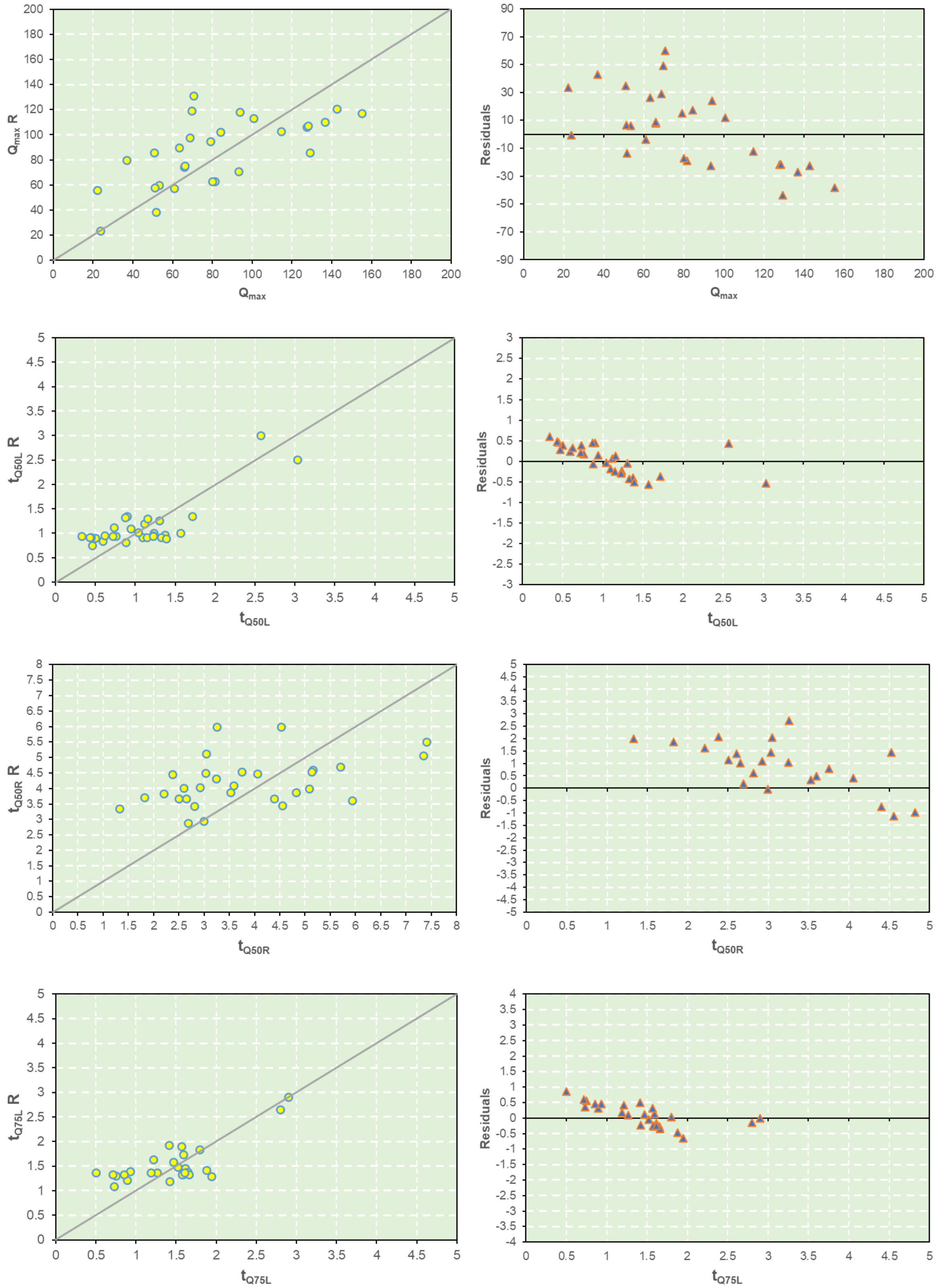
The findings from the regression analysis reveal a pronounced dependence on the geomorphological metric Cc across a spectrum of hydrograph attributes when determining the most effective regression equations. This metric heavily influences the determination of the optimal regression equations across various hydrograph attributes. This pattern emphasises the pivotal role of Cc in shaping the predictive accuracy of the models. Moreover, the validation regression analysis extends to the calculation of residuals, a pivotal aspect in assessing the goodness of fit for each regression equation.

Residuals, the differences between the observed values obtained through the time-area diagram method and the values predicted by the regression models, offer invaluable insights into the precision and reliability of the models. By examining the distribution and patterns of these residuals, researchers can gauge the extent to which a model accurately captures the underlying hydrological dynamics of the catchment area. The analysis of residuals is paramount for several reasons. First, it directly measures the prediction error, allowing for a detailed evaluation of a model's performance. A tightly clustered distribution of residuals around zero would indicate a model consistently producing accurate predictions across the dataset. Conversely, a wide spread of residuals could signal potential issues with the model's fit, suggesting that it may only partially account for some influential factors or be overly simplified. Second, the pattern of residuals can reveal biases in the predictions. For instance, if the residuals show a systematic pattern, such as consistently overestimating or underestimating the hydrograph attributes at specific ranges of Cc, this could indicate a model's inability to capture the nonlinear relationships or interactions between variables effectively. Such insights are critical for refining the models and selecting more complex or differently structured equations that better encapsulate the dynamics.

For illustrative purposes, Figure 4-11 provides a visual depiction of this analysis. The scatter plot (Left Image) directly compares observed and predicted values generated by the regression models, facilitating a visual assessment of model performance. Meanwhile, the residual plot (Right Image) is a diagnostic tool to identify potential shortcomings in the model, such as changing variance, non-linearity, or the presence of outliers. Both plots play crucial roles in regression diagnostics.

In the scatter plot, the x-axis represents the observed values of each hydrograph attribute, calculated through the time-area diagram method. The y-axis indicates the corresponding predicted values of each hydrograph attribute, derived from the regression model R. A well-fitted model would exhibit points in the scatter plot that closely align with the diagonal line, indicating a solid agreement between observed and predicted values. Conversely, the residual plot enables the detection of any patterns or systematic deviations in the distribution of residuals. If the residuals are randomly scattered around the horizontal axis with no discernible pattern, it suggests that the model adequately captures the variability in the data. However, suppose clear patterns or systematic deviations are observed in the residual plot. In that case, it may indicate issues such as non-linearity, non-constant variance of residuals, or the presence of influential outliers that could affect the model's performance.

The diagonal line in the scatter plot represents a perfect prediction, where the predicted values match the observed values. Each blue circular marker on the plot corresponds to an individual data point, indicating each hydrograph attribute's observed and predicted values. In the residual plot, the x-axis mirrors the scatter plot, displaying the observed values of each hydrograph attribute. The y-axis represents the residuals, which are the differences between the observed values and the predictions made by the model. A horizontal line at zero indicates perfect prediction, where the model's predictions align precisely with the observed values. The orange triangular markers on the residual plot represent the residuals for each data point. Ideally, these residuals should be randomly scattered around the horizontal zero line, indicating that the model's predictions are unbiased and have consistent accuracy across different values of each hydrograph attribute. Any discernible pattern or trend in the residuals could suggest systematic errors in the model's predictions that must be addressed.



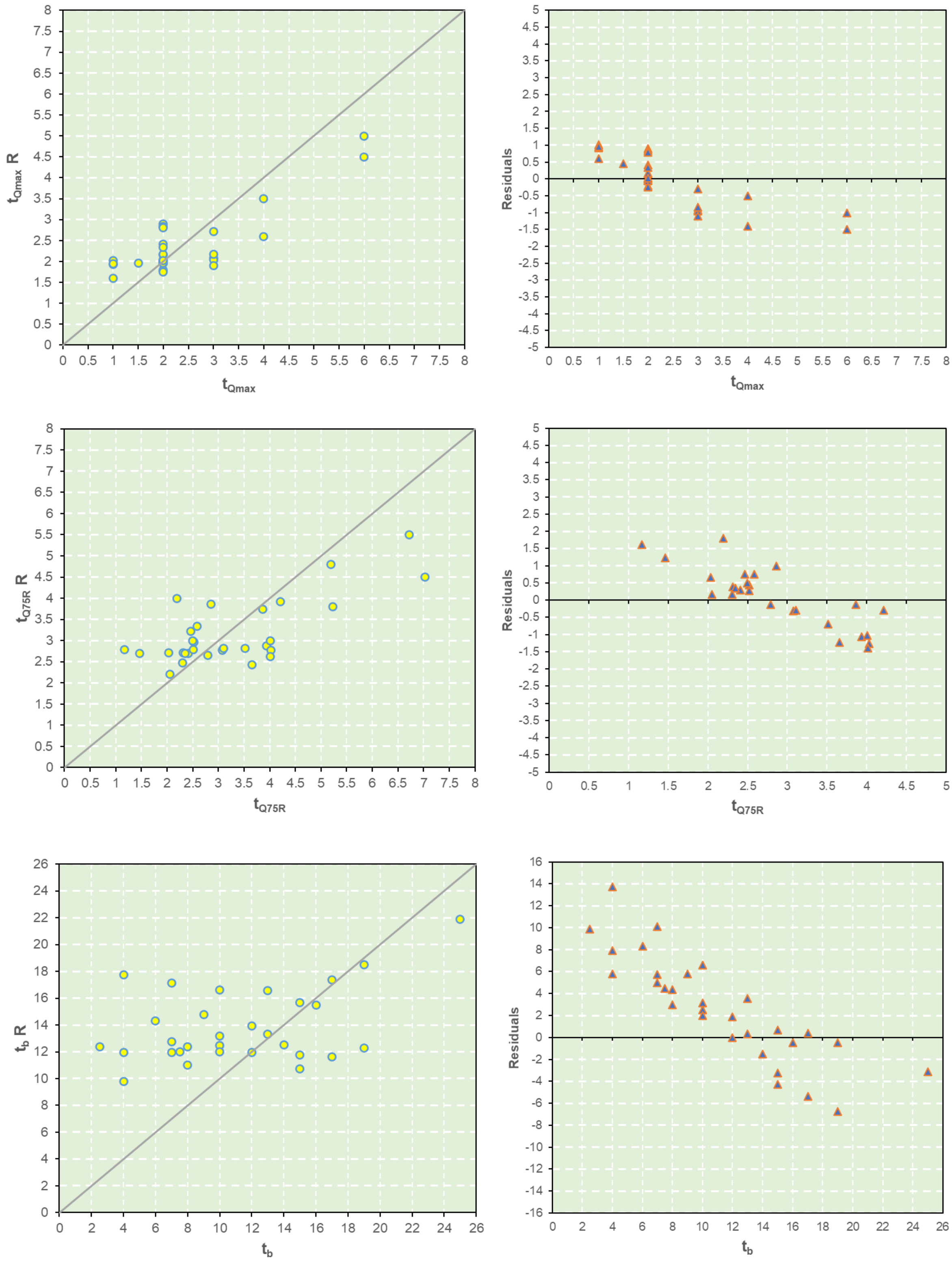


Figure 4-11: Residual analysis visualization in the validation regression analysis for UH attributes.

For Q_{max}, the scatter plot shows a reasonable agreement between the observed and predicted values, with data points clustered around the line of perfect prediction. However, some variations indicate that the model's predictions may only partially match the observed data for all points. The residual plot's spread of residuals around the zero line suggests that the model has some predictive capability. However, there are still some discrepancies between the observed and predicted values.

Regarding t_{Q50R}, the scatter plot indicates good agreement between the observed and predicted values, with data points closely distributed around the line of perfect prediction. This suggests the model has predictive validity, although some deviations from an ideal fit exist. The residuals are reasonably evenly distributed around the zero line, but there is a slight trend where they become more positive as t_{Q50R} increases. This indicates that the model tends to under-predict for higher values of t_{Q50R}. Similarly, for t_{Q50L}, the scatter plot illustrates a linear relationship between the observed and predicted values, with the regression line showing a positive slope. This indicates a positive correlation between the variables: as t_{Q50L} increases, t_{Q50L} R also tends to increase. This suggests that the model captures the overall trend in the data, although there may be some variability in the predictions compared to the observed values.

The scatter plot for t_{Q75L} illustrates a positive linear relationship between the observed and predicted values, as indicated by the upward slope of the trend line. This suggests that as t_{Q75L} increases, t_{Q75L} R also tends to increase, indicating a correlation between these variables. The data points are closely clustered around the trend line, indicating a robust linear relationship with some variability. In the residual plot, the residuals are randomly scattered around the zero line, suggesting that the linear model suits the data. There is no discernible pattern or systematic deviation from the zero line, indicating consistent variances of the residuals across different values of t_{Q75L}. However, there are a few outliers where the residuals deviate significantly from the zero line, suggesting potential anomalies or areas where the model may not capture all the variability in the data. Overall, this analysis suggests that the linear regression model has some predictive power for t_{Q75L}, as indicated by the agreement between observed and predicted values and the consistency of residuals. However, outliers indicate potential areas for further investigation or model refinement.

For the variable t_{Qmax}, the scatter plot reveals a positive correlation between the observed values (t_{Qmax}) and the predicted values (t_{Qmax} R), as the data points tend to rise alongside the line of perfect prediction. This suggests that the model captures the trend in the data to a reasonable degree. The spread of the data points indicates that while the model predicts the trend, there is some variance, with most data points falling close to the line but some scattered more widely. This variance suggests that the model may be less accurate at specific points. The residual plot for t_{Qmax} shows the differences between the observed and predicted values. Residuals are scattered on both sides of the zero line, indicating that the model overpredicts and underpredicts with no apparent bias towards one direction. However, a cluster of residuals with higher positive values suggests that the model significantly underpredicts the observed values for several points. Overall, the analysis of the t_{Qmax} variable indicates that the model has predictive validity and captures the general trend. Yet, the spread of the residuals and outliers points to areas where the model might be improved for more precise predictions, particularly where it underpredicts the actual values.

The positive linear trend is evident in the scatter plot for tQ75R, indicating a reasonable correlation between the observed and predicted values. Most data points are distributed around the line of perfect prediction, suggesting that as t_{Q75R} increases, the model's predictions also increase in a manner that aligns with this trend. The residual plot for t_{Q75R} illustrates that the residuals are predominantly above the zero line, yet there's no distinct pattern suggesting any systematic deviation in the model's predictions. This distribution of residuals implies that the model tends to overestimate the observed values slightly. The lack of any clear trend in the residuals, other than a slight skew towards positive values, suggests that the model's predictions generally maintain a consistent level of variance concerning the observed values. Overall, the scatter and residual plots for t_{Q75R} convey that the model captures the overall trend in the observed data with a natural degree of variability. The model seems to robustly reflect the system's behaviour when simulated, with the data points and residuals demonstrating the model's dynamic range and predictive strength.

The scatter plot for tb shows a clear positive relationship between the observed t_b values and the predicted t_b R. While not tightly clustered, the data points follow the line of perfect prediction, suggesting that the model predictions generally increase with the observed values, albeit with some scatter representing the complexity of the phenomenon being modelled. The residuals plot for tb reveals that as the observed tb values increase, the residuals become more varied and tend to be positive. This indicates that for higher tb values, the model's predictions are often higher than the observed values. While the distribution of residuals suggests that the model is entirely consistent at lower values of tb, at higher values, the model prediction does not track as closely to the observed data, which is indicated by the increasing spread of residuals. Together, these plots indicate that the model has an excellent foundational relationship with the observed data but also suggest an area where the model's predictions deviate more as tb increases. This deviation does not detract from the model's usefulness; instead, it highlights the natural variability in predicting complex systems and the robustness of the model across the range of tb values.

A well-informed choice of the best regression equations is achieved through careful analysis of the statistical measures and visual interpretation of the model evaluation metrics. These equations are celebrated for their accuracy and set a new standard for predicting hydrograph attributes, improving the usefulness of predictive models in both hydrological research and real-world applications. This thorough validation process strengthens the research's methodological base and notably contributes to hydrological modelling. It provides essential insights for managing water resources, planning environmental initiatives and FRM.

4.2.4 Comparison of observed and computed GUH

In this section, a comparative analysis is conducted between the UH provided by the PPC for four representative basins—Metsovitiko, Puli, Agia, and Mouzaki—and the GUH calculated using the empirical equations developed through this dissertation (Figure 4-12). The goal of this comparison is to evaluate the accuracy and performance of the derived GUH models in replicating the hydrological behaviour observed in these basins.

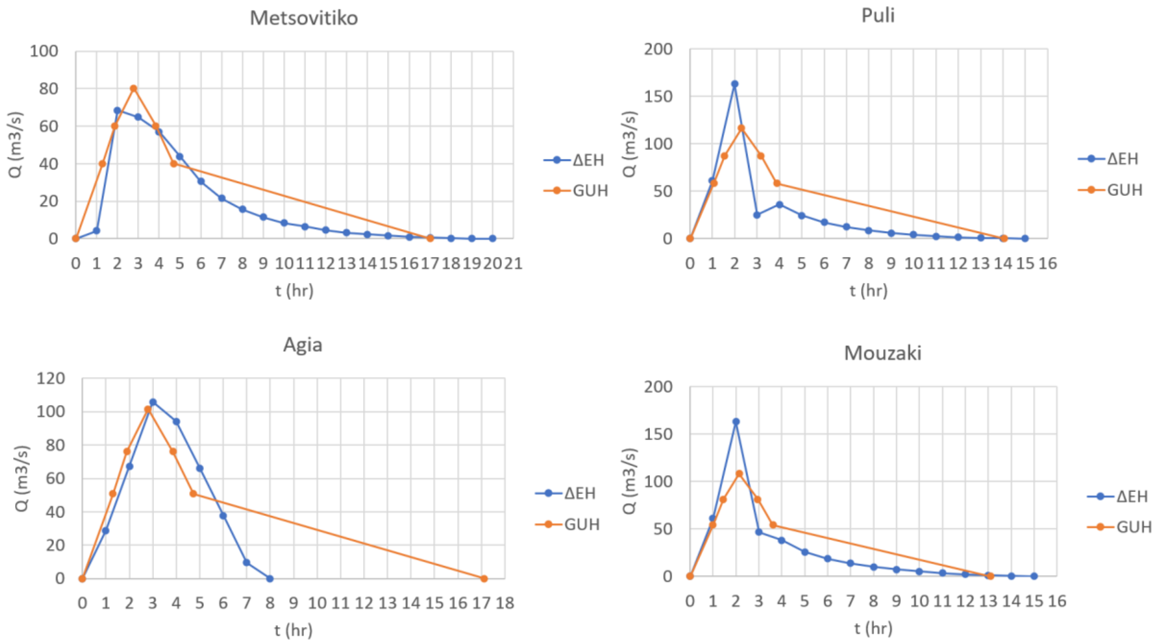


Figure 4-12: Comparison of observed and computed (GUH) unit hydrographs for Metsovitiko, Puli, Agia, and Mouzaki basins.

In the Metsovitiko basin, the observed UH shows a sharp peak followed by a gradual recession. The GUH, derived using the empirical equations based on geomorphological metrics, captures the overall shape of the hydrograph with a similar recession pattern. However, a slight overestimation in peak discharge is evident, along with a marginally earlier occurrence of the peak. Despite these differences, the alignment of the recession limbs in both hydrographs is noteworthy, suggesting that the model performs well in simulating the post-peak runoff process.

For the Puli basin, the GUH exhibits a very close fit to the observed UH, particularly in the recession phase. While the observed UH shows a sharp and steep peak, the GUH has a smoother peak with only a slight delay. The magnitude of the peak discharge is slightly underestimated, but this does not significantly affect the overall hydrograph shape. The strong agreement between the observed and calculated hydrographs in the recession limb suggests that the empirical equations effectively account for the basin's geomorphological characteristics. This result reinforces the reliability of the derived model in capturing both the timing and magnitude of baseflow processes in the basin.

In the Agia basin, the agreement between the observed UH and the calculated GUH is particularly strong. Both hydrographs peak at the same time, with the GUH almost perfectly replicating the observed peak discharge. The recession limbs of the two hydrographs also show remarkable similarity, indicating that the model has successfully captured the key hydrological processes governing runoff generation and dissipation in this basin. The accurate prediction of both the peak and the recession phase suggests that the empirical relationships are highly suited to this basin's geomorphological structure. This high degree of fit highlights the robustness of the GUH model in accurately representing runoff behaviour in basins with well-defined hydrological characteristics.

The Mouzaki basin presents a more complex case, with the observed UH displaying a sharp and pronounced peak, indicative of a fast-response system with steep slopes and rapid runoff. In contrast, the GUH exhibits a smoother peak with slightly lower magnitude. While the timing of the peak is well aligned between the two hydrographs, the discrepancy in peak magnitude suggests that the empirical model underestimates the rapidity and intensity of runoff concentration in this basin. Nevertheless, the alignment of the recession limbs indicates that, despite the peak differences, the model performs adequately in simulating the overall hydrograph shape, particularly in terms of runoff recession and flow duration.

The comparative analysis between the observed and calculated unit hydrographs reveals that the GUH models derived through geomorphological analysis provide a robust and reliable approximation of hydrological behaviour across diverse basin types. The empirical equations developed in this dissertation have proven effective in capturing the key characteristics of hydrographs, particularly in terms of recession dynamics and overall shape, although further refinements may be needed to improve peak discharge accuracy in more complex basins. The methodology developed here provides a solid framework for future applications in flood forecasting and water resource management, offering a practical and scientifically grounded solution for understanding and predicting hydrological responses in ungauged basins.

4.3 Implementation of Nature-Based Solutions

4.3.1 Application of land cover change and construction of retention ponds

This section presents a comparative analysis of flood hydrographs derived from a hydrological analysis conducted in the Sarantapotamos river basin upstream of the settlement of Magoula, Greece. The main objective is to assess the effectiveness of various NBS in flood mitigation, highlighting their respective roles in reducing peak discharge. The comparison involves the initial flood hydrograph, which represents the current climate conditions, and the hydrographs resulting from implementing two proposed NBS measures. Additionally, the analysis involves a comparative review between the baseline scenario and hydrographs generated from three future climate scenarios—encompassing both mean and worst-case projections—after implementing these two NBS measures. This comprehensive approach enables a clearer understanding of how NBS can enhance flood resilience under varying climatic conditions and helps identify robust flood risk management strategies in the Sarantapotamos River basin.

The analysis establishes a baseline scenario, simulating a peak discharge under current climatic conditions. This scenario is pivotal as it sets the standard against which the efficacy of NBS measures is measured. The examination of the baseline scenario reveals a peak discharge of 535.7 m^3/s occurring at 19 h. The deployment of land cover change as a strategic NBS measure yields noteworthy results. By modifying land cover to increase water absorption, the peak discharge is noticeably decreased to 465.8 m^3/s, delaying the time to peak to 20 h. This intervention slows the rush of water and lowers the overall flood volume from 118 hm^3 to 103 hm^3. Decreased peak discharge can be credited to changes in land cover patterns, which enhance stormwater infiltration, reduce surface runoff and lower flood volumes. Similarly, the construction of retention ponds contributes to a substantial reduction in peak discharge, reaching 383.3 m^3/s, with the time to peak accelerated to 15 h, assuming the peak occurs at approximately 75% of the ascending limb post-NBS implementation. A total of 245 retention ponds are estimated to be constructed, with a combined flood volume capacity of 3.3 hm^3. Consequently, the flood hydrograph following this NBS implementation indicates a total flood volume of 115 hm^3. Additionally, a combination of both NBS results in an even lower peak discharge of 318.5 m^3/s, representing a reduction of about 41% compared to the pre-NBS scenario, with the time to peak remaining constant at 15 h. This suggests that the combined NBS does not significantly affect the timing of the peak discharge compared to the retention ponds scenario. Notably, the flood volume significantly decreases to 99.7 hm^3, attributed to the retention ponds' capacity to withhold 3.4 hm^3 of floodwater. Relative to the total flood volume in the baseline scenario, this reduction corresponds to a significant decrease of approximately 15.3%. Moreover, it's important to note that achieving these results will require the construction of a total of 250 retention ponds. Figure 4-13 acts as a visual guide to these findings, showing the before-and-after effects of implementing NBS under current climate conditions. It provides a clear picture of how nature-based measures can significantly transform the narrative depicted by the hydrograph, proposing a sustainable route towards reducing the risk of flooding.

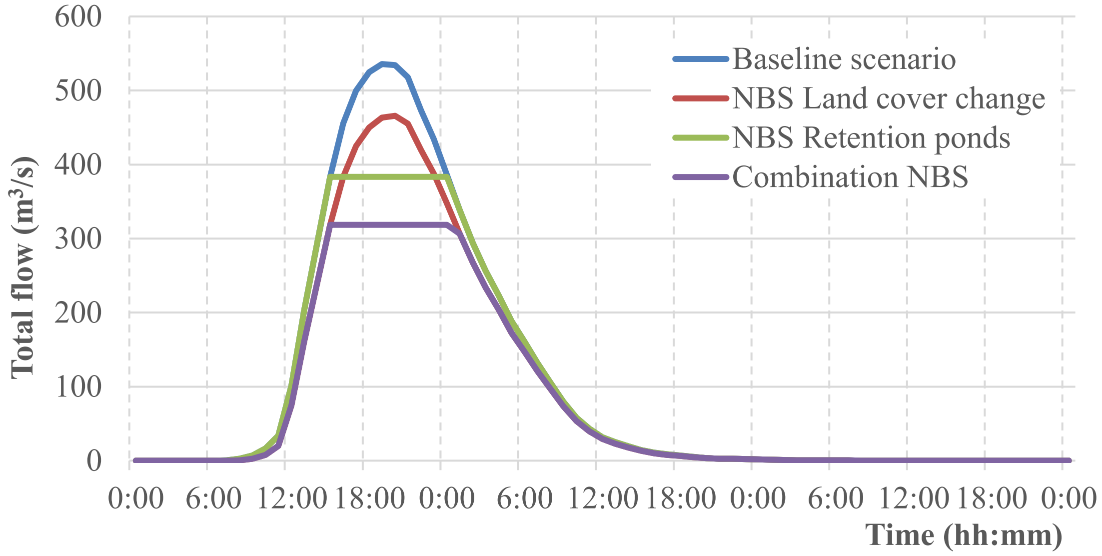


Figure 4-13: Flood hydrographs before and after NBS for current climate conditions.

Furthermore, the influence of climate change scenarios on the design precipitation used for calculating rainfall depths and, consequently, flood hydrographs is evaluated, as depicted in Figure 4-14. It looks closely at three climate scenarios: an upper-end scenario with much more rain, a mean scenario representing an average increase, and a lower-end scenario that might even bring less rainfall than today. Before considering climate change, the peak rainfall of the design storm is 61.6 mm, with a cumulative rainfall depth of 219.5 mm and an intensity of 9.1 mm/h.

However, under the upper climate change scenario, both the cumulative rainfall depth and rainfall intensity increase significantly to 962.3 mm and 40 mm/h, respectively. Additionally, the peak rainfall intensifies to 312.8 mm. This heightened design precipitation presents further challenges for flood management, underscoring the critical need for implementing effective NBS to mitigate the potential impacts of climate change. In contrast, the lower climate change scenario leads to a reduction in both cumulative rainfall depth and rainfall peak. The cumulative rainfall depth decreases to 154.2 mm, marking a decrease of approximately 30 % compared to the baseline scenario. Similarly, the rainfall peak is reduced to 63 mm, indicating a lower intensity of the design precipitation, which decreases to 6.4 mm/h. This scenario offers a more optimistic view regarding the risk of flooding.

In the mean climate change scenario, the cumulative rainfall depth reaches 325 mm, while the rainfall peak measures 130.6 mm, with the rainfall intensity increasing to 13.5 mm/h. Hydrological simulations conducted to assess the impact of these climatic scenarios on flood hydrographs underscore the importance of combining NBS with CCA strategies. Specifically, in the upper climate change scenario, the peak discharge increases to 4075 m^3/s, occurring at 19 h. The flood volume is also calculated to be 826.8 hm^3, indicating a significant increase compared to the initial volume of 118 hm^3. This represents a substantial percentage increase of approximately 600%. The observed rise in flood volume and peak discharge emphasises the necessity of implementing measures to enhance resilience against the potential risks and impacts of extreme weather events resulting from climate change. In the mean climate change scenario, the peak discharge reaches 1107.4 m^3/s, one hour earlier at 18 h. Furthermore, the flood volume increases to 211.7 hm^3, indicating a percentage increase of approximately 79.2% compared to the initial volume of 118 hm^3. The observed escalation in flood volume and peak discharge in the mean climate change scenario further underscores the need for effective adaptation measures to address flood risk.

Conversely, the lower scenario results in a peak discharge of 337.9 m^3/s, with no change in the time to peak at 19 h, while the total flood volume decreases to 65.6 hm^3. Figure 4-14 Showcases the changes in flood patterns as depicted in the hydrographs for each climate change scenario, providing a straightforward visual comparison of possible future river behaviour. This graphical representation highlights the differences in flood behaviour and emphasises the need to combine NBS with adaptive strategies to address the risks posed by various climate change outcomes.

The upper and mean scenarios are specifically chosen based on hydrological analyses conducted to calculate flood hydrographs under three climate change scenarios. These scenarios serve as the basis for evaluating the effectiveness of implementing NBS under these particular climate conditions. In the upper scenario, a focused investigation is conducted on the efficacy of two distinct NBS measures: land cover change and the strategic implementation of retention ponds. These measures are evaluated independently and in synergy to discern their cumulative impact on flood management.

Land cover modification, which aims to increase permeability and enhance the soil's water retention capacity, leads to a notable decrease in peak discharge rates. Specifically, the implementation of this measure results in a peak discharge of 3945.5 m^3/s, indicating a reduction of approximately 3.7 % from the baseline scenario of 4075 m^3/s. This outcome underscores the significance of land cover as a critical factor in hydrological responses to storm events. Remarkably, the time to peak discharge remained constant at 19 h, indicating that while the peak flow rate is mitigated, the overall temporal dynamics of the flood hydrograph are unaffected.

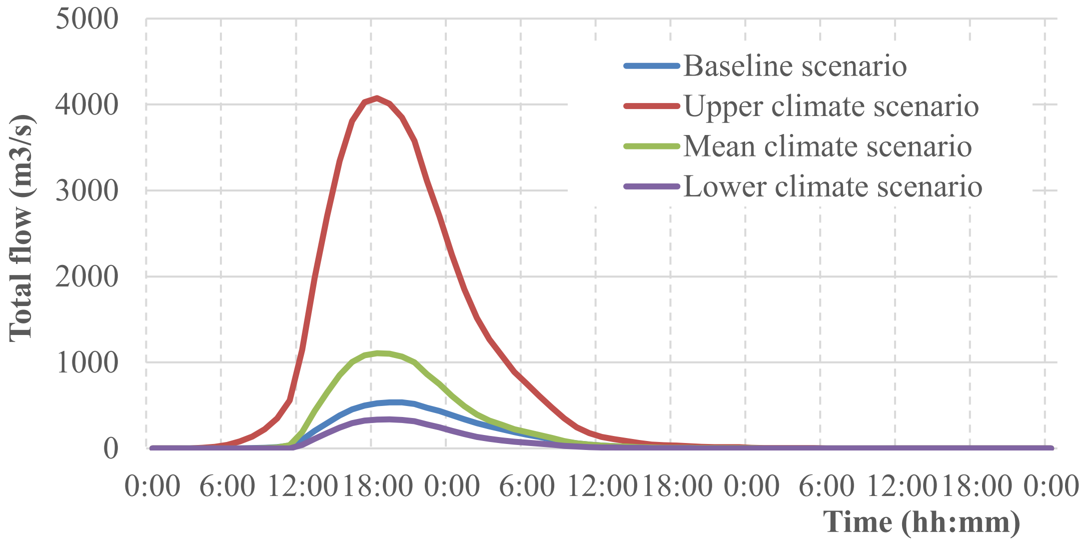


Figure 4-14: Flood hydrographs for future climate conditions.

Furthermore, investigating the use of retention ponds as an NBS for flood mitigation reveals remarkable outcomes in the context of climate change-induced hydrological extremes. Implementing retention ponds has significantly reduced peak discharge, with a new value recorded at 2702.9 m^3/s. Moreover, the time to peak decreases to 14 hours, considering the assumption of a 75 % decrease in the initial peak discharge. The presence of retention ponds provides valuable storage capacity during flood events and effectively mitigates the downstream impacts of flooding. Additionally, the calculated volume of these ponds, at 29.4 hm^3, further indicates the scale of intervention required to achieve such mitigation effects. The resultant final total flood volume, at 797.4 hm^3, provides a quantitative measure of the overall flood reduction achieved through this NBS. These results underscore the substantial effectiveness of retention ponds in mitigating flood impacts. Additionally, it is determined that 2198 retention ponds are required to achieve the desired flood mitigation goals. The findings illuminate the dual role of retention ponds in flood management: reducing peak discharge to mitigate immediate flood risks and contributing to the longer-term resilience of water systems against climate variability. This dual functionality enhances their appeal as a sustainable and adaptable solution to FRM in uncertain future climate conditions.

Finally, through the combined implementation of both NBS, the peak discharge is reduced to 2567.4 m^3/s while maintaining a constant time to peak of 14 h. This holistic strategy enhances the unique advantages of each NBS while showcasing their collective strength in improving flood readiness and resilience to climate fluctuations. Implementing retention ponds alone brings their water storage capacity to 30.2 hm^3, reflecting an optimised design to maximise flood storage without compromising ecological stability or land use priorities. The total flood volume at the basin's outlet, which stands at 767.55 hm^3, shows a 7.2%

decrease from the baseline scenario's 826.8 hm^3. This demonstrates the real-world advantages of using NBS in managing flood volumes. Furthermore, it is estimated that 2258 retention ponds will need to be constructed to achieve the desired flood mitigation objectives. It indicates the physical changes required within the landscape and presents a planning challenge that demands careful consideration of local topography, hydrology, and community impact. Figure 4-15 presents the flood hydrographs for the upper climate scenario before and after implementing NBS. The visual decrease in peak discharge and the maintenance of peak time offers a clear and concise depiction of the outcomes of these measures. The chart provides a compelling narrative of the impact of NBS, effectively communicating the significance of these interventions to stakeholders and decision-makers.

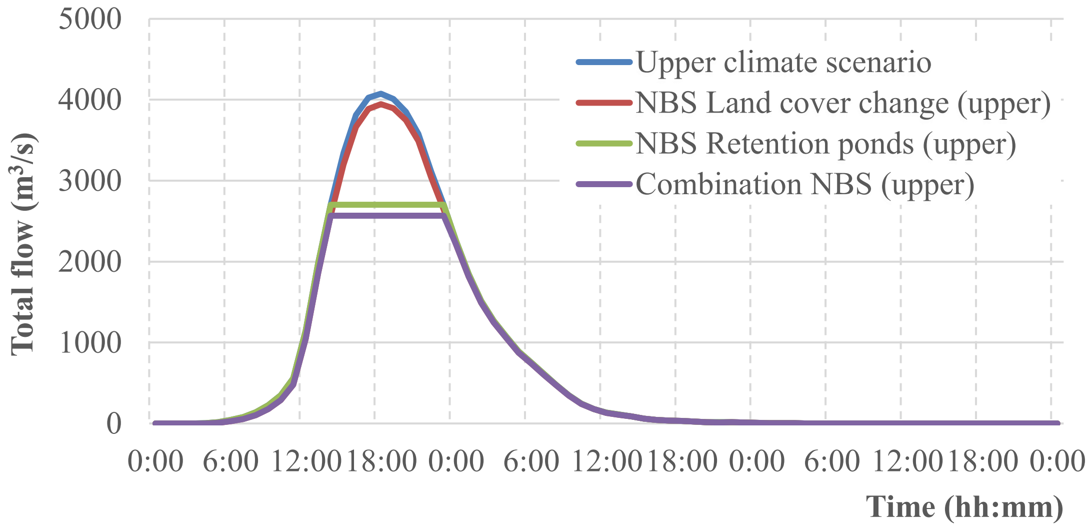


Figure 4-15: Flood hydrographs before and after NBS for the upper climate scenario.

In the context of the mean climate change scenario, notable transformations are observed following modifications in land cover. The peak discharge experiences a noteworthy decrease to 999.8 m^3/s, representing a reduction of 9.73 % from the pre-intervention scenario of 1107.4 m^3/s. This decrease is direct evidence of the effectiveness of land cover management strategies in improving the watershed's natural capacity to absorb and retain water. Interestingly, the time to peak remains unchanged at 18 h, while the total flood volume is decreased to 192.1 hm^3, representing a reduction of approximately 9.25 % from the initial volume of 211.7 hm^3. Moreover, implementing retention ponds leads to further reductions in peak discharge. The recorded value decreased to 851.7 m^3/s, with a shortened time to peak of 15 h. The ability of retention ponds to reduce peak flow's magnitude and speed highlights their role in re-shaping the flood hydrograph to mitigate flood risks. The calculated volume of these ponds, at 4.6 hm^3, shows a strategic and effective implementation of these features within the watershed. Consequently, accounting for the reduced volume due to the implementation of these ponds, the final total flood volume amounts to 207.1 hm^3. This underscores the significant impact of these ponds in minimising the intensity of flood events. It is determined that a total of 340 retention ponds will be necessary to achieve the desired flood mitigation goals. This network would represent a strategic investment into the region's hydrological infrastructure, with the dual purpose of flood mitigation and potentially creating additional environmental benefits such as habitat creation and enhanced biodiversity.

By adopting a combined approach, the peak discharge is further reduced to 755.9 m^3/s while maintaining a consistent time to peak of 15 h. Additionally, the estimated water storage capacity of the retention ponds is 4.4 hm^3. Thus, considering the reduced volume, the total flood volume at the basin outlet is 207.3 hm^3. It is estimated that 327 retention ponds must be constructed to achieve the desired flood mitigation objectives. These findings emphasise the comprehensive efforts required to effectively address flood risks and enhance the overall resilience of the basin. Figure 4-16 provides a graphical representation of these impacts, clearly delineating the hydrograph shifts pre- and post-NBS implementation. The figure's visual representation is both a compelling and informative resource, showcasing the quantifiable alterations in flow properties due to NBS initiatives.

The thorough assessment of NBS across different climate conditions has clearly shown that a holistic approach, combining land cover management and the construction of retention ponds, results in the most significant decrease in both the maximum flow rates and overall flood volume. This integrated strategy is in harmony with the multi-faceted goals of sustainable watershed management, leveraging the landscape's natural buffering ability to minimise flood risks. In particular, the creation of retention ponds emerges as an incredibly effective measure, leading to the most noticeable reductions in peak discharge rates. These structures act as essential hydrological modifiers in the watershed, offering temporary storage and regulated discharge of floodwaters. This directly results in lowered risks of flooding downstream. Conversely, land cover change is instrumental in influencing the hydrological response times of the basin.

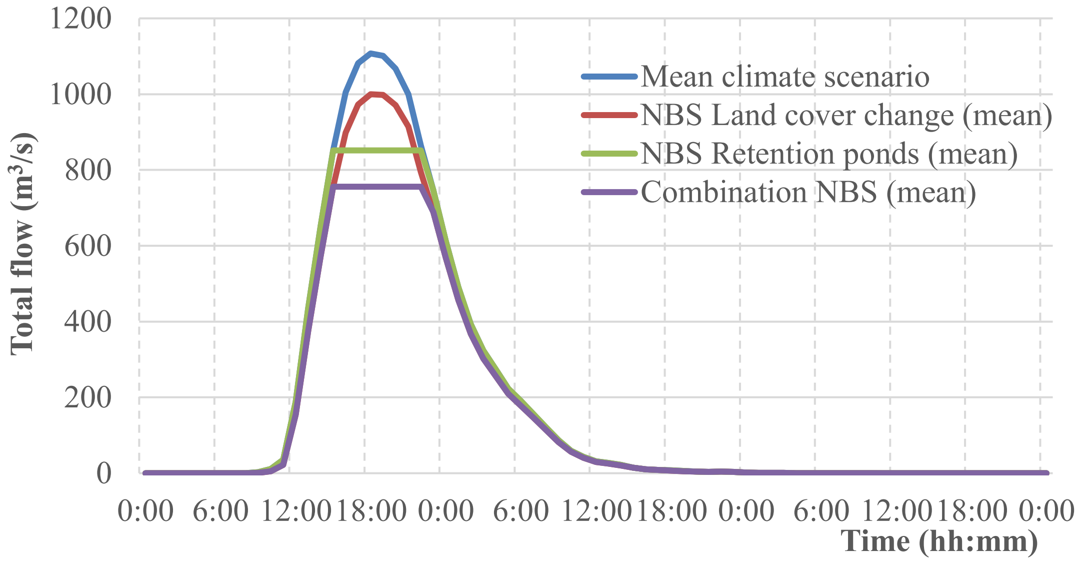


Figure 4-16: Flood hydrographs before and after NBS for the mean climate scenario.

Prolonging the time to peak spreads the flood wave over a more extended period. This reduces the chances of peak flows co-occurring, easing the pressure on river systems and flood defence infrastructure. Nonetheless, the optimal selection and design of NBS must be carefully customised to fit the specific characteristics of each catchment area actor like the landscape's shape and structure, current land use patterns, the density of waterways, and topographical details are crucial in determining how suitable and effective NBS can be. The interaction among these factors can affect not just the water management performance of NBS but also their ecological and socio-economic outcomes. This customised understanding ensures that NBS is not perceived as a universally applicable solution but rather as a set of adaptable strategies that demand careful consideration of local conditions. Therefore, it's crucial that watershed managers and decision-makers adopt a detailed and thoughtful approach to planning and implementing NBS, combining scientific understanding with stakeholder involvement and ecological awareness. In conclusion, the findings from this analysis contribute significantly to the body of knowledge on NBS and its role in climate-adaptive FRM. Demonstrating the effectiveness of combined NBS approaches supports their broader application. It emphasises the need for a strategic, informed, and localised application of these techniques to enhance flood resilience in vulnerable basins.

The effectiveness of NBS is highly dependent on its strategic location within a watershed, as noted by Reaney in 2022. Four key factors are critical to this effectiveness: the generation of local floodwaters, hydrological connectivity with the river network, the time for floodwaters to reach essential points, and the spatial distribution of rainfall events. In the context of the current analysis, preliminary investigations suggest that a combination of NBS, especially given the gentle terrain and accessible areas within the study region, results in the most significant reduction in peak discharge for all climate change scenarios. Retention ponds, in particular, emerge as an auspicious approach. Unlike land cover changes, which depend on variable soil permeability, retention ponds provide a more immediate and controllable intervention for flood mitigation. Due to their relatively simple design and construction requirements, retention ponds can be implemented quickly, which is essential for reducing flood risks and protecting vulnerable communities. When considering the cost implications of implementing the two proposed NBS, it's necessary to consider different methods and requirements. Land cover alteration may entail land procurement, infrastructure adjustments, and personnel training expenses. Conversely, constructing retention ponds could involve materials, labour, and ongoing maintenance costs. In the present study, given the substantial costs associated with land cover modifications and their related projects, the construction of retention ponds emerges as a more economically viable solution. However, conducting a thorough analysis of the specific area is crucial to understand its unique features and determine the best NBS to apply.

4.3.2 Land cover changes as NBS under changing conditions (Fire)

Building upon the foundational analysis detailed in the previous sections, this case study extends the investigation to the effectiveness of NBS under post-fire land cover changes in Northern Evia, located in Central Greece (Figure 4-17). Wildfires are a significant natural hazard, impacting human lives, ecosystems, and economies with catastrophic consequences. They alter the soil's surface condition by removing vegetation cover, which decreases the soil's ability to absorb water (Nalbantis and Lymperopoulos 2012; Folton et al. 2015). This degradation in soil conditions can modify the hydrological characteristics of a burned catchment area, leading to an increase in peak water flow and a decrease in the time it takes for water to concentrate during rain events (Diakakis et al. 2017). Such changes heighten the risk of severe flooding in areas downstream, posing risks of widespread harm to people and significant environmental, physical, and financial damages. Forest fires are notably prevalent in Mediterranean regions, particularly in the summer months, and are attributed to the area's Mediterranean climate. This susceptibility is potentially exacerbated by global warming and diminished rainfall.

The catastrophic fire event in August 2021, which devastated extensive areas of Northern Evia, serves as a critical case study for understanding the dynamics of hydrological responses under severe environmental stress and the role of NBS in mitigating these impacts. The fire spread rapidly, driven by harsh weather conditions, including extended periods of extreme heat, powerful winds, and low humidity, proving to be uncontrollable for eight days. The area affected was measured at 507950 acres based on data from the EFFIS

satellite (Copernicus 2021). The consequences of the blaze included the loss of wildlife and the complete obliteration of small villages, homes, natural landscapes, and businesses.
The case study focuses on two primary river basins in the northern region of Evia Island. Basin 1 encompasses an area of 115 km^2, of which 76 km^2 was affected by the catastrophic fire. Basin 2, covering 386 km^2, experienced burning across 164 km^2 of land. In basin 1, all precipitation flows into the Xiropotamos River, while the Kireas River drains basin 2. The research area is characterised by a typical Mediterranean climate, featuring hot summers and cold winters (Rozos et al. 2013), making it particularly vulnerable to devastating natural events like wildfires and floods. Wildfires are most common in the summer, driven by dry conditions and strong northerly winds. In terms of flooding, the area is prone to extreme high-intensity rainfall events, with a history of severe floods. The average annual rainfall is reported to be 1200 mm, based on measurements from weather stations in the northern part of Evia. The region's elevation ranges from sea level to 1349 m, with broad-leaved and mixed forests being the dominant vegetation types (CLC 2018).

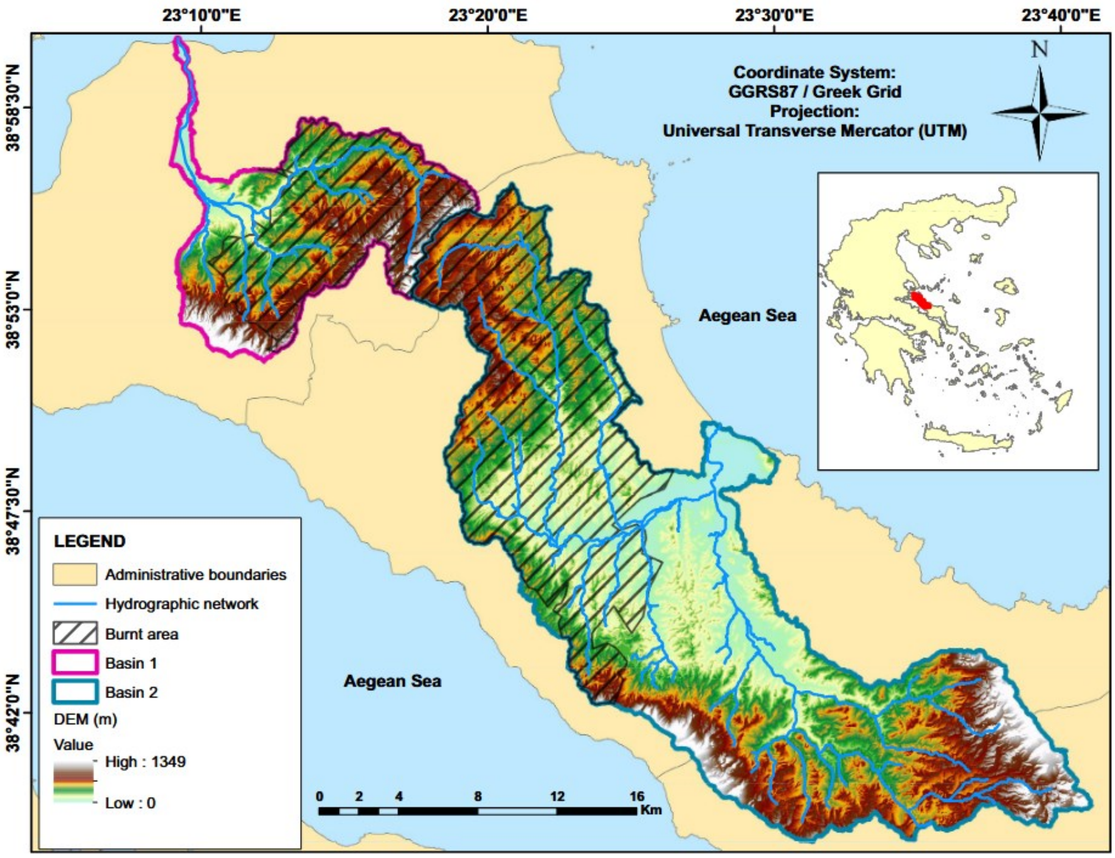


Figure 4-17: The study area. Source: (Theochari and Baltas 2022)

Theochari and Baltas 2022 applied a methodology deployed to ascertain flood-prone areas across two river basins in this area, incorporating MCDA and GIS techniques. Ordinarily, the upper parts of a basin experience increased runoff, posing a flood risk to downstream urban zones (Skilodimou et al. 2021). Following this principle, the study conducted by Theochari and Baltas 2022 pinpointed 27 settlements at risk using the MCDA approach and established five simulation points along the primary river course. This process led to the creation of five subbasins, each upstream of a simulation point, where hydrological analysis is conducted to assess the impact of a specific forest fire event on flood generation. This assessment evaluates fire-affected basins' hydrological response (Figure 4-18). Furthermore, the effectiveness of NBS is estimated through land cover changes in the portions of the subbasins that have been burnt, aimed at FRM.

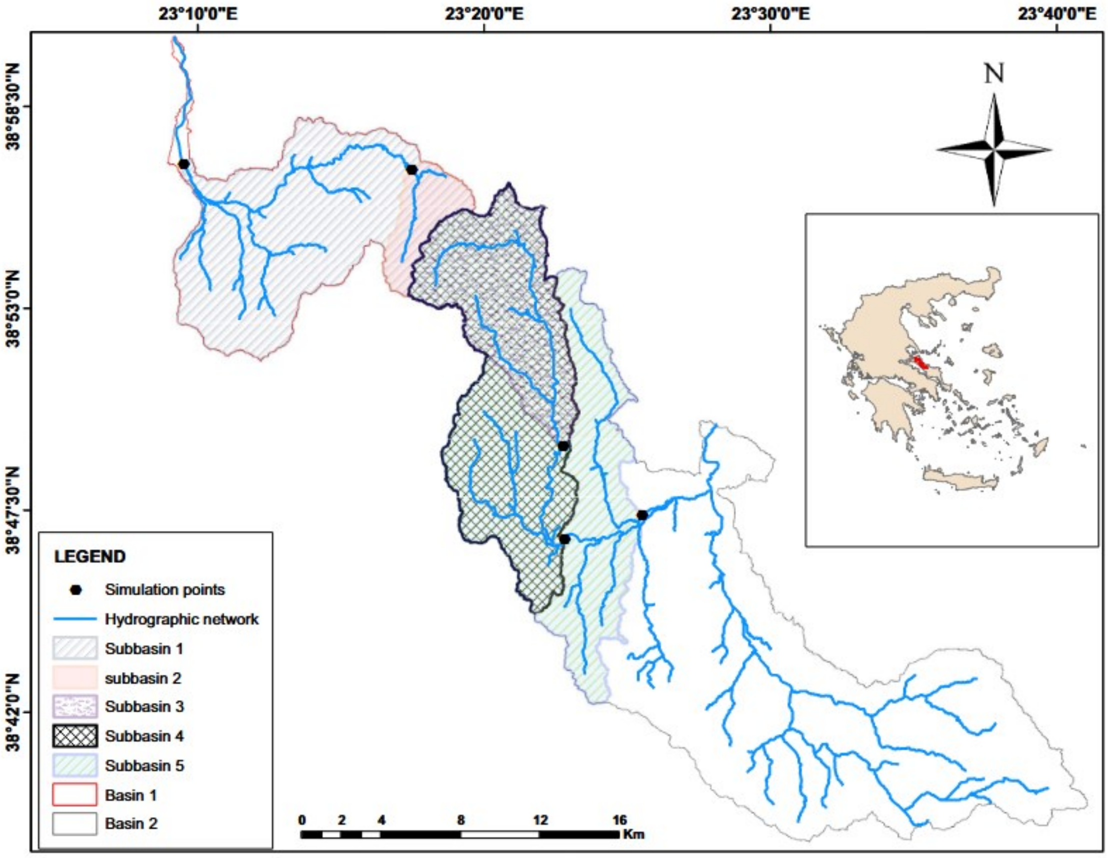


Figure 4-18: Determination of simulation points and calculation of their respective upstream subbasins. Source: (Theochari and Baltas 2022)

The selection of Northern Evia as an additional study area, alongside the Sarantapotamos basin, is motivated by the extensive damage caused by the fire in this region. This expansion of the study area allows for a comparative analysis of hydrological responses under varied ecological and geographical conditions, thereby enriching the research framework with diverse data points. The aim of identifying subbasins is to predict flood hydrographs at the outlets, both before and after wildfire incidents, by employing the HEC-HMS software. This tool enables a comparative analysis of the hydrological responses of fire-related subbasins. Developed by the US Army Corps of Engineers' Hydrologic Engineering Center, HEC-HMS is a semi-distributed model that blends physical and conceptual elements to model the rainfall-runoff dynamics across various terrains (USACE 2018).

For executing HEC-HMS simulations, essential elements include a basin model, meteorological model, control specifications, time-series data management, and paired data management, each responsible for calculating aspects such as runoff volume, direct runoff, channel flow, and baseflow based on data availability, methodological constraints, and general acceptability. Specifically, the basin model integrates basin characteristics, infiltration loss methods (USACE 2005), and transformation methods. While baseflow can be considered, it is excluded from this study due to minimal contributions to streamflow. The SCS CN method calculates precipitation losses, reflecting an empirical correlation with factors like location, soil type, land use, and prior moisture conditions affecting runoff. Each subbasin's CN distribution is assigned based on land cover and soil types, with average CN values for each subbasin calculated and inputted into HEC-HMS. Notably, CN values pre-fire significantly diverge from post-fire values due to changes in land cover linked to the burned areas. To estimate the distribution of runoff over time, it's necessary to integrate the total runoff volume ascertained by the CN method with the UH. The User-Specified UH has been chosen as the transformation method for converting excess precipitation into direct surface runoff. This UH calculation is carried out within a GIS setting, utilising the time–area diagram method for its execution. The UHs derived are integrated into the HEC-HMS software via its paired data manager feature.

Rainfall information is another critical piece of data for calculating discharge at the subbasin outlets. In this study, a design hyetograph is developed using the alternative block method, supported by the IDF curve from the Evia hydrometeorological stations, considering a return period of 100 years. These results facilitate the construction of the meteorological model within HEC-HMS, employing the gage weights method for this purpose. Following this, a control specification model is established to define the simulation's temporal pattern, with the simulation time step being set to match the interval used in the alternative block method. Ultimately, each simulation run merges these elements with specific run configurations to compute the flood hydrograph.

Analysing the UHs before and after fire incidents for each subbasin (referenced in Table 4-5) reveals that wildfires significantly influence the timing of peak discharge and the magnitude of the peak discharge itself by shortening the former and increasing the latter, respectively. The CN associated with the infiltration loss method, as displayed in Table 4-5, noticeably increases following a wildfire due to land use modifications. Specifically, Subbasins 2, 3, and 4 exhibit the highest CN values, with the first two completely burned and the third nearly so. These elevated CN values and the UH analysis significantly contribute to the enhanced flood hydrographs generated by the HEC-HMS model. Table 4-5 shows that an increase in

CN value correlates with a rise in peak discharge and a decrease in time to peak during rainfall events. For example, the peak discharge in subbasin 2 following the fire is four times higher than the estimate before the fire. Similarly, subbasins 1, 3, 4, and 5 show peak discharges that are three times higher than what was estimated before the fire. This trend is attributed to the extensive burn areas in these subbasins, which directly lead to higher CN values. Concurrently, the reduction in time to peak across all subbasins post-fire is attributed to increased land imperviousness, with subbasins 2, 3, and 4 seeing a decrease of approximately 30%, and subbasins 1 and 5 experiencing reductions of 8% and 16%, respectively. This variation is due to the differing extents of burnt areas across the subbasins, influencing the extent of increased imperviousness and the subsequent adjustments in CN values for the loss method.

The observed patterns in flood hydrographs concerning peak discharge and time to peak are similarly reflected in the UHs derived through the time-area diagram method. Post-fire, the peak discharge in UHs for subbasins 1, 2, 4, and 5 is three times higher, whereas, in subbasin 3, it is double that of the period before the fire. Furthermore, the post-fire UH time to peak is half of the pre-fire duration in subbasins 2, 3, and 4, indicating a faster response. In contrast, in subbasins 1 and 5, the reduction is less pronounced due to their smaller burnt area ratios. These detailed findings, outlined in Table 2, suggest that wildfire-induced changes in land cover significantly alter flood hydrograph characteristics, thereby increasing flood risks for entire communities. The significant alteration in land cover due to the fire in Northern Evia presents a unique opportunity to assess the applicability and effectiveness of NBS in the context of drastic environmental change.

In response to the increased surface runoff, decreased infiltration rates, and disruption of the hydrological equilibrium that escalated flood risks, large sections of the burnt area, primarily those not used for habitation or human activities, are replaced with two specific land cover categories: "Coniferous forest" and "Broad-leaved forest." This strategic choice capitalises on the inherent advantages of these forest types to rehabilitate ecological functions, enhance water absorption into the soil, and slow down runoff velocities. To address these challenges, the study employs NBS by integrating changes in land cover post-fire into the hydrological analysis to investigate their capacity to restore ecological functions, improve water infiltration, and diminish runoff speeds. Specifically, in Subbasin 1, an area of 3.26 km^2 is reforested with broad-leaved forests alongside 41.4 km^2 with coniferous forests. Subbasin 2 is replenished with 1.47 km^2 of broad-leaved forests and 8.41 km^2 of coniferous forests. In Subbasin 3, 19.27 km^2 are reforested with broad-leaved forests and 22.1 km^2 with coniferous forests. Subbasin 4 introduced 28.05 km^2 of broad-leaved forests and 40.73 km^2 of coniferous forests. Finally, Subbasin 5, the most significant area affected, is reforested with 37.71 km^2 of broad-leaved forests and 60.52 km^2 of coniferous forests. This examination utilises the generation of new flood hydrographs that incorporate post-fire land cover changes as NBS. Such an approach comprehensively evaluates how NBS can modify hydrological responses under altered land cover due to the fire.

To assess the effectiveness of land cover as NBS in the burned extents within the examined basins, the study re-applied the hydrological analysis previously described. However, this time, it maintains the post-fire UHs and adjusts the CN values to a more realistic figure reflective of the NBS's potential impact. This alteration of CN values, postulated as a measure of NBS effectiveness, aimed to simulate conditions closer to a restored ecological state, thereby potentially reducing flood risks by enhancing the landscape's capacity to manage rainfall more effectively. The results of this hydrological analysis for all scenarios, reflecting the integration of NBS into post-fire land cover conditions, are presented in the subsequent table. This table showcases the outcomes under various scenarios, comparing the hydrological behaviours pre- and post-NBS implementation, thereby providing insights into the efficacy of land cover changes as NBS within the context of the fire-affected basins. The effectiveness of the NBS post-fire is quantitatively evident in the reduced CN values, which have been logically decreased to an order that reflects the potential impact of the NBS implementation. For Subbasin 1, the CN value decreased from a post-fire high of 88 to 83, indicating improved infiltration and reduced runoff potential. Subbasin 2's CN value is returned to its pre-fire state of 80 from a pro-fire value of 90, subbasin 3 showed a restoration from 85 to 75, subbasin 4 from 85 to 75, and subbasin 5 from 84 to 74. These adjusted CN values post-NBS signify a reversion towards pre-fire conditions, suggesting that the NBS could substantially mitigate the increased flood risk brought about by the wildfires. Implementing NBS post-fire has demonstrated concrete advantages, as evidenced by the significant reductions in peak discharge values compared to the pro-fire scenarios. In Subbasin 1, the peak discharge reduction is approximately 5.3%, decreasing from 505 m^3/s post-fire to 478 m^3/s with NBS. Subbasin 2 observes a more substantial decrease of about 17.8%, with peak discharge values falling from 118 m^3/s to 97 m^3/s. For subbasin 3, the introduction of NBS reduces peak discharge by approximately 15%, from 247 m^3/s to 210 m^3/s. In subbasin 4, peak discharge values are reduced by around 7.2%, from 446 m^3/s to 414 m^3/s, and in subbasin 5, a notable reduction of approximately 15.6% is achieved, with values decreasing from 709 m^3/s to 598 m^3/s post-NBS implementation. These percentage reductions underscore the NBS's efficacy in moderating hydrological extremes. The reduction in peak discharge directly results in a decreased chance of flood events hitting critical levels, thus boosting the watershed's resilience to hydrological stress. The NBS strategy reinforces the landscape's natural defences and acts as a buffer that provides communities downstream with a measure of security against sudden flood events.

The time to peak, which is a critical factor in FRM, also shows a positive trend due to NBS implementation. While the reductions in time to peak are less pronounced than those for peak discharge, they still reflect an improved hydrological response, with subbasin 1 maintaining its post-fire time to peak of 23 hours, subbasin 2 at 6.5 hours, subbasin 3 showing a slight decrease from 11.5 to 10.5 hours, subbasin 4 with an increase from 21 to 22 hours that may indicate slower runoff and subbasin 5 maintaining at 21 hours. These subtle changes indicate that the NBS moderates the runoff response times, providing a temporal buffer in flood event management.

Table 4-5: The geomorphological and hydrological characteristics of each subbasin

Subbasin		**1**	**2**	**3**	**4**	**5**
Area (km^2)		103	14	55	104	160
Burnt area (km^2)		76	14	55	103	155
CN	**Pre-fire**	80	80	75	75	75
	Pro-fire	88	90	85	85	84
	NBS pro-fire	83	80	75	75	74
Peak discharge (m^3/s)	**UH pre-fire**	10	3	9.6	11	17
	UH pro-fire	29.5	10	21	28	47
	Flood hydrograph pre-fire	192	31	84	180	261
	Flood hydrograph pro-fire	505	118	247	446	709
	NBS Flood hydrograph pro-fire	478	97	210	414	598
Time to peak (hr)	**UH pre-fire**	14	6.5	8.5	20	14
	UH pro-fire	12	4	3.5	9	10
	Flood hydrograph pre-fire	25	9	14	31	25
	Flood hydrograph pro-fire	23	6.5	11.5	21	21
	NBS Flood hydrograph pro-fire	23	6.5	10.5	22	21

By comparing hydrological data from before and after the fire with the scenarios involving newly implemented NBS, the study clarifies how NBS can reduce flood risks and aid in the ecological recovery of areas affected by fire. Moreover, the choice of Northern Evia as a focal point for this case study is justified by the real-world implications of the fire, which necessitated an urgent evaluation of NBS in promoting sustainable watershed management and DRR. The insights gained from this analysis are pivotal in guiding future NBS implementation strategies, particularly in Mediterranean regions susceptible to wildfires and subsequent hydrological alterations. In conclusion, this case study underscores the critical role of NBS in enhancing landscape resilience against hydrological extremes post-fire. Through a comprehensive evaluation of land cover changes and the implementation of NBS in Northern Evia, this case study contributes valuable knowledge to hydrological modelling and environmental management. It provides a practical framework for tackling the issues arising from hydrological alterations caused by fires.

5. Conclusions and Future Research

The principal objective of this PhD dissertation is to enhance FRM strategies by developing and applying a comprehensive methodological framework. In contrast to prior studies that may have narrowly focused on individual elements of flood management, this research adopts a holistic approach. It combines the latest technology, advanced hydrological modelling, and eco-friendly practices to create a comprehensive approach for FRM. Initially, the research delineates a novel GIS-based multicriteria decision analysis for strategically placing hydrometric and hydrometeorological stations. The dissertation further advances into hydrological modelling tailored for Greece's ungauged basins by developing GUH. This innovative approach addresses the issue of limited data challenge by merging the time-area diagram technique with regression analysis, thereby offering a detailed understanding of hydrograph characteristics and their interrelation with geomorphological metrics. In its concluding phase, the dissertation evaluates the application of two NBS — land cover change and the construction of retention ponds — specifically within the Sarantapotamos River basin, upstream of the Magoula settlement. This evaluation is critical for discerning the efficacy, efficiency, resilience, and adaptability of NBS in mitigating flood risks under diverse climatic scenarios. Particularly noteworthy is the investigation of land cover change as an NBS in the post-wildfire scenario of North Evia, offering insights into hydrological and environmental recovery strategies. In summary, this dissertation presents a flexible and practical approach to FRM, tailored to the unique challenges of vulnerable regions like the Sarantapotamos River basin. It marks a significant step forward in combining technological innovation, hydrological expertise, and environmental sustainability to address the urgent challenge of FRM.

This dissertation is structured into three main parts, directly aligning with the pivotal questions it seeks to address regarding FRM strategies. The first examines the possibility of creating an optimal network for monitoring stations without on-site checks, considering the impact of different perspectives, data availability, and weighting methods on station placement. The second section explores the enhancement of hydrological models for ungauged basins through geomorphological metrics and GIS tools. The final part assesses the impact of NBS on flood mitigation, focusing on their effectiveness and contribution to flood management in the context of climate change. The initial primary question addressed by this thesis is formulated as follows:

"Can optimal hydrometric-hydrometeorological station network design through GIS techniques be achieved without on-site evaluation?"

Designing an optimal network for hydrometric-hydrometeorological stations poses significant challenges, notably considering on-site evaluations. Utilising GIS-based MCDM, this dissertation suggests that such a network design is feasible without direct physical assessments. By incorporating various criteria, including topographical, hydrological, and infrastructural factors, and employing analytical methods like the AHP and the FAHP, this study provides a detailed methodology for selecting station locations. Specifically, it demonstrates that through sophisticated GIS techniques and detailed criteria evaluation, one can identify suitable station locations that align with strategic flood management and water resource monitoring objectives. However, while the GIS-based methodologies can significantly reduce the need for in-situ evaluations, some criteria may still require physical site inspections to ensure the environmental and logistical feasibility of the locations. Before finalising the network design, conducting on-site visits to verify the suitability of the selected locations with the highest final scores might be necessary. These site visits can validate the GIS and MCDM findings by assessing aspects that are difficult to gauge remotely, such as land accessibility, local microclimatic conditions, or specific environmental protections, ensuring that the proposed locations are practical for establishing stations.

The research findings indicate that the criteria formulation and weight estimation significantly influence the resulting network design, underscoring the importance of a comprehensive and flexible approach to criteria selection and prioritisation. For instance, the distinction between the AHP and FAHP methods reveals how the subjective nature of weight assignments can affect the spatial distribution and number of recommended stations. Moreover, the study highlights the practicality of GIS-based methodologies in overcoming the limitations of physical site surveys, mainly through integrating detailed environmental data and advanced spatial analysis techniques. The integration of GIS in this process plays a pivotal role in managing spatial data from diverse sources and executing spatial decision-making tasks efficiently. The GIS-based MCDM approach identifies several suitable locations, from which those with the highest final scores are selected for network establishment, illustrating the practicality of GIS methodologies in overcoming the limitations of physical site surveys. This MCDA process transforms geographic data inputs into a decision output that delineates a clear relationship between the input data and the resulting map outputs. This process efficiently organises data into thematic categories within a GIS, simplifying and streamlining the decision-making process. The initial steps involve defining the main problem and objectives and selecting criteria and alternatives based on a deep understanding of the basin's environmental characteristics. This expanded analysis not only proves the feasibility of designing an effective hydrometric-hydrometeorological station network without on-site evaluations but also showcases the indispensable role of GIS in contemporary FRM. Using GIS for spatial analysis and decision-making, this dissertation introduces a progressive strategy combining technological advances with strategic environmental management. This sets a new standard for planning flood management infrastructure. The following questions are raised:

"Does the formulation of station installation criteria within a GIS environment vary depending on the researcher's perspective, experience, and data availability?"
"How does the choice of weight estimation method affect the resulting suitability map?"

This inquiry delves into the subjective aspects of GIS-based MCDM, acknowledging that the selection and prioritisation of criteria vary according to the researcher's perspective, experience, and data accessibility. The analysis within this dissertation highlights the importance of integrating local knowledge and empirical data into the decision-making process, acknowledging that the effectiveness of a hydrometric-hydrometeorological network design depends not just on the advanced tools used but also on the depth of understanding of the local environment and flood dynamics. This emphasises the need for a holistic view, combining technical precision with a thorough knowledge of the regional situation, ensuring that the designed network is scientifically robust and practically relevant. Differences in how criteria are set within a GIS framework can lead to variations in the final suitability map of site locations, influenced by the decision-makers viewpoint and the available data. For instance, criteria such as "distance from settlements" and "distance from flood-prone areas" are interpreted differently in studies by Theochari et al. across different years, demonstrating how perspectives on criteria importance and formulation can evolve even within the same research team. This evolution reflects the deeper insight that comes with increased familiarity with a study area or advances in GIS and data analysis technologies. The distribution of suggested station locations, even based on identical scenarios, criteria, and weights, may remain the same due to the datasets utilised, and the specific way criteria are defined. This divergence highlights the critical role of GIS environmental setup and dataset selection in the design process of station networks. The detailed delineation of criteria and careful selection of datasets for analysis represent key variables that significantly impact decision-making. Moreover, the flexibility in criteria expression and the selection of data for analysis are notably influenced by the perspective of the decision-makers. This influence is particularly evident in the design of hydrometric station networks, which tend to allow more flexibility in criteria formulation and hierarchy than hydrometeorological networks. Using normalised values instead of strict binary conditions allows for a more detailed data analysis, reflecting the complexity and variability typical of hydrological settings. This adaptability is vital for addressing the dynamic nature of watercourses effectively. Conversely, the design of hydrometeorological networks often entails stricter constraints. In such contexts, Boolean maps provide clear delineations between suitable and unsuitable locations, which is crucial for placing stations in areas that fulfil all conditions for reliable data collection. Formulating station installation criteria within a GIS environment and the subsequent design of a hydrometric-hydrometeorological station network is a complex, multifaceted process deeply influenced by individual perspectives, technological capabilities, and an intimate understanding of the study area. This process demonstrates the intricate interplay between technological tools and environmental insights, emphasising the need for a holistic approach that ensures the network's resilience, adaptability, and effectiveness in managing water resources and mitigating flood risks.

The choice between AHP and FAHP methods for weight estimation plays a pivotal role in shaping the suitability maps for hydrometric station locations. This crucial choice impacts the entire strategic framework for station placement, fundamentally influencing the network's configuration and capacity to manage flood risks efficiently. This dissertation illustrates that while AHP provides a more deterministic and perhaps inflexible framework for criteria weighting, FAHP introduces flexibility and adaptability through its use of fuzzy logic. This flexibility is beneficial in accommodating the inherent uncertainties and variabilities within hydrological and meteorological data. More specifically, AHP, with its structured and deterministic approach, simplifies complex decision-making into a series of hierarchical, manageable components. It breaks down decision-making into pairwise comparisons, systematically quantifying both qualitative and quantitative factors, thereby facilitating a transparent and rational selection process. AHP's strength lies in its ability to bring order and clarity to the decision-making process, ensuring that each criterion's importance is carefully considered and appropriately weighted according to a predefined scale. Conversely, FAHP introduces a flexible and detailed aspect by using fuzzy logic in determining weights. This approach is particularly effective in addressing the inherent uncertainties and variabilities associated with hydrological and meteorological data. By utilising triangular fuzzy sets, FAHP allows for a range of values to represent each criterion's importance, offering a more flexible interpretation that can accommodate the complex realities of environmental assessments. This approach improves the decision-making process by connecting the dots between strict numerical data and the qualitative assessments commonly found in environmental planning and management. The

comparison of suitability maps generated under different weighting scenarios reveals how these methodological choices can lead to diverse network configurations, affecting the distribution and number of stations deemed optimal. While AHP tends to produce more defined and constrained options for station placement, FAHP allows for greater flexibility, potentially identifying a more comprehensive array of suitable locations by accommodating data variability and uncertainty. This flexibility can be particularly advantageous in environments where data are sparse or highly variable, as it allows for a broader consideration of potential sites that might be missed with more strict analytical methods. The findings suggest that the methodological approach to weight estimation can significantly influence the strategic planning of hydrometric-hydrometeorological networks, with implications for FRM and water resource monitoring strategies.
The second main question raised in this dissertation is the following:

"What is the significance of establishing empirical relationships between geomorphological metrics and GIUH attributes in enhancing the applicability of hydrological models for FRM in ungauged basins?"

This dissertation reveals the critical role of integrating geomorphological metrics with GUH attributes to significantly enhance hydrological models, particularly for ungauged basins in Greece. Through an innovative approach that utilises GIS tools and ArcPy programming, this dissertation has successfully developed a method for deriving GUHs that relies on the geomorphological features of the basins. This method stands out by providing a robust and precise tool for hydrological assessments in areas where traditional data might be sparse or lacking. The core of this advancement lies in establishing empirical relationships between a basin's geomorphological characteristics and the attributes of GIUHs. These relationships facilitate the creation of hydrographs that reflect the unique hydrological responses of each basin to rainfall events. Consequently, this approach offers a detailed insight into flood risks, allowing for more accurate predictions and effective management strategies in ungauged basins. GIS-based methods are used to systematically analyse and establish a way to develop GUHs focusing on the basins' geomorphological features. This approach successfully addresses the usual difficulties of hydrological modelling in areas lacking data, offering a groundbreaking and applicable method in real-world scenarios. Integrating geomorphological metrics into the GIUH framework enhances the scientific robustness of hydrological models but also makes these models more accessible and applicable for FRM and water resource monitoring. This tailored understanding of flood risks, enabled by the precise modelling of hydrological responses based on geomorphological metrics, marks a significant advancement in managing flood risks more effectively, particularly in regions like Greece, where such data limitations have historically posed considerable challenges.

Moreover, the dissertation's approach to system analysis, focusing on the impact of channel velocity on hydrograph generation, further refines the model's accuracy. Utilising simulations to vary velocities and employing metrics such as the NSE for model validation underscores the meticulousness and depth of analysis undertaken. Such detailed examination ensures that the developed GUH models are theoretically robust and practically applicable, accurately mirroring hydrological dynamics in ungauged basins. The following questions are raised:

"How does the application of ArcPy and advanced GIS tools in hydrological modelling contribute to the development of GUHs for ungauged basins?"
"How do the geomorphological metrics derived from GIS tools and DEMs inform the development and validation of GUH models?"

The application of ArcPy alongside advanced GIS tools has been instrumental in developing GUHs for ungauged basins. By automating the process of generating time-area diagrams and computing geomorphological metrics, these technologies have significantly streamlined and enhanced the accuracy of hydrological modelling. This automation reduces the potential for human error and allows for the processing of large datasets, enabling a comprehensive analysis across numerous basins. The precision and efficiency provided by these tools have paved the way for the innovative approach presented in this dissertation, showcasing the potential for advanced GIS technologies to revolutionise hydrological studies. By employing these advanced GIS capabilities, intricate processes traditionally requiring extensive manual effort and prone to human error have been automated. This automation facilitates handling vast datasets, permitting an exhaustive examination across a wide array of basins. Such capability is indispensable for studying ungauged basins, where data scarcity often poses significant challenges to accurate hydrological modelling. The application of ArcPy and advanced GIS tools extends beyond simply enhancing data processing efficiency. It introduces a level of precision in modelling that was previously difficult to achieve. By accurately calculating geomorphological metrics and integrating them seamlessly into the hydrological models, these tools have enabled the creation of GUHs that closely mirror the real-world hydrological processes of ungauged basins. Furthermore, the capacity to process large datasets with these technologies means that the models developed are more accurate and comprehensive. They encapsulate a broader spectrum of scenarios and conditions, enhancing the models' applicability and relevance to real-world FRM. The insights gained from this extensive analysis facilitate a deeper understanding of the hydrological behaviour of ungauged basins, offering a solid foundation for predicting flood events and formulating effective management strategies.

The geomorphological metrics derived from GIS tools and DEMs are foundational to developing and validating GUH models. These metrics offer a detailed quantification of the basin's physical characteristics, such as slope, area, and shape, which are critical in understanding and predicting hydrological responses. The empirical relationships established between these metrics and GIUH attributes enable the formulation of GUHs that accurately reflect the hydrological behaviour of specific basins. Furthermore, validating these models through comparison with observed hydrographs from selected basins ensures their reliability and applicability in real-world scenarios. The thorough development and validation process underscores the value of geomorphological metrics in enhancing the predictive capability of hydrological models for ungauged basins, contributing significantly to the field of hydrology and FRM. This comprehensive approach to model development and validation, rooted in the detailed analysis of geomorphological metrics, contributes considerably to the advancement of hydrology and FRM. It underscores the potential of GIS tools and DEMs in transforming hydrological studies, offering a pathway to more informed and effective water resource management practices. The findings highlight the transformative impact of integrating geomorphological insights into hydrological modelling, marking a significant leap forward in predicting and managing flood risks in ungauged basins with greater accuracy and confidence.

The third main question raised in this thesis is the following:

"What role do Nature-Based Solutions (NBS) play in mitigating flood risks, and how can their effectiveness be quantitatively assessed within the framework of an integrated FRM strategy?"

This phase of the dissertation underscores the critical role of NBS in mitigating flood risks within the Sarantapotamos River basin and the burned areas in Northern Evia, Greece. Through the strategic implementation of land cover changes and the construction of retention ponds, the efficacy of NBS is evaluated by analysing pre- and post-implementation flood hydrographs. The analysis extends to assessing the resilience and adaptability of these solutions under current and future climate scenarios, revealing their significant potential to reduce peak discharge and modify flood volume, thereby enhancing flood resilience. The quantitative assessment of NBS effectiveness employs advanced hydrological modelling techniques using the HEC-HMS software, demonstrating that land cover changes and retention ponds can significantly mitigate flood impacts. This approach provides a tangible measure of the NBS's impact on flood dynamics, illustrating a reduction in peak discharge and a delay in peak times. These are crucial for managing flood risks and enhancing the basin's overall resilience to flooding. Furthermore, the dissertation delves into the effectiveness of NBS under varying climate scenarios, encompassing mean and worst-case scenarios. This analysis is pivotal, revealing how NBS can adapt and mitigate flood risks even under the threat of climate change. The strategic implementation of land cover changes and retention ponds showcases a marked decrease in peak discharge and modifications in flood volume, underlining the adaptability and resilience of these solutions across different climate conditions. A case study is also conducted to evaluate NBS in the context of post-wildfire land cover in Northern Evia, reflecting on the exacerbated flood risks due to altered soil and vegetation conditions. In this context, NBS, especially the restoration of burned areas with certain types of forests, demonstrate a notable capability in restoring hydrological balance and reducing flood risks. This aspect not only extends the applicability of NBS to areas affected by wildfires but also underscores the necessity of integrating NBS within a broader climate adaptation and FRM strategy. This dissertation assesses the effects of NBS on flood risks through detailed hydrological modelling, taking into account the complex issues caused by climate change and environmental harm. It provides valuable perspectives on strategically planning and applying NBS, making a solid argument for incorporating NBS into FRM strategies. It promotes a comprehensive method that merges technical accuracy with environmental awareness. The following questions are raised:

"How does implementing NBS, such as land cover change and the construction of retention ponds, contribute effectively to FRM?"
"How can the assessment of NBS effectiveness in flood mitigation contribute to the broader understanding of flood resilience and management in the context of climate change?"

Implementing land cover changes, including reforestation with broad-leaved and coniferous forests, effectively increases the basin's water absorption capacity, reducing surface runoff and flood volume. This NBS showcases the importance of ecological restoration in FRM by harnessing the natural landscape's ability to regulate water flow and enhance infiltration. The strategic reintroduction of native vegetation cover acts as a bioengineering tactic, restoring the ecological balance and, in turn, fortifying the landscape's defences against floods. This underlines the vital importance of ecological restoration in managing flood risks, showcasing how reviving natural systems can be a powerful tool for flood prevention. On the other hand, the construction of retention ponds represents a direct and tangible intervention in floodwater management. These structures significantly reduce peak discharge rates and provide a temporary reservoir for excess runoff, effectively mitigating immediate flood threats. Beyond their immediate utility in flood management, retention ponds contribute to the broader landscape's hydrological stability and resilience. By controlling the flow and volume of runoff, these ponds act as a buffer during extreme weather events, reducing the stress on natural watercourses and lowering the risk of overflow and subsequent flooding. Furthermore, they enhance the sustainability of flood management practices by offering a controlled mechanism to manage excess water during flood events, making them an indispensable tool in the FRM. The dual implementation of these NBS—ecological restoration through land cover change and engineered solutions via retention ponds—presents a holistic strategy in FRM. It addresses the immediate challenges posed by flooding and contributes to the long-term resilience and sustainability of water resource management practices. Through the detailed case studies of the Sarantapotamos River basin and Northern Evia, this research illuminates the multifaceted benefits of NBS in flood mitigation, showcasing their potential to transform FRM strategies by harmonising ecological restoration with engineering interventions. Conversely, the construction of retention ponds is a direct intervention to control floodwaters, demonstrating a substantial reduction in peak discharge and providing temporary storage for excess runoff. This NBS mitigates immediate flood risks and contributes to the long-term sustainability of flood management practices by offering a controlled mechanism to manage excess water during flood events.

Assessing NBS effectiveness, especially under varying climate change scenarios, contributes significantly to the broader understanding of flood resilience and management. By evaluating the performance of NBS under different climatic conditions, this research highlights the adaptability and resilience of these solutions to future climate uncertainties. The findings suggest that NBS, mainly when combined, can substantially reduce flood risks, underscoring the necessity for integrated FRM strategies that incorporate ecological and sustainable practices.

This analysis validates the effectiveness of NBS in enhancing flood resilience and sets a precedent for future studies and implementations, advocating for an environmentally sensitive approach to FRM. By demonstrating the quantitative benefits of NBS, this dissertation provides valuable insights for policymakers, environmental agencies, and local communities, encouraging adopting sustainable practices that align with climate adaptation and resilience objectives.

Reflecting on the comprehensive insights and methodologies established throughout this research, key highlights underscore the significant contributions and innovations, structured as follows: a) For the first time in Greece, it employs GIS-based multicriteria decision analysis for optimal hydrometric and hydrometeorological station placement, significantly improving data collection for flood management; b) it introduces innovative modelling of GUHs for ungauged basins, using geomorphological metrics to enhance hydrological predictions in areas lacking data; c) the study pioneers the evaluation of NBS within the Sarantapotamos River basin, demonstrating their effectiveness in flood mitigation under varying climate scenarios; d) it presents a holistic approach to FRM, combining cutting-edge technologies, advanced hydrological models, and environmental sustainability practices, setting new standards for the field. Overall, by merging innovative technologies, hydrological modelling, and sustainable practices, this dissertation advances the academic field and provides actionable insights for effective FRM worldwide.

5.1 Overview of Main Findings

This section provides a concise summary of the key findings across the distinct segments of the dissertation dedicated to advancing FRM strategies: a) Optimal hydrometric-hydrometeorological- station network design, b) Development of GUH for Ungauged Basins, c) Implementation and Assessment of NBS. A detailed summary is provided for each component, outlining the data and methodologies employed, the outcomes achieved, and the key conclusions drawn.

Optimal hydrometric-hydrometeorological- station network design

This dissertation segment explores the innovative application of GIS-based multicriteria decision analysis for optimally locating hydrometric and hydrometeorological stations within Greece's flood-prone areas. A GIS-based approach is utilised for multicriteria decision-making to optimise the design and implementation of a network of hydrometric-hydrometeorological stations. The analysis focuses on the Sarantapotamos River basin in Central Greece. The findings emphasise the significant influence of chosen criteria, their hierarchical arrangement, and their integration within a GIS framework on the suitability assessment of station locations. Additionally, the analysis underscores the critical role of geospatial data resolution and accuracy in determining final suitability scores and selecting appropriate station locations. Notably, the study reveals that the recommended number of stations is dictated solely by the WMO rather than decision-makers. The proposed network design approach offers flexibility in station location suggestions, with scenarios demonstrating varying allocations along the mainstream or southern areas of the river basin, mainly influenced by criteria related to flood-prone areas. Furthermore, the analysis indicates that while fuzzy logic can somewhat mitigate subjectivity, it may not be preferable to the standard version of AHP for specific applications. This is because FAHP tends to yield more potentially suitable locations, increasing the workload for final location selection. However, fuzzy logic could yield technically feasible results in scenarios involving a more comprehensive station network design with additional criteria. Overall, the methodology presented, requiring minimal spatial data, proves advantageous for identifying suitable station locations in expansive watersheds, offering a cost-effective and time-efficient solution.

Through a detailed examination of a wide range of spatial and environmental factors, the analysis has outlined a strategy for strategically placing stations, significantly improving the efficiency of data collection for predicting floods. The methodology's strength lies in its ability to provide a systematic approach to station placement, thereby increasing the reliability and relevance of the data gathered for FRM. The insights derived from this analysis underscore the pivotal role of precise data in flood prediction and highlight the transformative potential of GIS tools in refining flood management practices. This approach represents a significant shift from conventional station placement tactics, providing a model for implementing technology and data-focused approaches to flood management.

Development of GUHs for Ungauged Basins

The dissertation takes a significant step forward in hydrological modelling by developing GUHs specifically designed for Greece's ungauged basins. A novel approach is presented to developing a GUH tailored for ungauged basins in Greece. The methodology introduced aims to establish hydrological relationships based on geomorphological metrics, employing the time-area diagram method and ArcPy in the Python scripting language. By integrating hydrological data from the PPC of Greece and conducting detailed system analysis, the precision of hydrograph estimations in data-scarce regions is significantly improved. Furthermore, the correlation of morphometric parameters with GUH attributes facilitates the derivation of empirical relationships, thereby enhancing the understanding of hydrological behaviours across diverse basins. It is noted that across multiple basins examined, the 0.1-2.0 range of channel velocity consistently yields positive NSE values, indicating substantial agreement between simulated and observed hydrograph values and thus making it a preferable choice for subsequent stages of the research. The in-depth examination of the time-area diagram method across 70 drainage basins sheds light on the relationships between hydrograph attributes and geomorphological metrics. Visual representations, such as histograms, offer valuable insights into these correlations, aiding in understanding the connections between hydrograph behaviour and geomorphological characteristics. These findings are a basis for subsequent detailed regression analysis to develop equations to predict hydrograph features based on specific geomorphological metrics. The results underscore the significance of the geomorphological metric Cc in determining the predictive accuracy of linear relationships across various hydrograph attributes, guiding the selection of optimal regression equations. Additionally, the validation regression analysis prioritises minimising prediction errors (MAE and RMSE) alongside maximising R^2 values to ensure robustness and reliability. Significantly, through a methodical evaluation of regression equations for various hydrograph attributes, models like the T-Polynomial for Q_{max} and Cc-Linear for t_{Q50L}, t_{Q50R}, t_{Q75R}, and t_{Q75L} exhibit robust predictive capabilities, achieving a balance between fit quality and accuracy. The thorough examination of residuals, including scatter plots and residual plots, further contributes to assessing the validity of the models. These analyses indicate that the developed models possess reliable predictive power for hydrograph attributes, as demonstrated by the proximity of data points to the line of equality in scatter plots and the random distribution of residuals around the zero line.

This research addresses a notable absence in hydrological science, utilising geomorphological measurements and advanced modelling techniques, especially in regions needing comprehensive hydrological data. The custom GUHs proved exceptionally skilled in predicting flood risks with high accuracy, showcasing their invaluable utility in enhancing flood management capabilities. The success of this endeavour highlights the critical importance of incorporating geomorphological insights into hydrological models, thereby improving model accuracy and reliability. This innovative methodology paves the way for advanced flood prediction in Greece and sets a precedent for hydrological studies in other regions facing similar challenges.

Effectiveness of Nature-Based Solutions (NBS)

In evaluating NBS within the Sarantapotamos River basin, the dissertation provides a compelling case for integrating sustainable, eco-friendly solutions in FRM. This research underscores the importance of integrating NBS into FRM strategies for the Sarantapotamos river basin upstream of the Magoula settlement in Greece. A methodology is presented for effectively implementing NBS, including strategies such as land cover change and retention pond construction. Through hydrological modelling and analysis, the impacts of these NBS on flood dynamics are assessed. Specifically, a comprehensive evaluation of resulting flood hydrographs is conducted, considering current and future climate conditions. These conditions are represented by three climate change scenarios: lower, mean, and upper, which correspond to ± 95% confidence intervals.

NBS implementations are applied for both the mean and upper climate scenarios. This analysis yields a detailed understanding of the impacts and effectiveness of each NBS and their respective contributions to reducing peak discharge and mitigating floods. Findings concerning NBS implementation under current climate conditions reveal a significant reduction in peak discharge through land cover changes, with a decrease of approximately 9.3% compared to the baseline scenario. Furthermore, constructing retention ponds proves to be an effective NBS, leading to a substantial reduction in peak discharge of approximately 28%. The integration of multiple NBS presents the most significant reduction in peak discharge, approximately 40.5% compared to the pre-NBS scenario. Analysis of total flood volumes shows notable reductions across all NBS scenarios. The land cover change NBS decreases by approximately 12.3%, while the retention ponds scenario achieves a reduction of approximately 15.3%. The combined NBS yields the most substantial decrease in flood volume, reducing it by approximately 15.7%. Moreover, considering climate change scenarios in this study reveals significant impacts on design precipitation, subsequently affecting flood hydrographs.

The upper climate change scenario demonstrates intensified design precipitation, characterised by notable increases in cumulative rainfall depth, rainfall intensity, and rainfall peak, resulting in a peak discharge increase of approximately 3348% compared to the initial peak discharge. The total flood volume observed undergoes a significant increase of roughly 600% compared to the initial volume. In contrast, the lower climate change scenario demonstrates a decrease in cumulative rainfall depth and peak. The total flood volume diminishes to 65.6 hm^3, indicating a reduction of approximately 44.6% compared to the initial volume. In the mean climate change scenario, the observed rainfall intensity of 13.5 mm/h suggests an intermediate flood risk level compared to other examined climate change scenarios. The peak discharge increases by approximately 838% compared to the initial value, while the calculated total flood volume rises by approximately 79.2% compared to the initial volume. Under the upper climate change scenario, implementing land cover change and retention ponds leads to substantial reductions in peak discharge. Land cover change alone reduces the peak discharge by approximately 3.7%, while retention ponds decrease it by approximately 33.6%. These NBS measures also reduced the total flood volume by approximately 3.5% and 3.6%, respectively.

Similarly, in the mean climate change scenario, land cover change and retention ponds effectively decreased peak discharge by approximately 9.73% and 23.11%, respectively. The total flood volume was reduced by approximately 9.25% and 2.17%, respectively. In summary, among the evaluated NBS approaches, the construction of retention ponds has demonstrated the most significant decrease in peak discharge. Conversely, land cover changes have shown promise in regulating the timing of flood events by extending the time to peak. This research preliminary investigation suggests that the combined use of NBS results in the lowest peak discharge across all climate scenarios.

Additionally, the case study in Northern Evia that evaluates NBS in the context of post-wildfire land cover investigates the impact of land cover changes post-wildfire on flood dynamics. It explores the effectiveness of NBS in mitigating flood risks. The study area experienced a catastrophic wildfire event in August 2021, leading to significant alterations in land cover and heightened flood risks due to increased surface runoff and reduced infiltration rates. The research employs hydrological modelling techniques, including MCDA and GIS, to assess flood-prone areas and simulate hydrological responses before and after the fire incident. It focuses on two river basins in Northern Evia: Basin 1, covering 115 km^2 with 76 km^2 affected by the fire, and Basin 2, covering 386 km^2 with 164 km^2 burnt, and five subbasins within each basin to further analyse the hydrological impacts. The analysis of UH before and after fire incidents across all subbasins highlights significant alterations in flood dynamics. Following wildfires, there is a marked increase in the magnitude of peak discharge and the speed at which it occurs. For instance, in Subbasin 2, peak discharge escalates by a factor of four compared to pre-fire estimates, with similar trends observed in subbasins 1, 3, 4, and 5, where peak discharges surge to three times their pre-fire levels. These increases in peak discharge are directly linked to elevated CN values post-fire, which are particularly pronounced in subbasins 2, 3, and 4, experiencing complete or near-complete burn areas. The heightened CN values and UH analysis significantly contribute to the amplified flood hydrographs generated by the HEC-HMS model. Moreover, the reduction in time to peak discharge post-fire is evident across all subbasins, attributed to increased land imperviousness caused by the wildfire. Subbasins 2, 3, and 4 witness substantial reductions of approximately 30%, while subbasins 1 and 5 experience more moderate reductions of 8% and 16%, respectively. These variations in time to peak reflect the varying extents of burnt areas across the subbasins, influencing the degree of increased imperviousness and subsequent adjustments in CN values. Furthermore, the observed patterns in flood hydrographs are mirrored in the UHs derived through the time-area diagram method. Post-fire, peak discharge in UHs for subbasins 1, 2, 4, and 5 triples, while in subbasin 3, it doubles compared to pre-fire levels. Moreover, post-fire UH time to peak is halved in subbasins 2, 3, and 4, indicating a faster response to rainfall events. These findings underscore the significant impact of wildfire-induced changes in land use on flood hydrograph characteristics, amplifying flood risks for entire communities.

The substantial alteration in land cover due to the fire in Northern Evia presents a unique opportunity to assess the applicability and effectiveness of NBS in mitigating flood risks amidst drastic environmental changes. To address these challenges, the study proposes reforesting burnt areas with specific land cover types, such as coniferous and broad-leaved forests, as NBS to restore ecological functions and mitigate flood risks. The reforestation plan includes allocating 3.26 km^2 for broad-leaved forests and 41.4 km^2 for coniferous forests in subbasin 1. Similar allocations are made for the other subbasins within the study area, with specific areas designated for reforestation efforts based on the extent of fire damage and the ecological characteristics of each subbasin. Specifically, in subbasin 2, 1.47 km^2 are allocated for broad-leaved forests and 8.41 km^2 for coniferous forests. Similarly, in subbasin 3, 19.27 km^2 are designated for broad-leaved forests and 22.1 km^2 for coniferous forests. This pattern continued for Subbasins 4 and 5, with 28.05 km^2 and 37.71 km^2 allocated for broad-leaved forests and 40.73 km^2 and 60.52 km^2 allocated for coniferous forests, respectively. Hydrological simulations incorporating post-fire land cover changes as NBS demonstrated reductions in peak discharge and improved time to peak compared to pre-NBS scenarios.

For instance, in subbasin 2, peak discharge has reduced by approximately 17.8%, and time to peak has decreased to 6.5 hours post-NBS implementation. Overall, the study highlights the critical role of NBS in enhancing landscape resilience against hydrological extremes post-fire and provides valuable insights for sustainable watershed management and DRR in wildfire-prone Mediterranean regions. The quantitative findings from this study elucidate the significant potential of NBS in reducing flood peak discharges and volumes, affirming their effectiveness in mitigating flood risks under various climatic scenarios. This component demonstrates the adaptability and resilience of NBS as a flood mitigation strategy and advocates for a holistic approach to flood management that harmonises with ecological conservation goals. The thorough study of NBS effectiveness highlights the importance of creative management approaches that combine hydrology knowledge with environmental sustainability. This offers a guide for future flood prevention efforts focusing on people's and nature's well-being.

By dissecting these components in greater detail, this dissertation illuminates the multifaceted nature of FRM, offering insightful conclusions that bridge theoretical research with practical applications. The depth of analysis presented in this research contributes significantly to the field of hydrological sciences, setting a benchmark for future research in FRM and sustainability.

5.2 Future Research

The primary recommendations for future research are directly derived from the limitations of this study. The first set of recommendations centres on deepening the investigation, given the broad scope for advancement in this field. Other suggestions relate to enhancing the methodologies applied in this study. A concise list of recommendations for future research is provided below:

- Regarding criteria selection and integrating remote sensing data for the hydrometric-hydrometeorological station network design, the difficulties in on-site evaluations across extensive watershed areas necessitate exploring remote sensing technologies. This approach can significantly enhance the evaluation of technical standards required for station placement, such as streambed conditions and bank stability. Future research should focus on developing a methodology incorporating remote sensing data to accurately identify suitable locations for station installation, thereby addressing the large-scale evaluation challenge and ensuring compliance with ISO standards.
- Exploration of Advanced Factor Weighting Methods: Given the complexity of selecting and weighting criteria for station placement, future research should explore modifying

applied factor weighting methods. This entails a comparative analysis among different approaches to weighting and standardising criteria, aiming to identify methodologies that enhance the precision and reliability of station network design. Investigating various weighting techniques, including statistical and machine learning methods, could offer insights into optimising network configurations for enhanced flood warning and water resource management capabilities.

- Implementation Across Diverse Catchment Characteristics: Implementing the hydrometric-hydrometeorological station network design methodology at different spatial scales and in catchments with varied characteristics represents a critical area for future research. This approach would validate the proposed framework's adaptability and scalability and provide valuable data on its applicability in diverse geographical and environmental contexts. Such research should aim to document the effectiveness of the network design in achieving accurate flood predictions and efficient water resource management across a range of catchment types, further informing the refinement of design criteria and methodologies.
- Regarding the calibration and validation of GUHs, the reliance on limited hydrometric data necessitates the exploration of additional data sources to enhance the robustness of GUHs tailored for ungauged basins. Future research should prioritise integrating alternative hydrological data, possibly from satellite observations, to supplement the scarce data provided by the PPC of Greece. This approach could mitigate the constraints of the current dataset, enabling a more comprehensive analysis and application of the time-area diagram method.
- Future investigations into machine learning methodologies, including neural networks, are recommended to enhance predictive accuracy with machine learning. These advanced computational techniques could more effectively utilise the limited data available, enhancing the predictive accuracy of hydrological modelling for ungauged basins. Implementing these methodologies could transform how hydrological predictions are made, especially in regions where conventional data collection is challenging.
- Concerning incorporating climate change scenarios into GUH modelling, future research should integrate them to assess their impact on flood risk and water resource management. This includes exploring how the GUH methodology can be adapted to reflect changes in land use patterns over time, ensuring that the models remain relevant and accurate as environmental conditions evolve. The recalibration of models to account for these changes will be an essential step in maintaining the efficacy of GUHs in predicting hydrological responses.

- Exploring the Adaptability of GUH Methodology to Land Use Changes, it is essential to investigate the GUH methodology's responsiveness to alterations in land use and climatic conditions. This research should focus on recalibrating the GUH models to accommodate such changes, ensuring their applicability and accuracy in predicting hydrological responses in ungauged basins under varying environmental scenarios. The ability to adapt the GUH methodology to these changes will significantly enhance its utility for effective water resource management and flood risk mitigation.
- Regarding the effectiveness of the NBS and the CN estimation, future research should explore developing a multi-criteria approach that integrates ecological, hydrological, and socio-economic data specific to Greece. This approach aims to enhance the accuracy of CN estimation, overcoming the limitations posed by reliance on singular data sources. Integrating diverse datasets will allow for a more comprehensive understanding and application of NBS, particularly in assessing the impacts of land cover change.
- Concerning determining design criteria for retention ponds, future efforts should establish a standardised framework for regional topography, slope gradients, river network density, and cross-sectional studies. This framework should aim to move beyond the discretion of individual researchers, incorporating a systematic approach to criteria determination that uses both empirical data and advanced simulation models. This research direction seeks to standardise retention pond design across different landscapes, enhancing their effectiveness in water retention and flood mitigation.
- Future research is suggested to explore the impact of soil erosion on retention ponds' effectiveness and assess how soil erosion influences the sedimentation rates and capacity of retention ponds. Additionally, the performance of hydraulic simulations downstream of the basin, both before and after the application of NBS, should be examined. This includes evaluating changes in hydrological responses and flood risk reduction and providing insights into the resilience and adaptability of NBS under various environmental conditions.

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