Multiparameter Flood Risk Assessment and Management Planning at High Spatial Resolution in the Region of Attica, Greece

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***Abstract*—Floods are disastrous events as they induce fatalities, damages to the environment, properties, and infrastructure, at a global level. The Region of Attica, which hosts Athens (capital of Greece), has suffered various floods, including the severe flood in Mandra (2017) with 24 fatalities. In 2021, a Programming Agreement was signed between the Prefecture of Attica and the National Observatory of Athens to conduct the research study "Earthquake, fire and flood risk assessment in the Region of Attica" (Part A) in selected and most vulnerable areas. In the framework of this research and technical work, state-of-the-art methodologies were developed and implemented that support multiparameter flood risk assessment and management planning at high spatial resolution (building block level). This work integrates different data sources, including remote sensing, in-situ measurements, field visits, and simulations, and is characterized by considerable added value, as it supports the civil protection authorities as well as all the other relevant stakeholders in the decision-making, first response, and management of floods. Furthermore, this innovative approach is transferable, adaptable, and scalable, and it is now being implemented in the Garyllis river basin in Cyprus, in the framework of the "EXCELSIOR" H2020 Widespread Teaming project.**

***Index Terms*—Escape routes, flood management, flood risk assessment, flood risk mitigation, refuge areas.**

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I. Introduction

FLOODS can cause grave disasters, both in terms of deaths and material damages. Indicatively, in 2023, 164 floods were recorded worldwide, killing 7763 people, affecting 32.4 million people, and resulting to economic losses of 20.4 billion USD, respectively, according to the latest available data for 2023, published by the Centre for Research on the Epidemiology of Disasters [1].

In order to prevent the new risks and reduce the existing ones from natural hazards, the Sendai Framework for Disaster Risk Reduction 2015–2030 was adopted in March 2015, coordinated by the United Nations Office for Disaster Risk Reduction (UNDRR) [2]. The Framework's basic priority for action is the understanding of the disaster risks, from predisaster, prevention, and mitigation to preparedness and effective response to disasters [3].

Thus, in order to increase disaster resilience that is a core aim of sustainable development according to the Global Assessment Special Report 2023 on Disaster Risk Reduction [4], special attention should be given to assessing risks using reliable methods that combine the key factors of hazard, vulnerability, and exposure [5].

Efficient disaster risk management includes mitigation measures such as the design of civil protection measures, and the implementation of studies with proper interventions (both structural and nonstructural). This is even more crucial in highly dense urban areas, with large populations, critical infrastructure, and important socioeconomic activities.

The ongoing urban development and growth, including the continuous expansion of the cities into floodplains, contribute to increased flood risk. In addition to the rapid urbanization, the pressures of inadequate planning, shrinking green spaces, and the impacts of wildfires further increase the flood risk. These challenges highlight the value of innovative approaches that combine advanced technologies with local insights to assess the flood risk and design effective flood mitigation measures towards more resilient urban flood management strategies [6].

II. Research Study

In the framework of a Programming Agreement signed in March 2021 between the Prefecture of Attica (Greece) and the National Observatory of Athens (NOA) (Part A), a research study funded by the Region of Attica was conducted entitled "Earthquake, fire and flood risk assessment in the Region of Attica" in selected and most vulnerable areas [7]. Within this project, a holistic multiparameter risk assessment methodology has been developed and implemented at high spatial resolution.

The research study on flood risk assessment is implemented by the NOA, Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing (IAASARS), Operational Unit "BEYOND Center of Earth Observation Research and Satellite Remote Sensing" in cooperation with the National Technical University of Athens (NTUA), School of Civil Engineering, Department of Water Resources and Environmental Engineering, Research Group ITIA.

III. Study Area

The study area is the Region of Attica, the most highly dense area in Greece that includes its capital, Athens. It constitutes a region with significant characteristics, such as long coastline, large inland area, and nine islands, various geoenvironmental units, high population density (i.e., 3.792.469 residents, over 17 000 per sq. km, and 36,4% of the country's population according to the Hellenic Statistical Authority (2021) [8]), crucial infrastructures, and socioeconomic activities.

The Mandra river basin is presented for the purpose of this manuscript, which was affected the most by the severe flash flood that occurred after heavy rainfall in west Attica on 15 November 2017. The tragic outcome was that 24 people lost their lives, and many assets as well as critical infrastructures were completely or partially damaged. The FloodHub team of the Operational Unit "BEYOND Center for Earth Observation Research and Satellite Remote Sensing" of IAASARS/NOA was activated and studied the area, both by using satellite remote sensing and photo-interpretation, and by visiting the area for data collection and more detailed analysis. This included the identification of uncovered and covered parts of the streams and their former natural riverbank, the examination of the adequacy of the cross-section of the streams and the engineering works, the identification of critical points, the taking of photographs, and, finally, the suggestion of appropriate mitigation measures for the prevention of future failures and disasters. The FloodHub team created an interactive web application [9] and produced detailed maps Fig. 1 depicting the updated hydrographic network, following human interventions, the maximum extent of the flood (both mapped and simulated), as well as some of the critical factors that contributed to the massive disaster: arbitrary human interventions within the riverbank, the absence or inadequacy of technical works (flood protection and road drainage), and

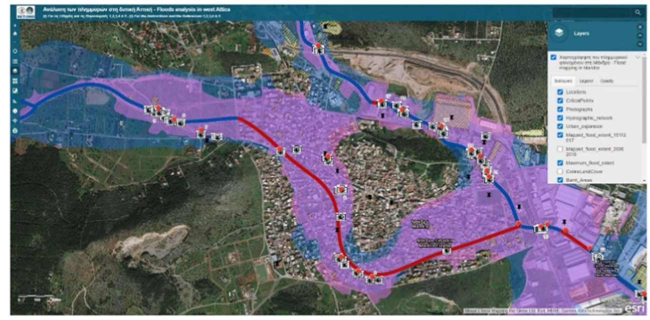

Fig. 1. Detail in Mandra city: mapping of the flood on 15 November 2017 with high-resolution Sentinel-2 satellite data (magenda) and simulation of the maximum flood extent (blue).

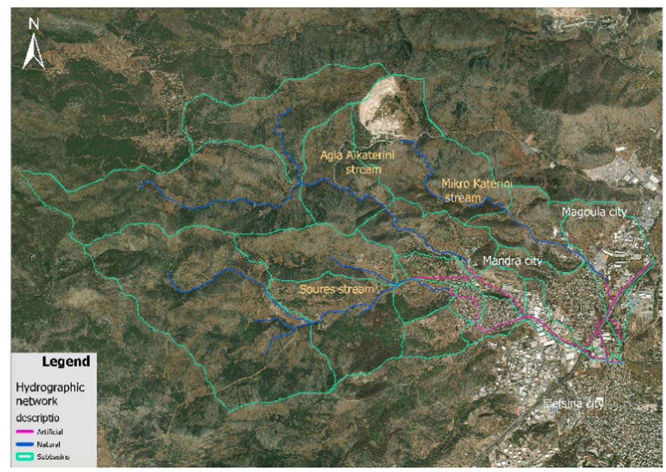

Fig. 2. Mandra river basin in 2025 with its 20 sub-basins and hydrographic network layers for the Agia-Ekaterini, Soures, and mikro-Katerini streams.

partly landscape changes on the one hand due to some small burnt areas upstream, and mainly due to urban expansion where building obstructs the flow of the streams [10].

Following the flood of 2017, a series of flood protection technical works were implemented, including a partial diversion of a stream. Currently, in 2025, the Mandra river basin includes the streams of Agia-Ekaterini and Soures that cross the city of Mandra, as well as mikro-Katerini stream that crosses Magoula city, while all of them join Sarantapotamos river. There is a partial diversion of Agia-Ekaterini stream to Soures stream, upstream of the city of Madra, while the rest of the flow passes through the city of Mandra. Then, there is a full diversion of these three streams to Sarantapotamos river, upstream of the city of Elefsina (see Fig. 2).

IV. Methodology

Scientific research for risk analysis is necessary in order to implement the proper methodology according to the needs of the study. The methodology is based on the guidance and standards provided for risk assessment, such as international Frameworks and EU Directives. The uncertainty estimation constitutes a key element in the analysis of the natural hazard, due to the high impact on the results and the potential cause of failure in the risk assessment. Also, it is essential to record the assumptions

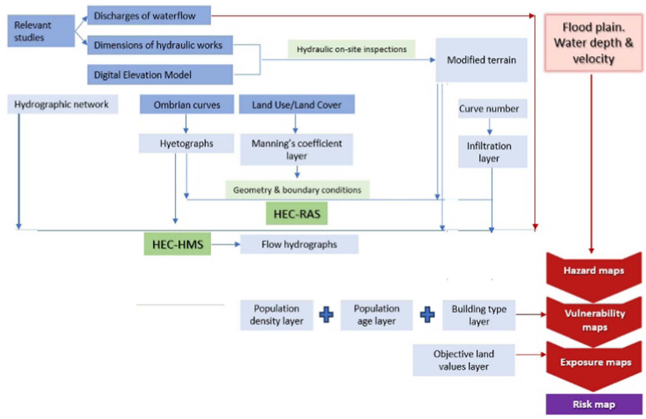

Fig. 3. Methodological framework for flood risk assessment in Attica Region.

made during the risk analysis, and to evaluate their impact on the accuracy of the final results [11].

The definition of the spatial resolution of the risk elements is critical to the risk assessment, since it is required at multiple scales, from local to national, regional, or even global; while every level has its own objectives and spatial data requirements. Therefore, the use of Geographic Information Systems and remote sensing has become an absolute necessity and an integrated approach in disaster risk management. Over the last years, remote sensing applied to natural hazards has shown a great potential in providing valuable information at various scales, both spatial and temporal. Recent advances in technology and processing techniques have considerably promoted disaster risk reduction research [12]. Generally, the remotely-sensed data alongside the processing techniques vary according to the corresponding application. Different types of satellite images (optical, radar, multispectral) with various spatial resolutions are processed and used as input in hazard modelling and in other stages of the risk assessment process. Both input and output layers may range from medium to very high resolution, covering a wide range of needs from preparedness to crisis response. Advances in remote sensing technology have significantly improved satellite imagery [13], developing a wide range of processing techniques. Machine learning and deep learning algorithms, such as the random forest, are utilized for model prediction and mapping as well.

The combination of multisource remote sensing with in-situ data from sensors (e.g., telemetric hydro-meteorological stations) as well as field investigation is proposed for more reliable results and efficient disaster risk reduction [14].

Flood risk is assessed by an integrated methodology that includes geo-spatial data, remote sensing, in-situ observations, and hydrologic and hydraulic simulations. This holistic multiparameter methodology was developed by the FloodHub research group of the BEYOND/IAASARS/NOA in cooperation with the ITIA research group of NTUA.

Fig. 3 presents, in a schematic way, the methodological framework for flood risk assessment, which is validated using all available information on historical flood events, high-risk locations indicated by the local population and the competent authorities, as well as the recorded citizens' calls for aid to the Fire Service in flooded areas.

A. Data Collection

All available data, including geo-spatial data and Earth observation data at the highest available resolution [e.g., digital elevation model (DEM) and land cover], as well as the relevant technical studies, are collected, quality checked, enriched by photo-interpretation, and, if needed, updated.

The DEM of the Hellenic Cadastre of 2 m spatial resolution, derived from large-scale orthoimagery LSO25 for the period 2014–2016, is used [15]. This DEM is primarily used as a background to the hydraulic models, but also indirectly for estimating ground slope, average longitudinal stream gradient, average sub-basin elevation, and downstream/exit sub-basin elevation in the hydrological calculations. &Igr;n the hydraulic models, the engineering works are incorporated in the DEM. The modified DEM is checked over the entire catchment area and further modified locally, so that there is a smoother floodplain for the flow.

Regarding the land cover data, the polygons of the European Urban Atlas of the Copernicus Land Monitoring Service for the period 2012–2018 [16] are used and updated. New polygons are created through photo-interpretation, and the burnt areas for the period 1985–2021, obtained from the FireHub service of BEYOND/IAASARS/NOA, are also added [17].

Detailed field visits are conducted according to a standardized methodology and reporting template to estimate the dimensions of the technical works (such as bridges and culverts), to identify obstacles or hydraulically sensitive points in the riverbed, critical infrastructure, and services in the area, and to collect feedback from the residents.

Data collection is made through three courses of action:

1) collaboration with public entities for the collection of data and studies in the area of interest,
2) indirect communication with the general public through online questionnaires, and
3) direct communication with the general public during field visits and by loose-format interviews about their experiences.

1) Collaboration With Public Entities: The collection of all available data from public entities, such as the Region of Attica, Municipalities, Forestries, and the Fire Service, is given high priority. The cooperation between academic and research institutions as well as public authorities is crucial for the quantification of risks associated with natural hazards, since the combination of theoretical knowledge and practical experience can optimize the risk assessment. In this direction, all potentially useful sources of information are examined, such as past and ongoing studies, activities, research.

2). Indirect Communication With the General Public: For the purpose of additionally acquiring the residents' opinion, an online questionnaire is launched [18], including questions about past flood events and proposed mitigation measures. The questionnaire is forwarded to acquaintances and social media, so that it is filled in by random people in the area of interest. People working in public institutions are also asked to participate in this research by filling in the questionnaire, given their professional experience and technical expertise. Moreover, the questionnaire link is sent to the involved Municipalities within the areas of interest, with the request to distribute it to their citizens. Informed consent is obtained with a relevant statement, which is included in the questionnaire.

3). Direct Communication With the General Public: With the aim to identify flood-prone areas and collect people's feedback, a direct contact is made through brief interviews with the residents and employees in the area of interest during the field visits along the streams and rivers in the areas of interest. In particular, people are asked about past flood events, specific locations prone to flooding, and proposed mitigation works. The online questionnaire is also used during the on-site visits to directly record responses from residents.

This three-course action approach is considered important, as it establishes a more integrated approach in flood risk assessment, allowing engineers to combine knowledge and experience from several points of view, and thus, to result in a more efficient and widely acceptable design of mitigation measures, but also, in the public engagement during and after their implementation.

In total, 242 responses are collected from the online questionnaire. While it is not possible to determine the exact response rate (mainly because it is not known whether the Municipalities actually share the online questionnaire with their citizens), the experience of the research team indicates that personal interaction significantly enhances participation and response quality.

In particular, the citizen's input focuses on their past experiences with flooding incidents in their area and is mapped accordingly, accompanied by relevant notes. Locations identified as flood-prone by citizens are marked as checkpoints by the on-site research team. In total, 145 checkpoints are examined in the Mandra river basin, and 73 locations out of them are evaluated as high risk and are validated following the production of the flood risk maps (a percentage of 50.34%).

The citizen's feedback is also presented to the decision-makers and first responders in relevant workshops on flood resilience in Mandra organised by the Operational Unit "BEYOND/IAASARS/NOA", to support mitigation planning and civil protection [19].

B. Design Hydrographs

Rainfall hydrographs are derived from updated ombrian (or else intensity-duration-frequency) curves, which are constructed and adapted to each river basin, following a new advanced methodology [20], [19], [21], [22]. A previous study in the Attica region [23] suggests that the wider region is characterized by climatic homogeneity with minor differences, mainly attributed to the altitude of the different areas. Based on this fact, and in order to increase the reliability of the final estimate, the new methodology for spatial estimation of rainfall curves from multiple available samples of Attica has been developed, which utilizes the most modern methods of estimating extremes [24]. Therefore, for the construction of the rainfall curves, rainfall data are collected on small time scales of 5 min to 1 h using

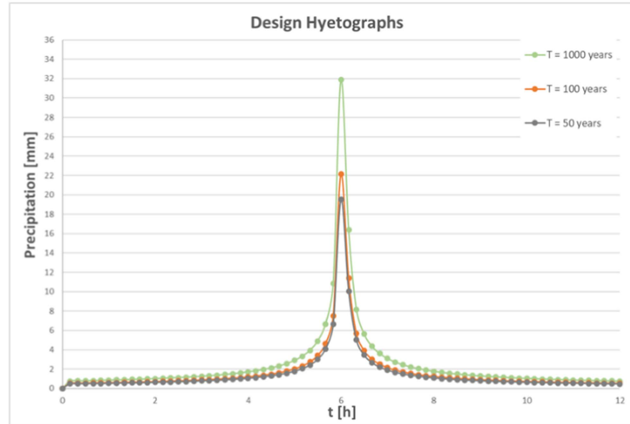

Fig. 4. Design hyetographs of the entire river basin for 12-h rainfall and 50, 100, 1000 years return periods.

pluviographs, and on a daily scale from rain gauges in the wider area of Attica. Available data from previous studies are used, stations are updated, where possible, and new stations are added wherever appropriate. The final sample consists of 29 stations at 18 sites managed by 4 public institutions, which jointly cover the period from 1860 to 2020.

In order to ensure consistency among data sources, given that data from both automatic rain-recorders (high temporal resolution) and conventional rain gauges (daily resolution) are used for the derivation of design rainfall curves, a comparative analysis is performed at overlapping locations and time periods. This analysis confirms that the datasets are generally consistent for the purposes of the present work. The use of the satellite-based precipitation products (integrated multisatellite retrievals for GPM) as an additional data source is also evaluated. However, these are found to be insufficiently accurate for modeling rainfall extremes in the study area. As a result, satellite data are not included in the final derivation of design rainfall curves.

Then, by applying the ombrian curves, hyetographs are compiled in each sub-basin for the three standard return periods (50, 100, 1000 years) according to the EU Flood Directive [25], on a time scale equal to the considered rainfall duration and with a time step of 10 min. The surface reduction factor ϕ [26] is applied and the alternating block method [27], [28] is selected.

Fig. 4 presents the design hyetographs of the entire river basin for 12-h rainfall and 50, 100, 1000 years return periods.

C. Hydrological Analysis and Modeling

Sub-basins are designed for a more accurate estimation of runoff in each sub-basin, based on the river network (both natural and artificial) and the characteristics of the terrain and land cover.

Therefore, 20 sub-basins are designed (see Fig. 2), and the schematic of the catchment area is developed (see Fig. 5). Particular attention is paid to the simulation of the partial diversion of the Agia Ekaterina stream to the Soures stream during the setup of the schematic.

Subsequently, the simulation is run in the open-source HEC-HMS 4.10 rainfall-runoff model [29]. A combination of the Runoff curve number (CN) method of the soil conservation

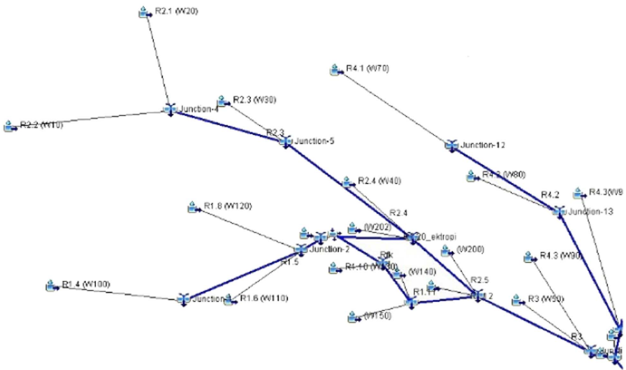

Fig. 5. Rainfall-runoff model schematic for the Mandra river basin.

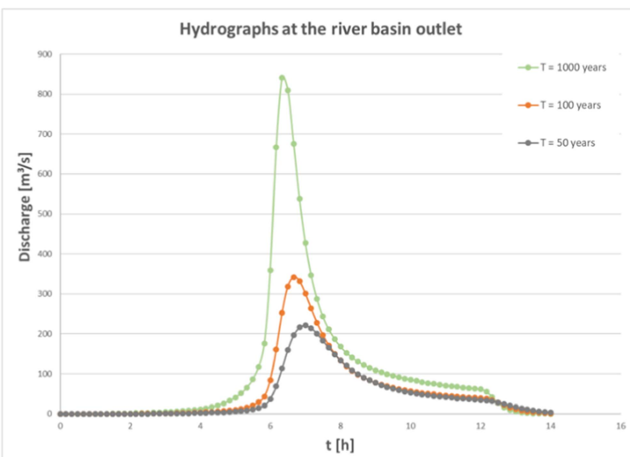

Fig. 6. Design hydrographs at the outlet of the river basin for wet antecedent soil moisture conditions (CN III), 12-h rainfall and 50, 100, 1000 years return periods.

service (SCS) is applied to estimate the hydrologic losses, and the synthetic unit hydrograph method of the SCS is applied for the spatiotemporal transformation of the distributed active precipitation to flood runoff (i.e., design flood hydrograph), where peak lag times for each sub-basin are used as input to the rainfall-runoff model [30].

The different scenarios are simulated based on the flood return period T (50, 100, 1000 years) for wet antecedent soil moisture conditions (CN III), and the hydrographs are evaluated by checking the connections at different nodes of the network and by comparing the scenarios with each other.

Fig. 6 presents the design hydrographs at the outlet of the river basin for wet antecedent soil moisture conditions (CN III), 12-h rainfall and 50, 100, and 1000 years return periods.

D. Hydraulic Modeling and Hazard Assessment

In the open-source hydraulic model HEC-RAS 6.3 2-D [31], the spatially distributed rainfall (rain-on-grid) method is used, which combines the influence of the topography of the terrain with the hydraulic solution of two-dimensional Saint-Venant equations, and is found to approximate the more generalized

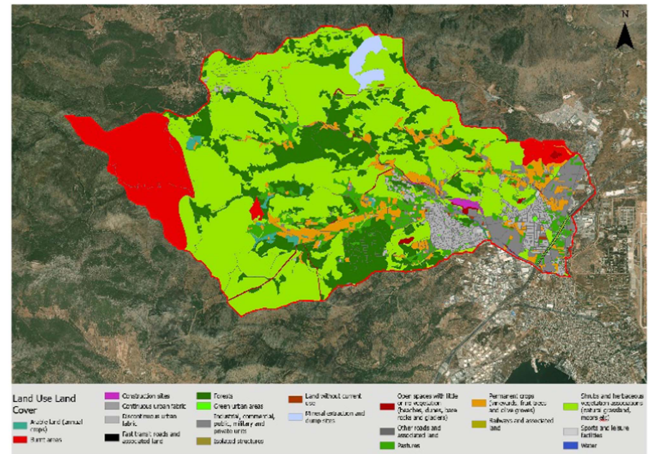

Fig. 7. Land cover map of the Mandra river basin updated with the burnt scar mapping (in red).

direct rainfall method method [32]. The total hyetograph for each return period is entered without subtracting losses, which are estimated internally by the SCS method for CN III.

The land cover data are obtained from the European Urban Atlas of the Copernicus Land Monitoring Service for the period 2012–2018 [16], and they are updated through photo-interpretation. Also, burnt areas for the period 1985–2021, derived from the FireHub service of BEYOND/IAASARS/NOA, are integrated in order to update the land cover data (see Fig. 7).

Then, for each land cover class a value of the Manning roughness coefficient is assigned in the floodplain and riverbed based on the land-use maps, the sensitivity analysis, and the field measurements. It is noted that for basins and rivers with similar climatic, land-type, and topographic conditions, similar conclusions on the sensitivity of these parameters can be drawn and applied.

The hydraulic solution is performed with a variable computational step, and it is carried out at high spatial resolution (from 10 to 25 m depending on the area of the catchment), and becomes even more detailed (from 1 to 10 m) in areas of high interest (such as near the stream and road network) and intense topographic relief variations.

Finally, these hydraulic models are used to produce the water depth and velocity maps for the flood hazard assessment for different flood scenarios.

E. Vulnerability, Exposure, and Flood Risk Assessment

Furthermore, vulnerability is considered a weighted estimation of population density and population age (socioeconomic parameters), as well as building type (disaster resilience parameters), based on the most recent published data of the Population and Housing Census by the Hellenic Statistical Authority [33].

The population density is classified in 5 classes (with values from 1 to 5) following the application of the Jenks optimization method (Natural Breaks), so that the vulnerability increases proportionally with increasing population density (see Table I).

TABLE I
POPULATION DENSITY RANGES USED TO CREATE THE VULNERABILITY CLASSES

Population density (persons / m^2)	Vulnerability classes
0–0.005205	1–Very low
0.005206–0.011719	2–Low
0.011720–0.020531	3–Medium
0.020532–0.040545	4–High
0.040546–0.094797	5–Very high

TABLE II
CREATION OF AGE GROUPS AND WEIGHT CLASSES

Population age (years)	Age groups	Age group weights
20–39	1	0.05
40–49	2	0.1
50–59	3	0.15
10–19 and 60–69	4	0.25
0–9 and > 70	5	0.45

TABLE III
NORMALIZED AGE RANGES USED TO CREATE THE VULNERABILITY CLASSES

Normalized population age	Vulnerability classes
0–0.158824	1–Very low
0.158825–0.202000	2–Low
0.202001–0.245833	3–Medium
0.245834–0.340909	4–High
0.340910–0.45	5–Very high

Five age groups are created depending on how easy or difficult it is for individuals to cope with a flood event, and for each age group, a weight is assigned, so increased weights are assigned to the very young and very old age groups (see Table II).

The values of the population age are normalized and classified in 5 classes (with values from 1 to 5) following the application of the Jenks optimization method (Natural Breaks) (see Table III).

In order to assess the flood vulnerability according to building characteristics, the presence (or absence) of a pilotis, as well as the construction material, is taken into account. The construction material indicates how easily a building can be swept away by the rushing force of the flood water [34]. Five vulnerability classes are created (with values from 1 to 5) (see Table IV).

For the assessment of the total vulnerability, the above-mentioned layers are synthesized. In particular, in a first stage, the synthesis of the layers of population density and age is carried out (see Table V), and then the resulting layer is combined with the building characteristics (see Table VI).

Exposure is based on the objective land value (€/m2), as obtained from the Ministry of Finance [35]. The exposure is

TABLE IV
BUILDING CHARACTERISTICS AND THEIR VULNERABILITY CLASSES

Building characteristics	Vulnerability classes
Buildings with pilotis only	1–Very low
At least one building made of concrete, metal, and without pilotis	2–Low
At least one building made of wood, bricks, and without pilotis	3–Medium
At least one building made of stone and without pilotis	4–High
At least one building made of other materials	5–Very high

TABLE V
SYNTHESIS OF THE VULNERABILITY BASED ON POPULATION DENSITY AND AGE (WHERE 1: VERY LOW, 2: LOW, 3: MEDIUM, 4: HIGH, 5: VERY HIGH)

		Vulnerability based on population density				
Vulnerability based on population age		1	2	3	4	5
	1	1	2	3	4	5
	2	2	2	3	4	5
	3	3	3	4	4	5
	4	4	4	4	5	5
	5	5	5	5	5	5

TABLE VI
SYNTHESIS OF THE VULNERABILITY BASED ON POPULATION DENSITY AND AGE AND BUILDING CHARACTERISTICS (WHERE 1: VERY LOW, 2: LOW, 3: MEDIUM, 4: HIGH, 5: VERY HIGH)

		Vulnerability based on building characteristics				
Vulnerability based on population density and age		1	2	3	4	5
	1	1	2	3	4	5
	2	2	2	3	4	5
	3	3	3	4	4	5
	4	4	4	4	5	5
	5	5	5	5	5	5

TABLE VII
OBJECTIVE LAND VALUE AND THEIR EXPOSURE CLASSES

Objective land value (€/m^2)	Exposure classes
< 1000	1–Very low
1000–1300	2–Low
1300–1600	3–Medium
1600–2000	4–High
> 2000	5–Very high

TABLE VIII
SYNTHESIS OF THE FLOOD HAZARD AND FLOOD TOTAL VULNERABILITY (WHERE 1: VERY LOW, 2: LOW, 3: MEDIUM, 4: HIGH, 5: VERY HIGH)

		Flood hazard				
Flood total vulnerability		1	2	3	4	5
	1	1	1	1	2	3
	2	1	2	2	3	4
	3	1	2	4	4	5
	4	2	3	4	5	5
	5	3	4	5	5	5

classified in 5 classes (with values from 1 to 5), so that the vulnerability increases proportionally with increasing land value (see Table VII).

Finally, hazard, total vulnerability, and exposure are combined to estimate flood risk. Specifically, in order to carry out this synthesis, the flood hazard layer is initially merged with the overall vulnerability layer, in order to create a single layer (see Table VIII). The resulting layer is then combined with the exposure layer (Table IX).

Based on the flood risk assessment and the in-situ observations from the field visits, critical points are identified and classified in three risk priority levels according to a series of criteria, such as the flood depth, their proximity to the simulated flood extent and the recorded locations of citizens' calls for aid to the Fire Service, the threat they pose for human lives and critical infrastructures, etc.

F. Mitigation Planning

Mitigation measures are proposed for the extreme scenario of the 1000 years return period, including the definition of safe shelters and design of safe escape routes for the population at risk.

TABLE IX
SYNTHESIS OF THE FLOOD TOTAL VULNERABILITY AND HAZARD AND FLOOD EXPOSURE (WHERE 1: VERY LOW, 2: LOW, 3: MEDIUM, 4: HIGH, 5: VERY HIGH)

		Flood exposure				
Flood total vulnerability and hazard		1	2	3	4	5
	1	1	1	1	1	1
	2	2	2	2	2	3
	3	3	3	3	4	4
	4	4	4	5	5	5
	5	5	5	5	5	5

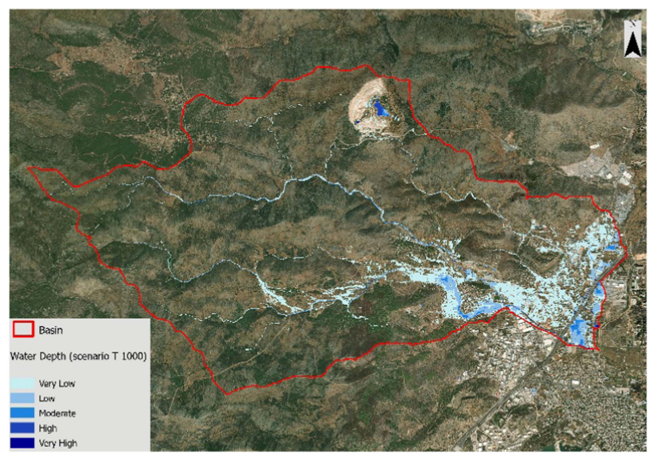

Fig. 8. Map of flow depth variation (flood hazard) for the 1000 years return period and the 12h rainfall duration.

For this purpose, a multicriteria analysis is performed considering the following criteria.

1) The shelters should be public buildings in good condition with roof (not open-air).
2) The shelters should be spatially well-distributed to cover all the population at risk.
3) The shelters should be located at both sides of each river / stream, so that people don't need to cross them.
4) The escape routes should not cross the hydrographic network.
5) The escape routes should respect the traffic directions.
6) The escape routes should follow the optimum ways possible (fastest and safest).

V. RESULTS

Following the methodology described above, Figs. 8 and 9 show the flood hazard with the variation of the flow depth and flow velocity, respectively, from the outputs of the hydraulic

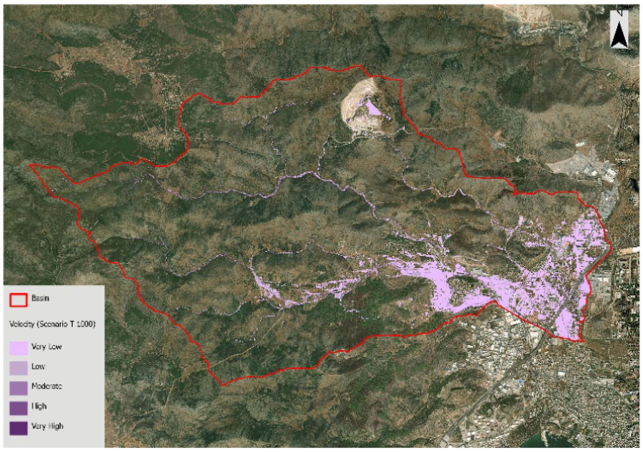

Fig. 9. Map of flow velocity variation (flood hazard) for the 1000 years return period and the 12h rainfall duration.

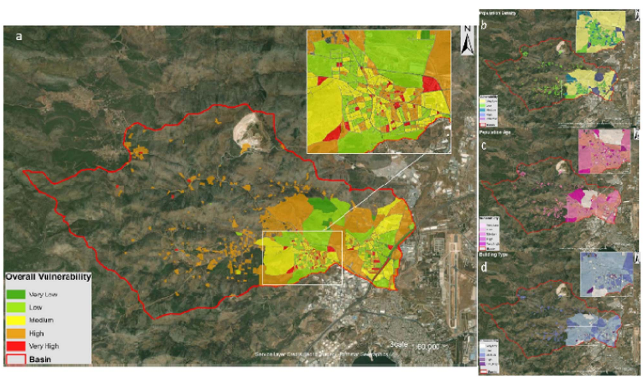

Fig. 10. Map of overall (a) vulnerability, which is a composite of vulnerability layers based on (b) population density, (c) population age, and (d) building type.

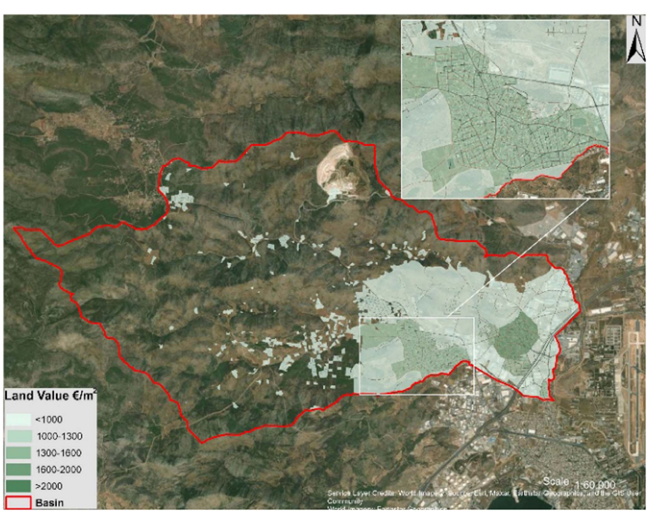

Fig. 11. Map of the land value, which is considered to correspond to exposure.

model for the 1000 years return period and the 12 h rainfall duration. It is noted that, despite the flood protection works so far, parts of the urban area of Mandra are still under high flood depth for the extreme scenario of the 1000 years.

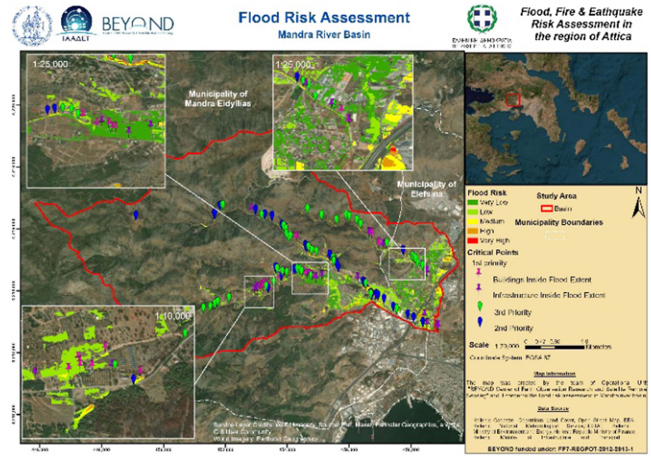

Fig. 12. Map of flood risk assessment and critical points of first, second, and third priority.

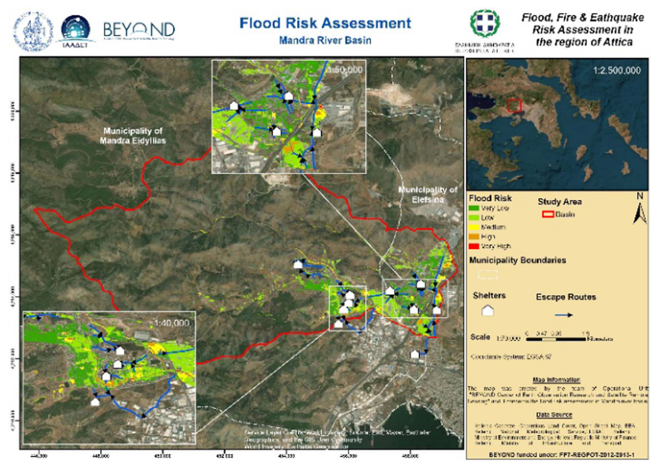

Fig. 13. Proposed shelters and escape routes in case of flood.

Fig. 10 shows the overall vulnerability, which is produced by coestimating vulnerability based on population density, population age, and building type. It is noted that only a few scattered blocks show very high overall vulnerability to flood.

The layer of financial exposure is set out in Fig. 11. As expected, the land values are higher in the urban areas of Mandra and Magoula.

The flood risk assessment is presented in Fig. 12 along with the critical points, which are classified into three priorities. The critical points of first priority are mostly buildings and infrastructure within the flood extent, and they pose a severe danger to the local population and the passers-by, both the pedestrians and those in vehicles.

Taking into account the flood risk and the critical points, safe shelters and escape routes are proposed for the population at risk (see Fig. 13). Public schools are identified as the most appropriate shelters, especially in the urban areas, and safe escape routes are designed so that all the areas under medium, high and very high flood risk are covered.

The results are validated with the record of civilians' calls to the Fire Service requesting aid for water pumping from 2006 to 2022. Indeed, the urban areas at risk of flood (even for the

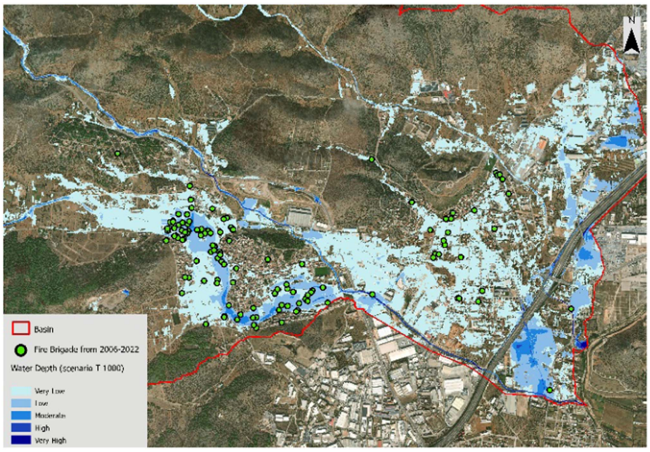

Fig. 14. Calls of the Fire Service from 2006–2022 with the 100 years return period scenario in Mandra.

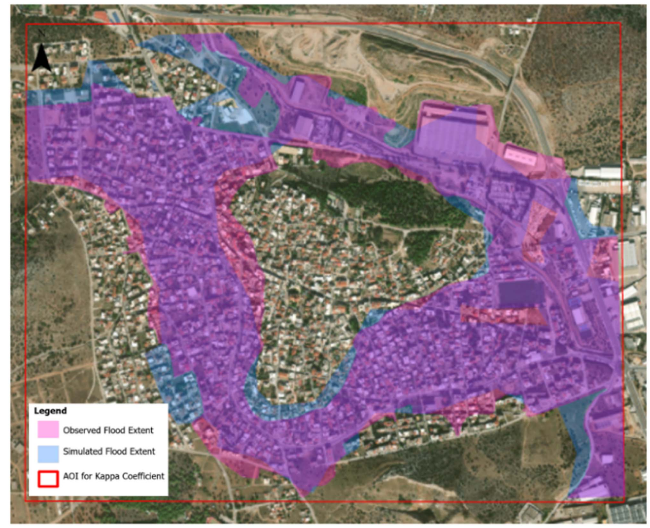

Fig. 15. Validation using the Kappa coefficient between the observed (magenda) and the simulated (blue) flood extent in the urban area of Mandra.

scenario of the 100 years return period) are the areas where civilians diachronically report flooding and request aid (see Fig. 14).

In order to further validate the flood model against historical events, a spatial comparison is conducted between the simulated and the observed flood extents for the extreme flash flood event of 15 November 2017. The Kappa coefficient is used to assess the spatial correlation between the modeled and observed flood extents in the urban area of the river basin, where flood impacts are most critical. It is calculated using GIS-based overlay analysis in order to derive confusion matrix components. The resulting Kappa coefficient value of 0.75 (75%) indicates a substantial match, demonstrating that the simulation effectively captures the spatial distribution of the flood in dense urban areas (see Fig. 15).

All the above-mentioned results are valuable for the needs of the relevant stakeholders and the competent authorities who are directly or indirectly involved in civil protection. Therefore, dedicated training sessions are organized for them by the Operational Unit “BEYOND/IAASARS/NOA”. This includes codesign and support for the organization and implementation of civil protection exercises, both map exercises and field exercises, at the local and regional levels [36], [37], [38], [39].

Last but not least, the studies’ general outcomes are also disseminated to the public in order to raise awareness and contribute to the preparedness of the general population [40], [41].

V&IGR;. Discussion

This research study analyses the flood hazard, vulnerability, and exposure of selected areas, in conjunction with the actual physical and socioeconomic parameters of each study area. Taking all this into consideration, the study estimates the flood risk—in the most objective and reliable way by scientific and technological innovations—and proposes appropriate mitigation measures. It is important to note that it is the first time that such a holistic approach for the risk assessment is implemented on a building block level in Greece, and with such analytical key steps and promising output.

Furthermore, this work introduced an innovative approach in the process of flood risk assessment and management planning, engaging the public. Public participation was identified as an integral part of any general effort to contribute to the data selection, as well as to reach public support for the flood protection works. Particularly, the participation of the public was approached through questionnaires, loose-format interviews, and discussion that, regardless their simplicity, managed to contribute both to appeasing the public and to gaining valuable insights and information regarding flood-risk issues in the areas of interest, which was the desired core issue.

Various challenges were encountered during the hydraulic simulation due to model instability, which are mainly caused by the complexity of the topography of the study area. For this reason, and due to the inherent uncertainty of the models [42], various tests were performed by varying the resolution of the computational mesh, the solution scheme, and the required values of the adjusted variable time step based on the Courant conditions, until the solution results were free of instabilities/errors, had acceptable computational load and were hydraulically correct.

More specifically, in order to improve the accuracy of the model’s computations while maintaining reasonable computational time, the spatial resolution of the 2-D mesh was carefully adjusted. This involved aligning the breaklines and refinement regions appropriately with the terrain, especially in critical areas such as riverbanks, road networks, and other key topographic features. The variable time step scheme was implemented in conjunction with the adjustment of key controlling parameters (such as the initial, minimum, and maximum time steps, as well as the Courant number thresholds), in order to optimize the model’s numerical stability and computational efficiency. With regard to model calibration, the CN parameter was adapted appropriately, since it is among the most sensitive parameters in hydrologic modeling. Finally, the model validation was performed by comparing the simulated flood extent with the observed flood extent for the extreme event of 15 November 2017, demonstrating very high model accuracy.

Moreover, in the process of vulnerability and exposure estimation, additional challenges were faced due to data gaps. A multicriteria technique was developed and applied in order to fill the data gaps, using both photo-interpretation and logical assumptions.

Further challenges needed to be addressed in the proposal of mitigation measures for the extreme scenario of the 1000 years return period, including definition of refuge areas and design of escape routes, because not all requirements were always covered for a specific area. In such cases, safety was prioritized to distance.

Furthermore, a feasibility assessment needs to be conducted to evaluate whether the proposed evacuation and sheltering plans can realistically function during a flood event, by analyzing the real-world constraints, mainly the road capacity for the escape routes, and the shelter occupancy limits for the safe shelters. This is beyond the scope of this preliminary assessment and lies under the responsibility of the Civil Protection authority.

It is worth noting that this integrated methodology is now being implemented in the Garyllis river basin in Cyprus [43], following minor adaptations in accordance with the available data, in the framework of the “EXCELSIOR” H2020 Widespread Teaming project.

VI&IGR;. Conclusion

In conclusion, the holistic methodology developed in this research work consists of state-of-the-art techniques that provide multiparameter flood risk assessment and management planning at a high analysis level (building block level) using a variety of data sources. This innovative work, with the combined use of satellite remote sensing and specialized data analysis and event simulation models, is characterized by considerable added value as it supports civil protection authorities and stakeholders in the management of floods and in decision-making towards flood resilience for the benefit of society as a whole. The contribution of this work is dual, both on the prevention phase and on the operational phase during a crisis; on the prevention phase, it offers the prioritization and implementation of the necessary interventions according to the risk level, and on the operational phase, it shows how to successfully evacuate the affected areas with safety and order.

Indeed, the prototype knowledge created through this work is currently supporting the Prefecture of Attica in the optimum implementation of the National Civil Protection Plan and the work of Civil Protection Coordination Bodies. This serves the operational requirements during a flood event, as well as the preparedness and the strategic decision making towards flood resilience. Moreover, this advanced solution is transferable, adaptable, and scalable, as shown by its implementation in Cyprus.

All the above-mentioned were repeatedly confirmed and evaluated positively according to the stakeholders’ feedback received both in Greece and Cyprus.

Furthermore, the specific methodology serves the implementation of the Sendai Framework for Disaster Risk Reduction, given that it develops disaster risk assessments and maps, based on the understanding of disaster risk in all its known dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics, and the environment. The acquired knowledge supports the relevant authorities toward adopting effective policies and practices for disaster risk management, and is crucial for the risk assessment both in the prevention and mitigation stages.

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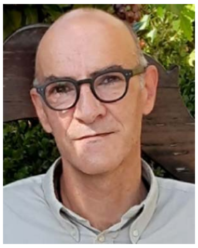
Panayiotis Dimitriadis received the Graduate degree from the National Technical University of Athens (NTUA), Zografou, Greece, in 2006, and the Master of Science from Imperial College of London under a scholarship in hydrology for environmental management, in 2008, and the Ph.D. degree in stochastic analysis of large-scale hydrometeorological and small-scale turbulent processes from NTUA, in 2017.

He is currently a Civil Engineer. In 2018, he worked as a Postdoctoral Researcher with the National Observatory of Athens in stochastic analysis of flow dynamics in natural rivers, and in 2019 until 2022, as an Adjunct Assistant Professor with the University of West Attica, Aigaleo, Greece, in the courses of Urban Hydraulic Works, Dams-Hydrodynamic Works, Fluid Mechanics, Hydraulics, Introduction in Computational Hydraulics, and Flood Mitigation Works, as well as at the NTUA in Computational Fluid Dynamics. He has collaborated through Projects held at NTUA and as a Freelancer Civil Engineer, with consultancy companies in the U.K. (ENTEC U.K. Ltd, London) and Greece (Public Power Corporation SA, Athens Water Supply & Sewerage Company SA, Hellenic Ministry of Environment and Energy, Decentralized Administration of Attica, among others), and worked as a Research Assistant in scientific programs held with NTUA in the subjects of water resources management, hydrological design, computational fluid dynamics, flood risk management, stochastic simulation of renewable energy resources, and laboratory hydraulic experiments in spillways design and sediment transport. He is currently collaborating with Athens Water Supply & Sewerage Company SA. He has excellent skills in programming languages and in statistical analysis of large datasets and has more than 2000 citations (h-index 24 and i10-index 48), and more than 70 publications in scientific journals (based on Google-Scholar, ResearchGate, and Scopus). Since 2024, he has been serving as a Convener of the EGU session HS3.8 "Advances in stochastic analysis, modelling, simulation and prediction for hydrological and water-related processes".

Dr. Dimitriadis has been granted five European (ESF, MIS5049175), Academic (from UNIWA and NTUA), and National (Eugenides Foundation) scholarships and awards.



G.-Fivos Sargentis was born in Athens, in 1972. He received the Degree in civil engineering in 1998 from the National Technical University of Athens (NTUA), Zografou, Greece, and the dual Ph.D. degrees—one from the School of Architecture on "The Use and Technical Aspects of Materials in Sculpture" in 2006 and a second one from the School of Civil Engineering on "Issues of prosperity: Stochastic evaluation of data related to environment, infrastructures, economy and society" in 2021.

His diploma thesis was entitled "Aesthetic element in water …". He is a Dr. Engineer and Sculptor. His academic career includes teaching and research at NTUA, where he has served as Laboratory Teaching Staff since 2014. His scholarly work has been published in international conferences and peer-reviewed journals, focusing on key research areas such as: Issues of Prosperity; the Water-Energy-Food (WEF) nexus; Natural Hazards; Civil Engineering; and the intersection of Art and Aesthetics. He is member of the Technical Chamber of Greece (TEE-TCG) and the Chamber of Fine Arts of Greece.

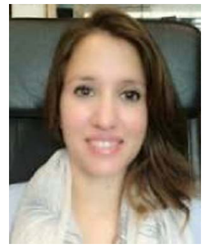
Theano Iliopoulou received the Ph.D. degree in civil engineering from the National Technical University of Athens (NTUA), Zografou, Greece, in 2020, in the domain of stochastic methods for hydrological extremes, the MSc. degree in hydrology and water resources management from Imperial College London, London, U.K., in 2014, awarded with a distinction, and the Diploma in civil engineering from NTUA, in 2013.

She is a member of the Laboratory Teaching Staff, the Department of Water Resources and Environmental Engineering, the National Technical University of Athens (NTUA), Zografou, Greece. Her research interests revolve around rainfall hydrology, hydroclimatic extremes, and their spatio-temporal dynamics, as well as novel applications of stochastic methods in water resources and environmental research. She has coauthored 27 papers in international scientific journals, 2 book chapters, and more than 70 presentations in international conferences. She has worked as a Researcher in several research projects and as an Adjunct Lecturer with the University of West Attica, Aigaleo, Greece. Since 2019, she has been serving as a Convener of the session HS7.4 ("Steps towards future hydroclimatic scenarios for water resources management in a changing world") of the European Geosciences Union.

Romanos Ioannidis received the Diploma in civil engineering in 2015, and the Ph.D. degree in spatial planning and architectural design for the integration of civil infrastructure into landscapes: Inferences from renewable energy works and dams in 2022, both from the National Technical University of Athens (NTUA), Zografou, Greece.

He is an Assistant Professor with Politecnico di Milano, the Department of Architecture, Built Environment, and Construction Engineering. His research is centered on crowdsourcing public perception of landscapes and architecture, landscape planning, and the architectural design of large infrastructure works, with a particular focus on renewable energy and water infrastructure. His postdoctoral work included a year of research visits and collaborations with Université Sorbonne Paris Cité, Forschungszentrum Jülich (Helmholtz Association), and Politecnico di Milano. His research and teaching have been supported by scholarships from prestigious institutions, including Campus France of the French Government, DAAD of the German Government, the Bodossaki Foundation, the Eugenides Foundation, the Greek Ministry of Education, Politecnico di Milano, and the NTUA. He has contributed to various European and National research projects and also has experience working as a freelancer with engineering and architectural firms. He is always eager to connect with professionals, researchers, and organizations interested in landscape research, spatial planning, and sustainable infrastructure design.

Dr. Ioannidis was the recipient of international and national awards, including the Seal of Excellence from the European Commission, the Best Scientific Publication Award from the Metsovion Interdisciplinary Research Center, and the Ecopolis Award for Best Diploma Thesis.



Dimitra Dimitrakopoulou received the Graduate Degree of Civil Engineer in 2005, and the Master degree in water resources science and technology in 2007, both from the National Technical University of Athens (NTUA), Zografou, Greece. She is currently working towards the Ph.D. degree with the School of Civil Engineering, NTUA.

She is a Hydraulic Civil Engineer. Her areas of expertise include wastewater treatment plants process design, gravity and pressure networks hydraulic calculations, storm water management, tender documents preparing (Yellow Book – Fidic, Greek rulebooks), environmental impact assessment studies, submarine pipes designs. During her eighteen-year working experience, she has enriched her skills in academic, scientific, and professional sections. She has successfully been involved in several projects in Greece, Cyprus, and Bosnia & Herzegovina. She has played a significant role during each project's life duration, from contract signing to the project's completion. Her involvement in all infrastructure civil engineering projects has been characterized by a global approach with deep knowledge of technical issues. Her excellent communication skills and her ability to take initiative, based on critical thinking, composes an integral engineer with leadership perspectives. She is a Freelancer Engineer, providing consulting and design services. Her expertise includes wastewater treatment plant process design, gravity and pressure networks hydraulic calculations, Tender Documents technical specifications, storm water management, and submarine pipe designs.

Efthymios Chardavellas received the Graduate degree in civil engineering from the National Technical University of Athens (NTUA), Zografou, Greece, in 2020.

He is a Civil Engineer. Since 2020, he has collaborated as a Freelancer Civil Engineer, in both Public-State Sector and Private Companies, in Environmental related projects (Nature Based Solutions (NBSs) Construction Projects, Flood Risk Management and Flood Mitigation Projects) as well as Residential Buildings Construction Projects. He has advanced skills in various programming languages and in modeling 1-D, 2-D, and 3-D (Computational Fluid Dynamics) Open Channel Flows, as well as in seismic resistant and resilient structures design and in structural retrofitting studies. He is a member of the Technical Chamber of Greece (TEE-TCG).

Marcos Julien Alexopoulos received the M.Sc. degree in flood risk management from the IHE Institute for Water Education, Delft, The Netherlands, in 2021.

His thesis examined the use of reanalysis products for rainfall–runoff modeling in Slovenian catchments. He is a Researcher in environmental modeling and analytics, affiliated with the National Technical University of Athens, Zografou, Greece, focusing on flood risk assessments, hydrodynamic modeling, and the integration of remote sensing and GIS. His recent work includes evaluating the effects of digital elevation model resolution on Rain-on-Grid flood simulations and urban flood modeling, as well as developing multiscale flood risk assessment methods for cultural heritage sites. He has also been affiliated with the German Aerospace Center (DLR) in work on critical infrastructure resilience. His research interests include 1-D/2-D/3-D hydrodynamics, rainfall–runoff coupling, data assimilation with reanalysis and remote sensing products, and data-driven hazard modeling.

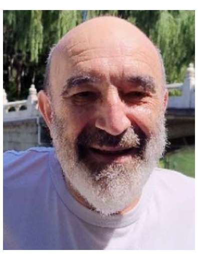
Antonis Koukouvinos received the Diploma in surveying engineering from the National Technical University of Athens (NTUA), Greece, in 1984.

He has a rich research experience with participation in more than 35 research projects (Department of Water Resources and Environmental Engineering, NTUA). His indicative research projects include Open Hydrosystem Information Network (OpenHi.net), 2018–2020, Development of a Geographical Information System and an Internet application for the supervision of Kephisos protected areas, 2008–2009, FILOTIS—Database for the Natural Environment of Greece), 2007, Development of Database and software applications in a web platform for the "National Databank for Hydrological and Meteorological Information," 2009–2011, CRESSENDO Combined REnewable Systems for Sustainable ENergy DevelOpment, 2014–2015, Investigation of management scenarios for the Smokovo reservoir, 2005–2006. Furthermore, he has more than 70 publications in scientific journals, conference proceedings, and international workshops meetings.

Nikos Mamasis received the Graduate Diploma in rural and surveying engineering from the School of Rural and Surveying Engineering of the National Technical University of Athens (NTUA), Greece, in 1985 and the Ph.D. degree in Hydrology: technological, energy, geophysical and historical dimensions from the School of Civil Engineering of NTUA, Greece, in 1997.

He is a Professor with the School of Civil Engineering, National Technical University of Athens (NTUA), Zografou, Greece. His scientific fields are in the areas of Hydrology, Hydroelectric Energy, Hydrometeorology, Geographical Information Systems (GIS), Hydrological Modeling, Water Resources Engineering, and operation of Ancient Hydraulic Works. He has more than 35 years of experience in teaching undergraduate courses (Engineering Hydrology, Energy Technology, Hydroelectric Works, Ecology) with NTUA. He has more than 25 years of experience in teaching postgraduate courses (in the fields of Hydrometeorology, Floods and Flood Protection Works, Water Resources Management and Advanced Hydrology) in postgraduate programs of NTUA and other Universities. He has supervised more than 150 diploma and Master's theses. He has 55 publications in scientific journals and 40 fully evaluated conference publications. Generally, he has more than 350 publications.

He received



Demetris Koutsoyiannis received the Graduate Diploma in civil engineering and the Doctorate in Hydrology from the School of Civil Engineering of the National Technical University of Athens (NTUA), Greece, in 1978 and 1988.

He is a Professor Emeritus of Hydrology and Analysis of Hydrosystems with the National Technical University of Athens, Zografou, Greece. He has served as a Dean of the School of Civil Engineering, Head of the Department of Water Resources and Environmental Engineering, and Head of the Laboratory of Hydrology and Water Resources Development. He was the Editor of Hydrological Sciences Journal for 12 years (2006–2018), and a member of the editorial boards of *Hydrology and Earth System Sciences*, *Journal of Hydrology*, *Water Resources Research*, *Hydrology*, *Science*, and *Science of Climate Change*. His distinctions include the Lorenz Lecture of the American Geophysical Union (AGU) (San Francisco, USA, 2014) and the Union Plenary Lecture of the International Union of Geodesy and Geophysics (IUGG) (Melbourne, Australia, 2011). He has served as a Professor of Hydraulics at the Hellenic Army's Postgraduate School of Technical Education of Officers Engineers (Athens, 2007–2010). He has been a visiting Academic/Professor with the Imperial College (London, 1999–2000), Hydrologic Research Center (San Diego, 2005), Georgia Institute of Technology (Atlanta, 2005–2006), University of Bologna (2006 and 2019), and Sapienza University of Rome (2008 and 2019).

Dr. Koutsoyiannis was the recipient of International Hydrology Prize–Dooge medal (2014) by the International Association of Hydrological Sciences (IAHS), UNESCO, and World Meteorological Organization (WMO), and the Henry Darcy Medal (2009) by the European Geosciences Union (EGU).

Charalampos (Haris) Kontoes (Member, IEEE) received the Doctorate degree in remote sensing of the environment from National Technical University of Athens, Zografou, Greece, in 1992.

For his Doctoral degree, he received grant from the European Commission in the Institute for Space Applications of the Joint Research Centre at ISPRA (Environmental Mapping Group, JRC). He holds the position of Research Director in the Institute for Astronomy and Astrophysics Space Applications and Remote Sensing of the National Observatory of Athens (NOA/IAASARS) and leads the Operational Unit BEYOND Centre of Earth Observation Research and Satellite Remote Sensing. Since 1992, he has been assuming responsibilities in managing Earth Observation operational & research projects, focusing on risk assessment and mitigation, disaster risk reduction, environmental resource management and sustainable development, agriculture and food security, energy, and Big Data analytics for cross-sector needs. He leads a multidisciplinary team of researchers with active participation in Space related projects funded by ESA, EC, COPERNICUS, GEO, and International Funding Institutions (WB, EIB, etc.). In his capacity as National Delegate he participates in Space Policy Boards and Program Committees (e.g., ESA PBEO, EC Space Program Committees (FP7, H2020), COPERNICUS Committee, Space Advisory Committee). As a Scientific Director of BEYOND, he has been coordinating the development and sustained operation of Copernicus Data Hubs, as well as the operation of the Hellenic Sentinel Data Hub for the distribution of big Sentinel satellite data worldwide. He is assuming full responsibility for the Ground Segment facilities operated by NOA/BEYOND. He leads the UN-SPIDER Regional Support Office Greece in support of capacity building, outreach, horizontal cooperation, and technical advisory support, and he coordinates the Group on Earth Observations (GEO) Enabling Mechanism GEO-CRADLE, providing GEO Capacity Building in the Balkans, Black Sea, Middle East, Africa, and Pacific Asia Regions. He has authored more than 200 publications in reviewed journals and scientific conferences.

Dr. Kontoes is a member of the editorial board of highly ranked Scientific Journals (*IJPRS, IJRS, SENSORS*, IEEE GEOSCIENCE, and *RS*), and he is acting as a member of the Advisory Boards of EU and ESA programs and initiatives.