3rd International Electronic Conference on Water Sciences (ECWS-3)

Flood risk management methodology for Lakes and adjacent areas: The Lake Pamvotida Paradigm

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Objectives

- Floods are one of the most devasting natural hazards with high mortality percentage, destruction of infrastructure and large financial losses. According to the EU Flood Directive (Directive 2007/60/EC), several scenarios should be investigated such as scenarios with low, medium and high probability of flooding (eg: T = 50, 100, 1000 years).
- This study presents a methodological approach for flood risk management at lakes and adjacent areas that is based on the implementation of the EU Floods Directive (2007/60/EC) in Greece. Contemporary engineering approaches have been used for the estimation of the inflow hydrographs.
  - The hydraulic-hydrodynamic simulations implemented in the following order:
    a) hydrologic modelling of lake tributaries and estimation flood flow inflow to the lake,
    b) flood inundation modelling of lake tributaries,
    c) simulation of the lake as a closed system,
    d) simulation of the lake outflows to the adjacent areas,
    e) simulation of flood inundation of rural and urban areas adjacent to the lake.

Flood inundation modelling for lakes and adjacent areas

- The main goal is to highlight the possible disastrous effect of fluvial floods on human health, economic activities, cultural heritage, and the environment for three typical design return periods (T = 50, 100, 1000 years), according to the European Union Flood Directive 2007/60/EC and the respective Greek legislation.
- **Flood risk management methodological framework for lakes and adjacent areas :**
  - The single event-based deterministic approach is adopted, based on three modelling components:
    1. a synthetic storm generator/estimator;
    2. a hydrological simulation model; and
    3. a hydraulic simulation model.
- Basic assumptions: The flood hazard is connected to the determination of the input rainfall return period.
- Results: Flood hazard maps (for T = 50, 100, 1000 years) corresponding to the “average” hydrological scenario as well as two “extreme” scenarios, which allow providing lower and upper uncertainty bounds of the estimated flood quantities for each return period of interest. The proposed framework is described in the next paragraphs.

Synthetic Design Storm Estimator

- Basic assumption : Flood risk is determined in terms of return period, T, of the design rainfall (hyetograph).
- Several rainfall scenarios investigated, setting D = 24 h (which is about five times larger than the time of concentration of the basin) and Δt = 15 min.
- Semi-distributed approach - Spatially-varying rainfall inputs across sub-basins, thus accounting for the heterogeneity of the storm regime over the study basin, which is due to climatic reasons as well as relief and orography effects.
  - The computational procedure for extracting design hyetographs across sub-basins comprised three steps:
    a) estimation of partial rainfall depths for all temporal scales and return periods of interest, on the basis of spatially-averaged Intensity Duration Frequency (IDF) curves relationships;
    b) derivation of a synthetic hyetograph, by placing the partial depths at specific time intervals across the given duration (i.e., 24 h); and
    c) application of an empirical reduction formula, to transform point to areal estimations.
- The IDF relationships could be described by the following equation, proposed by (Koutsoyiannis et al., 1998):

$$i(d, T) = \lambda' \, (T^{\kappa} - \psi') \, / \, (1 + d/\vartheta)^{\eta}$$

where λ', ψ', κ, ϑ and η are parameters that were estimated using a stepwise approach (Monte Carlo approach, Tyralis et al., 2013).

Hydrological Modelling

- For each return period of interest (***T* = 50, 100, 1000 years**), three scenarios (herein referred to as **low, average and high**) have been formulated, in order to account for joint rainfall and hydrological uncertainties. Specifically, the design rainfall estimation provided by the IDF relationship is assumed to correspond to the average scenario (or median 50%), while its 80% confidence limits, which are measure of rainfall uncertainty, correspond to the two extreme scenarios (e.g. low-20% and high-80%) (Efstratiadis et al., 2014). The design hyetorgraphs have been produces by IDF curves using the Alternating Block Method (ABM) for return periods of T=50 and 100 years, and the method of Worst Case Design Storm (WCDS) for the return period of T=1000 years.
- **Hydrological uncertainty** has been expressed in terms of **three typical antecedent soil moisture conditions (dry, moderate, wet**). SCS-CN approach (SCS, 1972) used for the estimation of excess rainfall.
  - Antecedent soil moisture conditions:
    a) the dry (or **low**) represented by **CNI**,
    b) the moderate (or **average**) represented by **CNII**,
    c) and the wet (or **high**) represented by **CNIII**. and transformation of the hyetograph to flood runoff.
- The transformation of the excess rainfall over the basin to flood hydrograph at the outlet junction is made by using the dimensionless curvilinear unit hydrograph approach of SCS of the HEC-HMS modelling system.

Hydraulic-Hydrodynamic Modelling

- Under complex and composite flow conditions and wide flood plains, a 2D-modelling approach is generally suggested due to the provision of more accurate or realistic results (Papaioannou et al., 2016). Therefore, the two dimensional (2D) HEC-RAS model is used for the hydraulic/hydrodynamic flow simulation and flood routing within streams/rivers and lakes.
- Digital Elevation Model (DEM) processing (pixel size = 5m) :
  - Digital Surface Models (DSM) that derived from 1:5000 aerial photos was merged
  - Total DSM has been processed to fill/sink the erroneous areas
  - The final DSM has been re-corrected using typical elevation downgrading methods for the DEM generation
- **Roughness coefficient** estimation - **CORINE** land cover data and standard **roughness coefficient tables** (e.g. Dimitriadis et al., 2016)
  - Based on EU Flood Directive guides the “upper” and “lower” boundaries of Manning’s roughness coefficient were estimated, as −50% and +50% of the average Manning’s roughness coefficient values, respectively.
- Hydraulic structures detection through: **a)** Aerial photographs, **b)** A GIS database of the technical works, **c)** Field observations and **d)** Information collected by several authorities.

Hydraulic-Hydrodynamic Modelling

- Flood protection works and the geometry of all hydraulic structures incorporated to the final DEM
- A basic concern in flood inundation modelling of urban and suburban areas is the building representation within the 2D hydraulic-hydrodynamic model
- **Urban and suburban areas flood inundation modelling component:**
  - The main methodologies followed for the representation of the built up areas are:
    - (a) The cells of the mesh that are within a building block area are defined as solid object.
    - (b) The cells of the mesh that are within a building block area are assigned with big elevation values in order to work as a blocked area.
    - (c) The cells of the mesh that are within a building block area are assigned with big roughness coefficient values.
  - Recent studies that investigated the building block representation methods showed that all techniques have disadvantages and advantages and none of them prevail among the others (Bellos and Tsakiris, 2015). Therefore, **the second building block** representation methodology is followed in this study **for large urban areas (cities)** and **the third method for suburban areas and small settlements (villages)** based on the modelling simulation time and the scale (large scale applications) of the proposed framework.

Hydraulic-Hydrodynamic Modelling

- Three (3) hydrologic/hydraulic scenarios have been formulated and simulated for every basin/sub-basin, stream/river reach and lake and every return period, considering uncertainty.
  - **Low scenario** represents the dry antecedent soil moisture conditions (**CNI**), the design synthetic storm is estimated for the 20% confidence level of IDF curves using the ABM for the storm time distribution, and low Manning's roughness coefficient (e.g. $n_{low}=n_{average}-0,5*n_{average}$).
  - **Average scenario** represents average antecedent soil moisture conditions (**CNII**), the design storm is estimated by the median IDF curves (50%) using the ABM for the storm time distribution, and the estimated Manning's roughness coefficient ($n_{average}$) and
  - **High scenario** represents high antecedent soil moisture conditions (**CNIII**), the design storm is estimated for the 80% confidence level of IDF curves using the WCDS for the storm time distribution and high Manning's roughness coefficient (e.g. $n_{high}=n_{average}+0,5*n_{average}$).
- In total, nine (9) scenarios were simulated for the three (3) return periods (e.g. T=50, 100, 1000 years).

Average values of Manning's roughness coefficient based on CORINE land cover data.

LABEL1	LABEL2	LABEL3	Mannings n
1 Artificial surfaces	1.1 Urban fabric	1.1.1 Continuous urban fabric 1.1.2 Discontinuous urban fabric	0.013
	1.2 Industrial, commercial and transport units	1.2.1 Industrial or commercial units 1.2.2 Road and rail networks and associated land 1.2.3 Port areas 1.2.4 Airports	0.013
	1.3 Mine, dump and construction sites	1.3.1 Mineral extraction sites 1.3.2 Dump sites 1.3.3 Construction sites	0.013
	1.4 Artificial, non-agricultural vegetated areas	1.4.1 Green urban areas 1.4.2 Sport and leisure facilities	0.025
2 Agricultural areas	2.1 Arable land	2.1.1 Non-irrigated arable land 2.1.2 Permanently irrigated land 2.1.3 Rice fields	0.03
	2.2 Permanent crops	2.2.1 Vineyards 2.2.2 Fruit trees and berry plantations 2.2.3 Olive groves	0.08
	2.3 Pastures	2.3.1 Pastures	0.035
	2.4 Heterogeneous agricultural areas	2.4.1 Annual crops associated with permanent crops	0.04
		2.4.2 Complex cultivation patterns	0.04
		2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation	0.05
		2.4.4 Agro-forestry areas	0.06
3 Forest and semi natural areas	3.1 Forests	3.1.1 Broad-leaved forest 3.1.2 Coniferous forest 3.1.3 Mixed forest	0.1
	3.2 Scrub and/or herbaceous vegetation associations	3.2.1 Natural grasslands	0.04
		3.2.2 Moors and heathland	0.05
		3.2.3 Sclerophyllous vegetation	0.05
		3.2.4 Transitional woodland-shrub	0.06
	3.3 Open spaces with little or no vegetation	3.3.1 Beaches, dunes, sands	0.025
		3.3.2 Bare rocks	0.035
		3.3.3 Sparsely vegetated areas	0.027
		3.3.4 Burnt areas	0.025
		3.3.5 Glaciers and perpetual snow	0.01
4 Wetlands	4.1 Inland wetlands	4.1.1 Inland marshes 4.1.2 Peat bogs	0.04
	4.2 Maritime wetlands	4.2.1 Salt marshes 4.2.2 Salines 4.2.3 Intertidal flats	0.04
5 Water bodies	5.1 Inland waters	5.1.1 Water courses 5.1.2 Water bodies	0.05
	5.2 Marine waters	5.2.1 Coastal lagoons 5.2.2 Estuaries 5.2.3 Sea and ocean	0.07

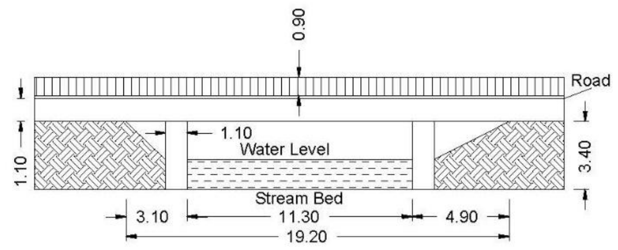
Ground Survey of hydraulic structure BR_50 at Stravia stream

Hydraulic Structure	Bridges
Description: Bridge (BR)	
Structure Code: BR_50	
Area: GR05_ GR0514FR2001	
Stream: Stravia	
Topographical Survey Date: 17/06/2016 Team: ..	

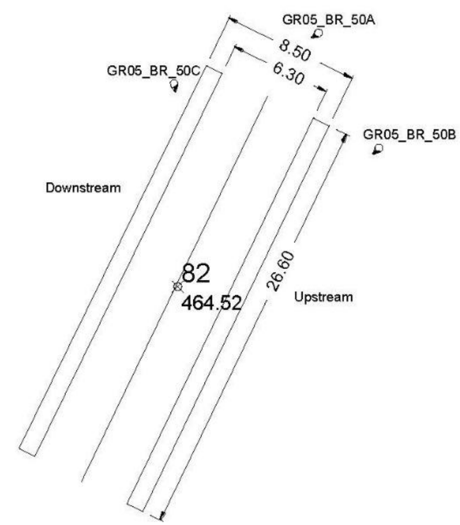
Coordinates (Greek Grid)		Point
X	221653.991	82
Y	4405762.885	
Z	464.520	

Hydraulic Structure Description	
Type	Box
Material	Reinforced Concrete
Dimensions (LxW)	26,60 x 8,50
Total Water Flow Width	**Upstream:** 19.20 **Downstream:** 19.20
Stream bed elevation	460
Distance between Road deck and stream bed	4.50
Type of flow	**steady / ~~unsteady~~**
Obstacles in water flow:	**YES / ~~NO~~** Piers 2 x 1.10 x 3.40
Road Type: Asphalt	**Road Width: 6.30**
	Road Elevation: 464.5
Deck height: 1.10	
Photographs: GR05_BR_50A, GR05_BR_50b, GR05_BR_50C	

Face



Floor Pan



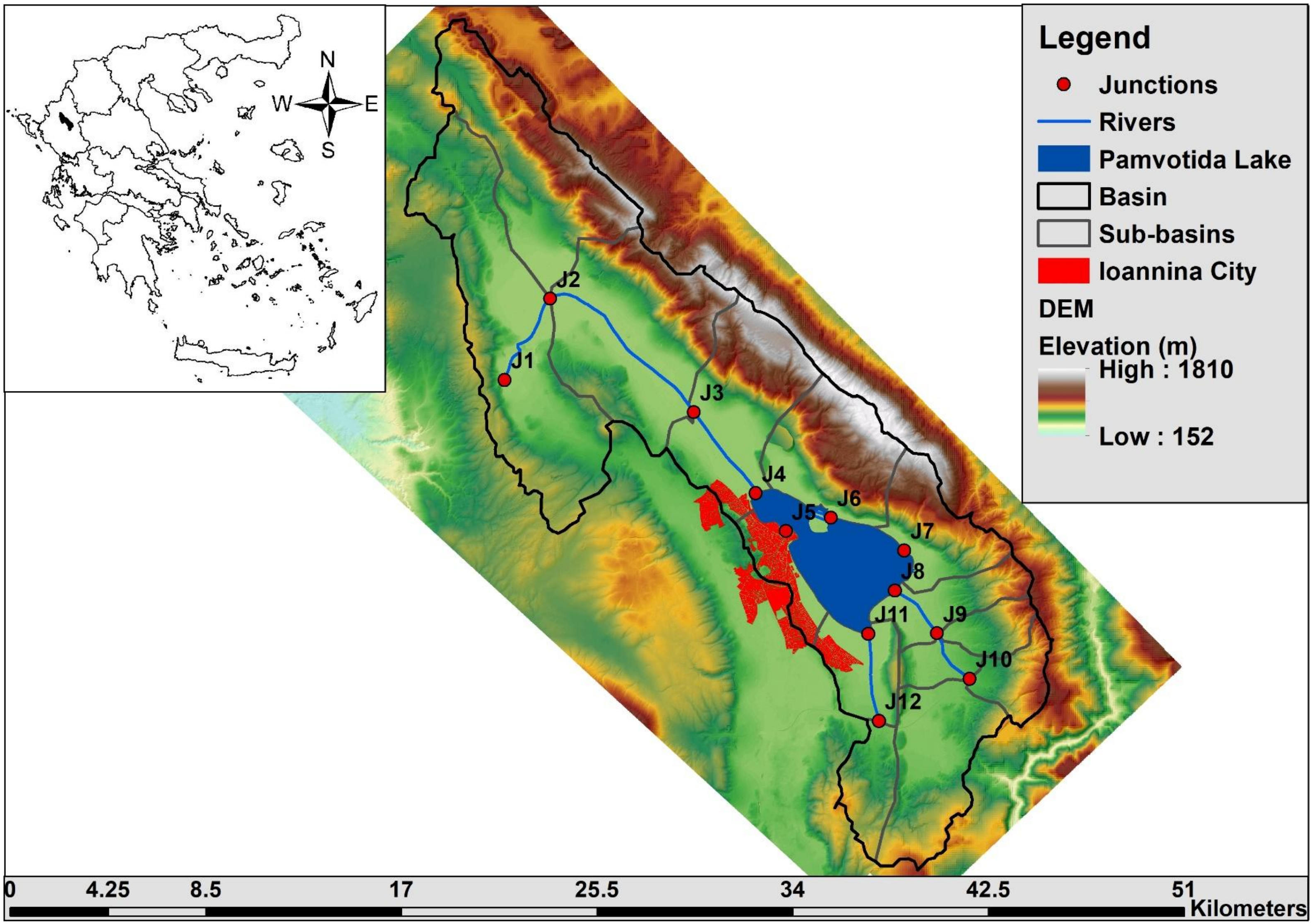
Photographs of hydraulic structure BR_50 at Stravia stream

GR05_BR_50_A  P121521	GR05_BR_50_B  P121626
GR05_BR_50_C  P121847	

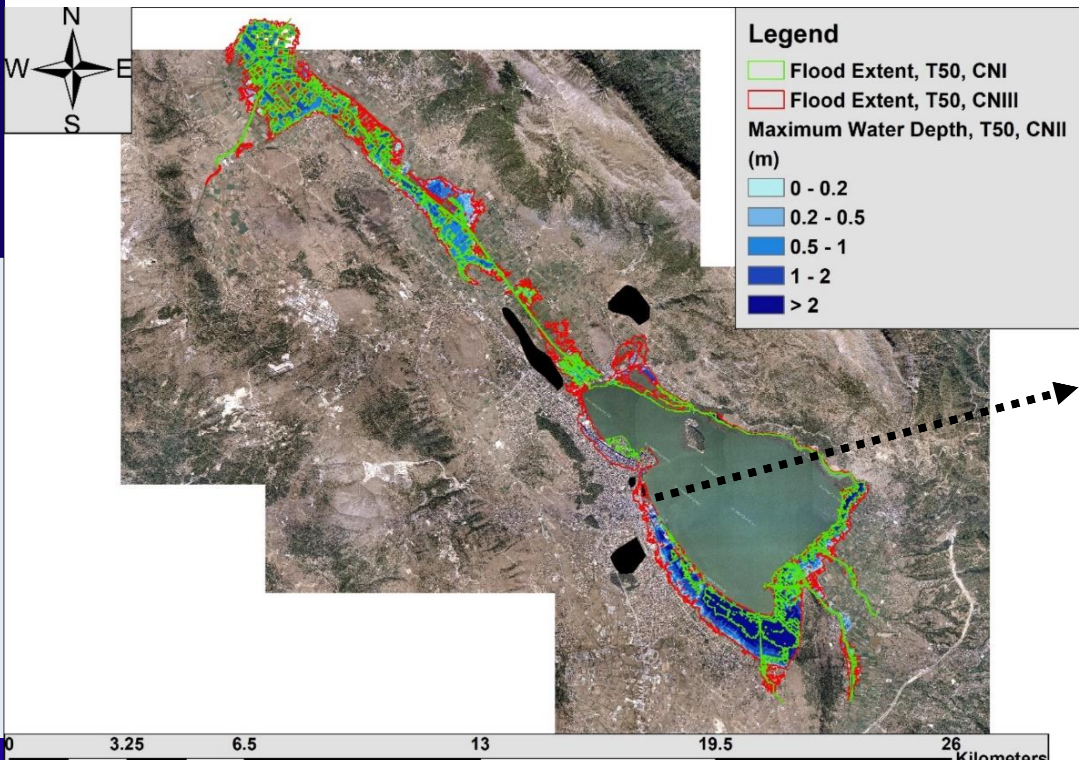
Methodology application: The Lake Pamvotida Paradigm

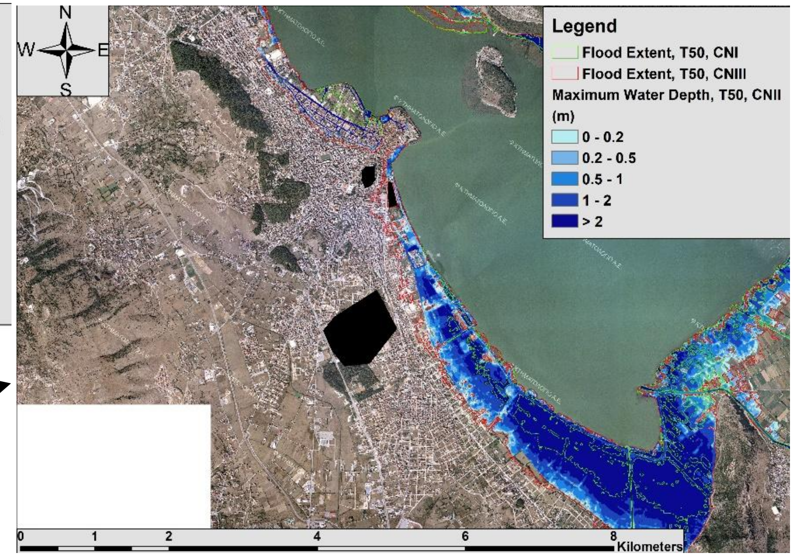
- The hydrological and hydraulic model of the basin consists of
  - 15 sub-basins,
  - 13 flow nodes, and
  - 11 stream reaches.
- Basin is division :
  - the upstream sub-system consists of 10 sub-basins, which drain into the Lake Pamvotida.
  - The downstream sub-system is divided into four (4) sub-basins (to the Northwest; Fig. 1).
- The lake has five inflow nodes (i.e. J5, J6, J7, J8, J11) and it is modelled as an independent sub-basin (GR0514FL2009) and its runoff is concentrated in the node J4.
- When the stage of the lake increase above a certain threshold, a part of the stored volume overflows to the lower sub-system, which begins from node J4 and ends to node J1 and then it is diverted to the Kalama River basin through a canal.
- In total, eight (8) stream reaches with total length of 46.7 km are located in the potential flood hazard zone and they have simulated for the routing of flood hydrographs and the estimation of flood hazard.

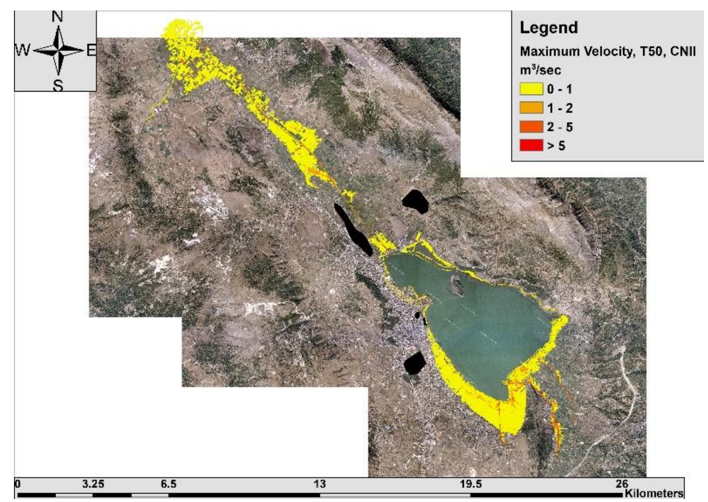
Study Area: The Lake Pamvotida Paradigm



Pamvotida watershed: Hydraulic modelling results

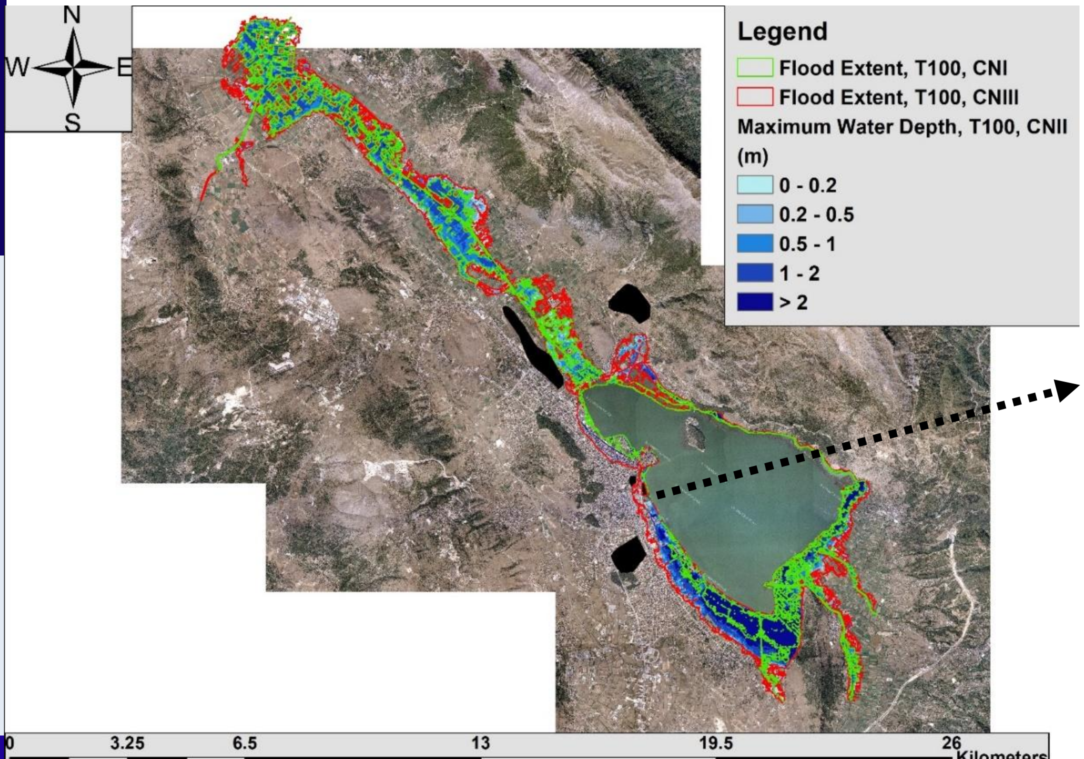


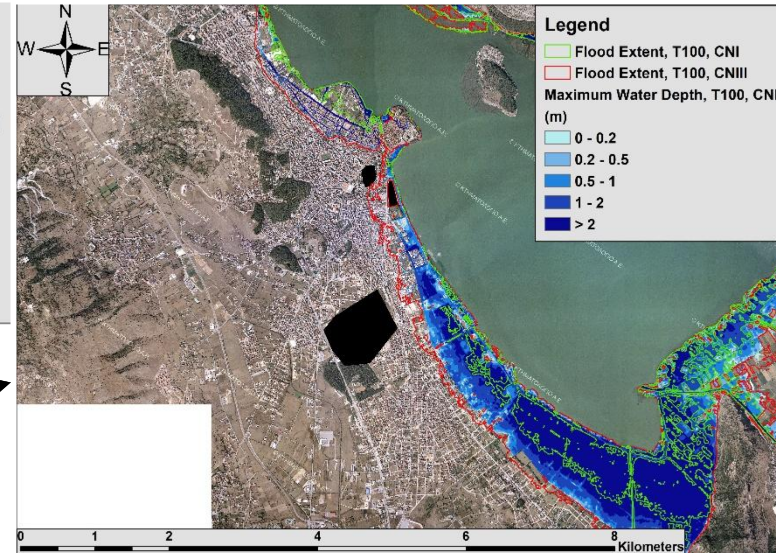




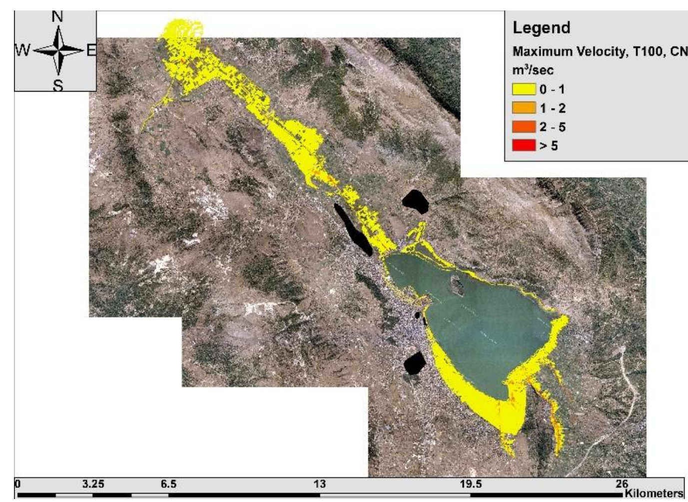
Flood extent and water depths of return period T = 50 years for all configurations of input rainfall, soil moisture conditions and roughness coefficients (up) and simulated velocities (down) only for average moisture conditions (CNII)

Pamvotida watershed: Hydraulic modelling results

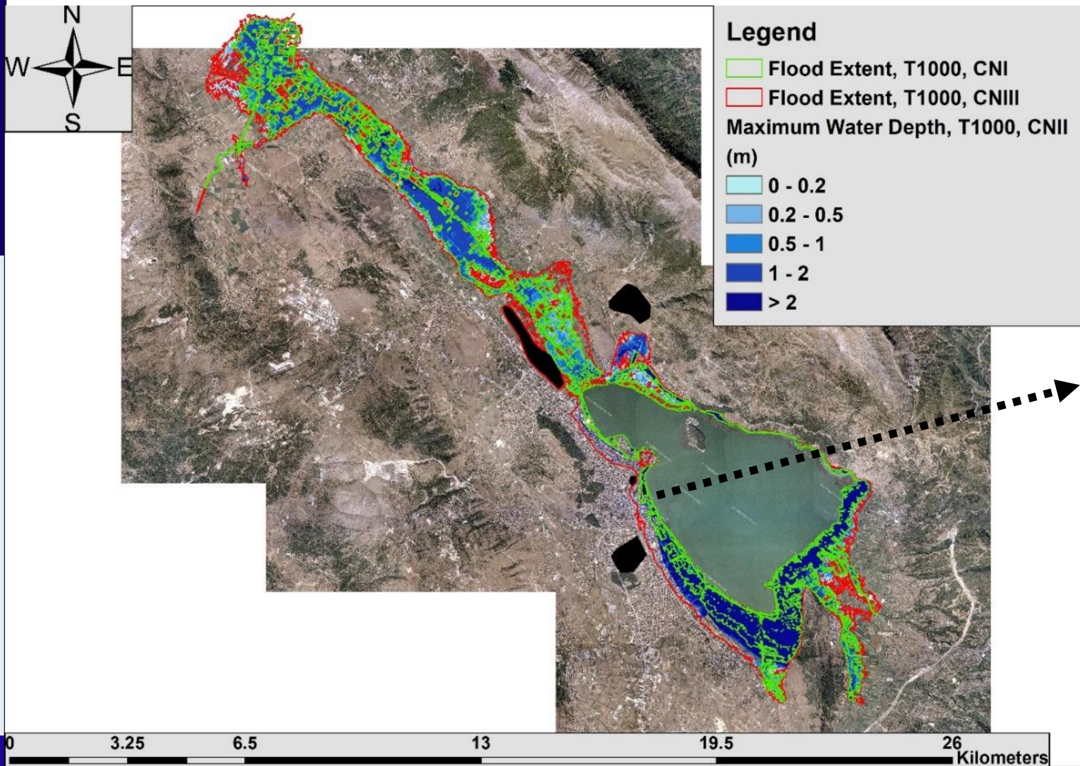


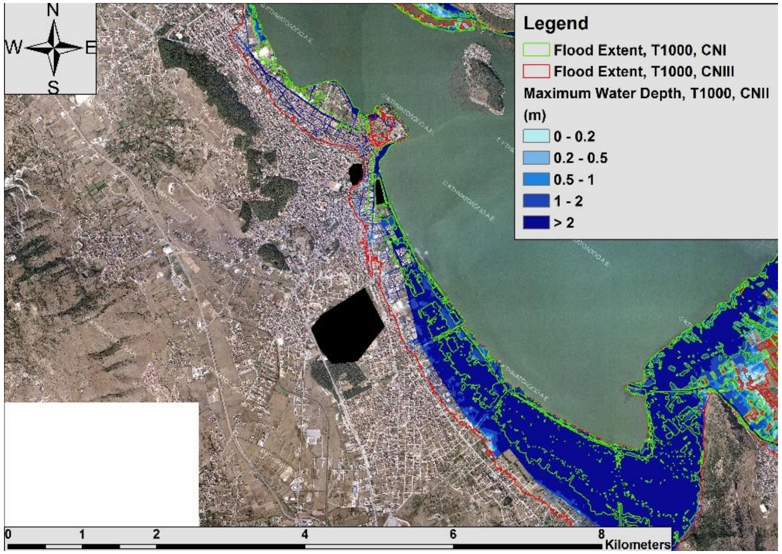


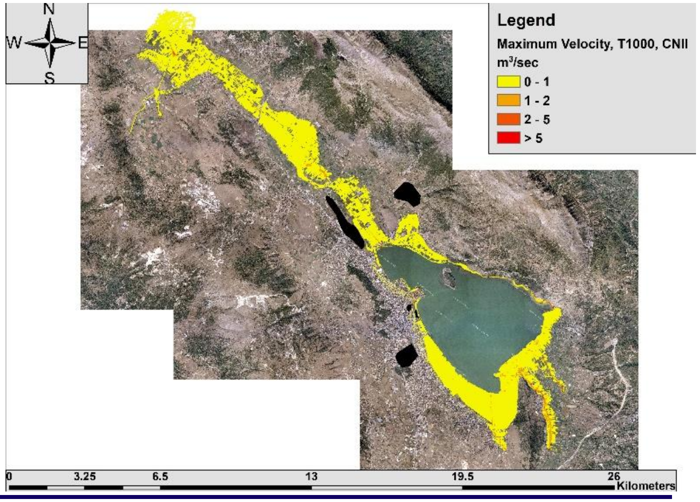
Flood extent and water depths of return period T = 100 years for all configurations of input rainfall, soil moisture conditions and roughness coefficients (up) and simulated velocities (down) only for average moisture conditions (CNII)



Pamvotida watershed: Hydraulic modelling results







Flood extent and water depths of return period T = 1000 years for all configurations of input rainfall, soil moisture conditions and roughness coefficients (up) and simulated velocities (down) only for average moisture conditions (CNII)

Pamvotida watershed: Hydraulic modelling results

Total inundated area (km²) of Lake Pamvotida basin for all examined hydrologic and hydraulic scenarios at the selected return periods.

Basin	Hydrologic/Hydraulic Scenario	Return Period (years)		
		50	**100**	**1000**
Lake Pamvotida	**Low**	7.89	11.47	18.17
	Average	16.34	20.06	26.69
	High	19.56	24.42	34

Pamvotida watershed: Hydraulic modelling results

- The two methodologies, outlined before, for rural and not significant settlements and for significant urban areas (e.g. Ioannina City) have been applied in the hydraulic simulations.
- The results indicate that the inundated area increases with the return period of the event and the depth of water is more sensitive than the water velocity.
- Results are quite **diverse**, since the uncertainty bounds of all key flood quantities (peak flows, flood volumes, inundated areas, etc.) strongly overlap the risk expressed in terms of return period of rainfall.
- **Special attention** should be given to the developed methodology and its application only for specific return periods and hydrologic-hydraulic conditions due to the great variability in the peak discharge estimation.
- An **ensemble of methods and scenarios** should always be applied for **engineering purposes**, in order to choose the most appropriate technique in relation to the flood prone areas and proposed flood protection measures.

Conclusions

- In this study, a methodological approach for implementing the EU Floods Directive 2007/60/EC in Greece is developed, emphasized for flood risk management in rural, urban and suburban areas, which is demonstrated for the Lake Pamvotida basin.
- The methodology is based on typical hydrological and flood inundation modelling and mapping techniques for ungauged catchments. Spatially-distributed design hyetographs are applied for hydrologic and hydraulic 2D modelling of floods taking into account parametric and structural uncertainty.
- According to the flood extent values, it seems that the uncertainty induced in hydrological modeling, with respect to extreme rainfall estimation and antecedent soil moisture conditions, dominates against the return period.
- It should be emphasized that these two components are not the sole sources of uncertainty within rainfall-runoff transformations. This makes it essential to move to more rigorous methodological approaches (e.g. stochastic), instead of quantifying the flood risk on the basis of the return period of rainfall.

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THANK YOU FOR YOUR ATTENTION!