URBAN WATER MANAGEMENT AND HYDROINFORMATICS GROUP

Outlining a master plan framework for the design and assessment of flood mitigation infrastructures across large-scale watersheds

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Introduction: describing the problem

The area of interest: **Western Thessaly region**

- Damages and losses induced by the **Medicane Ianos** over the greater Thessaly region.
- Need for **developing a Master Plan** for the West Thessaly flood protection.

The final area of interest occupies approximately **6400 km^2**, thus:

- A **mega-scale** hydrological, hydraulic and water management study.
- Poses multiple **conceptual** and **computational** challenges.

Which is the goal of the study?

1. Provide a synthesis of **already proposed** as well as **new** projects (dams, embankments, ditches).
2. **Prioritize them** under a **multipurpose** prism.

Structure of the presentation

- Description of the **methodological framework**.
- Final planning → **Strengthen the flood protection** of the area.
- Combine **large-scale projects** (dikes, multi-purpose dams) and **retention basins** (temporary reservoirs).

Part A: Methodological framework →

- **Preliminary assessment** of specific areas where high risk is expected due to flood phenomena
- Semi-distributed **representation of the rainfall-runoff transformations** and the flood routing processes
- **Coupled 1D/2D hydrodynamic simulation** of the flood prone riverine system

Part B: Technical works utilized or proposed →

- **Large-scale projects**, i.e., dikes, multi-purpose dams (permanent reservoirs)
- **Retention basins of controlled inundation** (temporary reservoirs)

Objective →

Sketch a framework for facing similar studies in a **holistic manner** - Maintain a high level of **computational efficiency** and explainability

PART A:

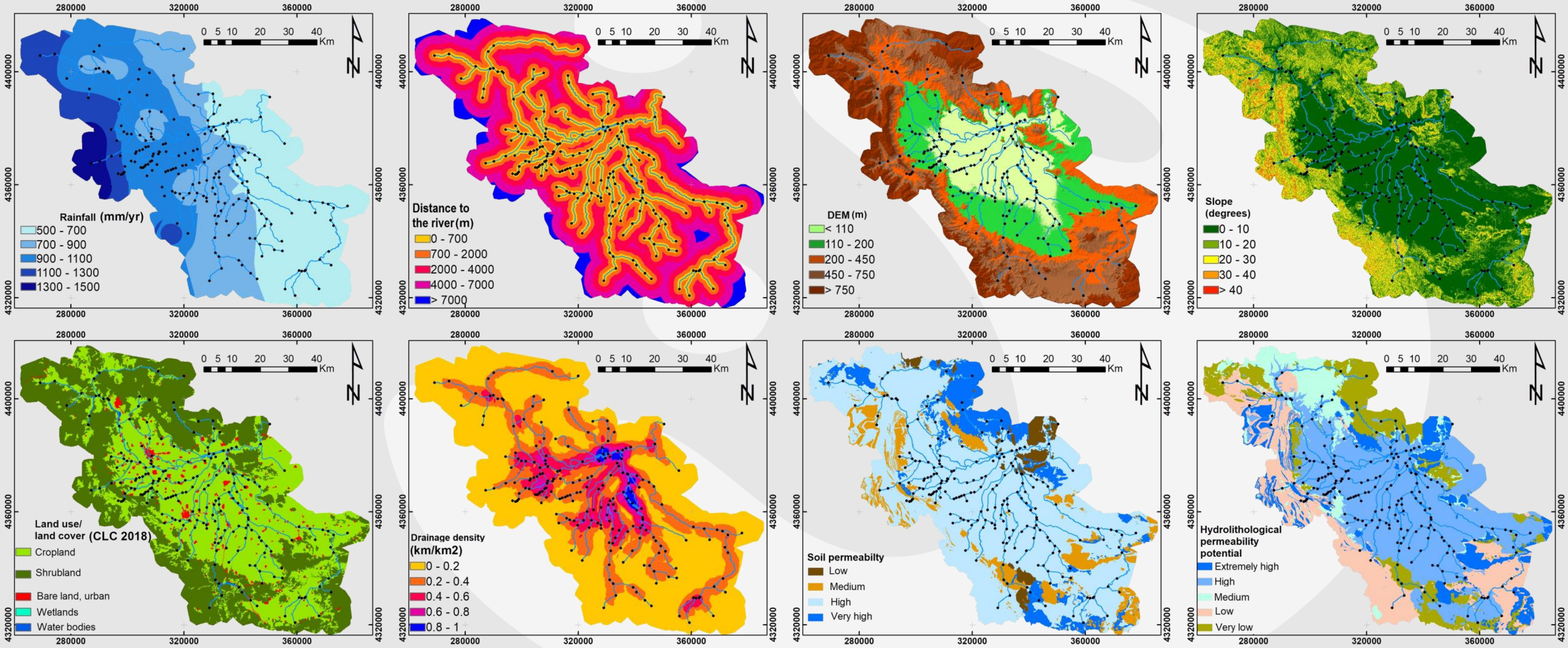
Methodological framework

Preliminary assessment of specific areas where high flood risk is expected (1/3)

- Simple geospatial criteria were utilized, following Allafta and Opp (2021) and Theochari et al. (2021).
- Eight thematic layers were compiled:
  1. mean annual rainfall
  2. distance from river network
  3. elevation
  4. terrain slope
  5. land use/land cover
  6. drainage network density
  7. soil permeability
  8. hydrolithology
- The information of these layers is “translated” into **flood susceptibility scores**, from **1 (very low) to 5 (very high)**
- We produce an overall flood susceptibility map, as a weighted overlay of individual layers

Parameter (Unit)	Class	Parameter Weight	Class Rank
Rainfall (mm/year)	500-700 700-900 900-1100 1100-1300 1300-1500	19.57%	1 2 3 4 5
Distance to the river (m)	0-700 700-2000 2000-4000 4000-7000 > 7000	16.06%	1 2 3 4 5
DEM (m)	< 110 110-200 200-450 450-750 > 750	14.20%	1 2 3 4 5
Slope (degrees)	0-10 10-20 20-30 30-40 > 40	13.99%	1 2 3 4 5
Land use/land cover	- Shrubland - Cropland - Bare land, Urban - Wetlands - Water bodies	11.07%	1 2 to 3 4 5 5
Drainage density (km/km^2)	0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1	10.57%	1 2 3 4 5
Soil permeabilty	-Very high -High -Medium -Low	8.89%	1.25 2.5 3.75 5
Hydrolithological permeability potential	-Extremely high -High -Medium -Low -Very low	5.65%	1.25 2.5 4 4 5

Preliminary assessment of specific areas where high flood risk is expected (2/3)



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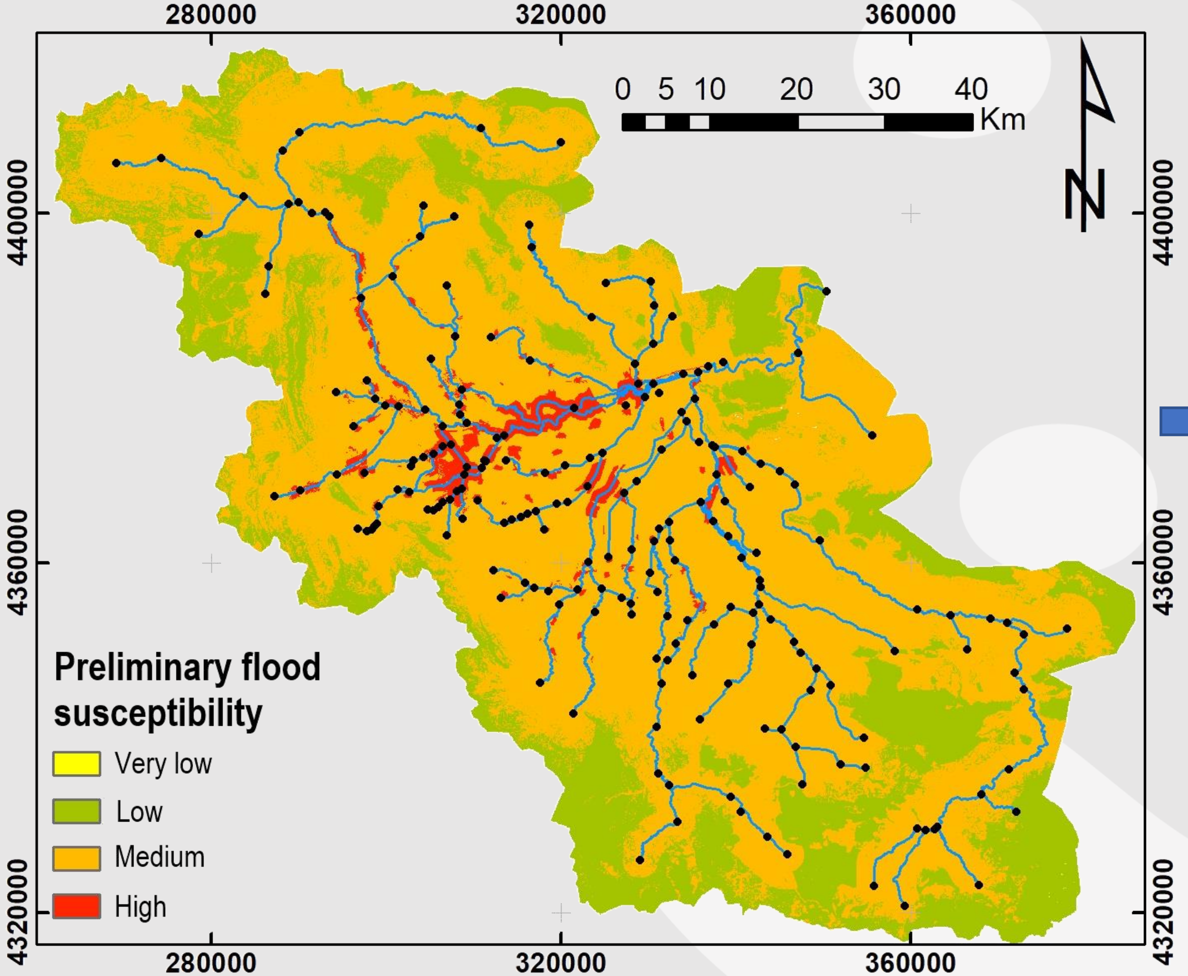
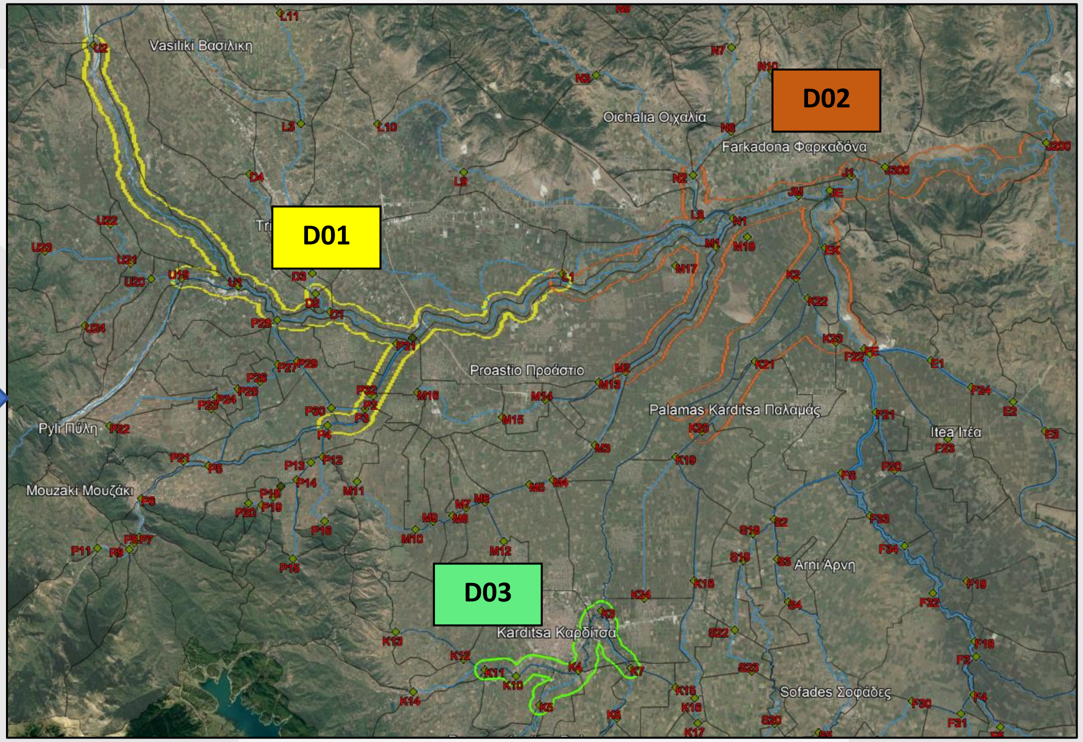
Preliminary assessment of specific areas where high flood risk is expected (3/3)

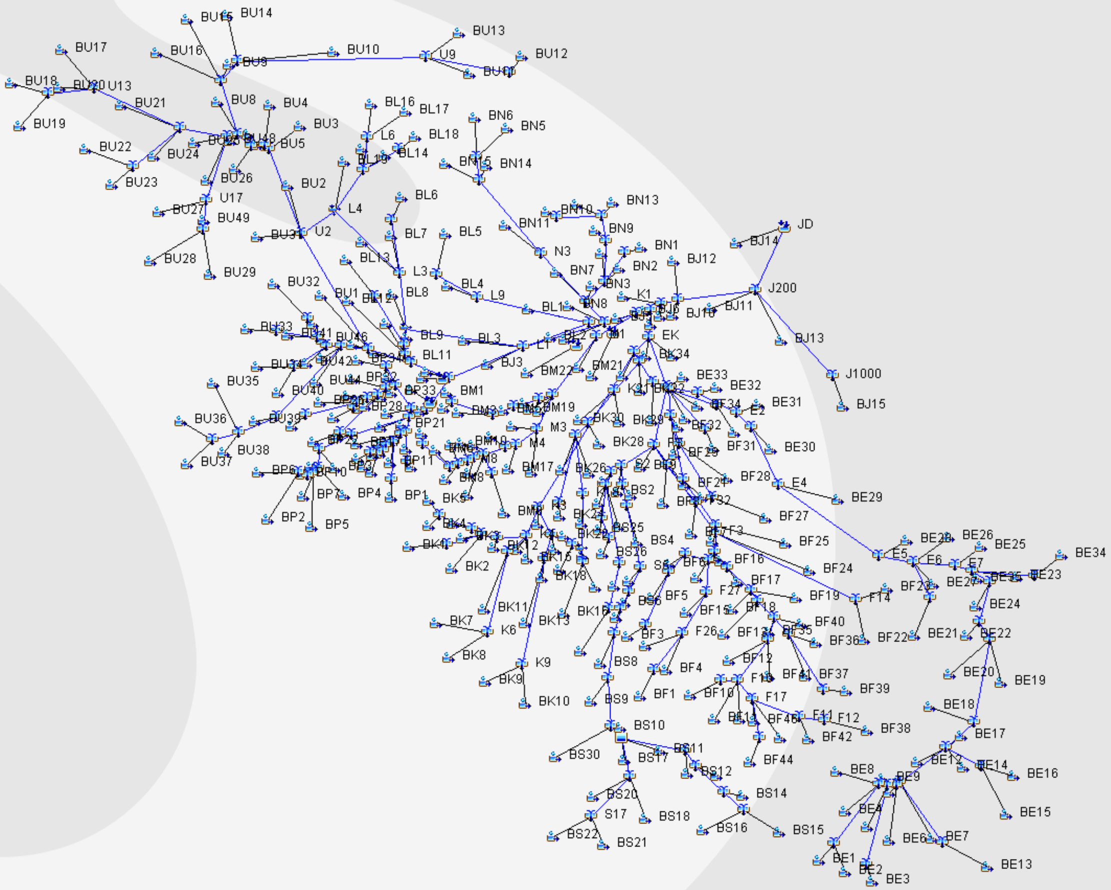




1. Based on the flood susceptibility map, **three domains were chosen** to be analyzed in hydrodynamic simulations.
2. A **coupled 1D/2D model** is set up for each domain.

Representation of the rainfall-runoff simulation (1/3)

- **Goal of the simulation:** produce design flood hydrographs to drive the hydrodynamic analysis.
  1. **Semi-distributed discretization** of the hydrological system.
  2. **A network-type model** consisting of nodes, stream/river branches, and sub-basins (212 nodes, 210 branches and 306 sub-basins).
- **Event-based approach**, following the combined NRCS-CN and synthetic unit hydrograph (SUH) methods.
  1. **NRCS-CN:** transformation of the design storm event over each sub-basin into flood runoff.
  2. **SUH:** routing to the corresponding outlet node.
- The point hydrographs through all sub-basins are **synthesized** and propagated along the hydrographic network by applying **a novel conceptual approach.**



Model implemented in HEC-HMS environment

Representation of the rainfall-runoff simulation (2/3)

- **Routing →** linear kinematic wave method for **steep (>1%)** channel slopes and the wave-diffusion Muskingum method for **mild** ones.
- Their common input → **a characteristic time parameter, K: the average travel time between the upstream and downstream junctions at the associated reach element.**
- The estimation of parameter K across the stream network is based on a **pseudo-hydraulic kinematic approach** (Efstratiadis et al., 2022):

$$V_i = \frac{1}{n_i} R_i^{2/3} J_i^{1/2} \qquad R_i^{2/3} = c$$

$$t_c - t_u = \frac{L_1}{V_1} + \frac{L_2}{V_2} + \ldots + \frac{L_N}{V_N}.$$

time of concentration of the entire catchment

time of concentration of the most upstream sub-basin

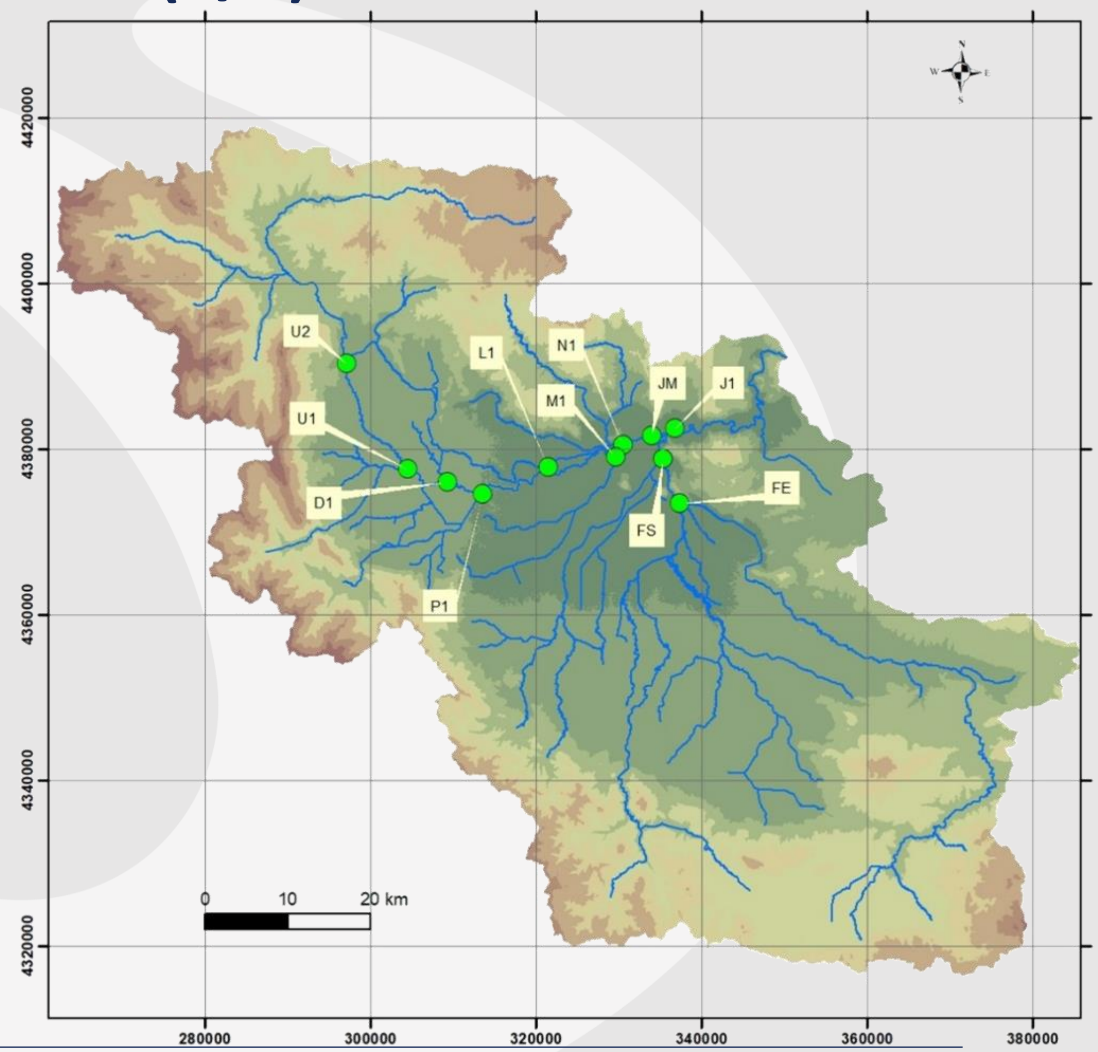
$$c = \frac{1}{t_c - t_u}\left(\frac{n_1 L_1}{J_1^{1/2}} + \frac{n_2 L_2}{J_2^{1/2}} + \ldots + \frac{n_N L_N}{J_N^{1/2}}\right) = \frac{\beta}{t_c - t_u}$$

- After determining **c** for each rainfall scenario, we estimate the **mean velocity at each reach element** of the stream network and the corresponding travel time, ***Li/V* → K**

Representation of the rainfall-runoff simulation (3/3)

- Through **the HEC-HMS simulations** we produce the **design hydrographs** at **key-junctions** of the system →

  Drivers of the hydrodynamic models (coupled 1D-2D).
- The hydrographs are acting as **upstream** and **internal** boundary conditions (**BC**s) of the hydrodynamic models.
- Automated **procedures** and **interfaces** of **HMS** and **RAS** with the data processing system **HEC-DSS** are developed in R environment.
- All the produced hydrographs are stored in **HEC-DSS database files**.



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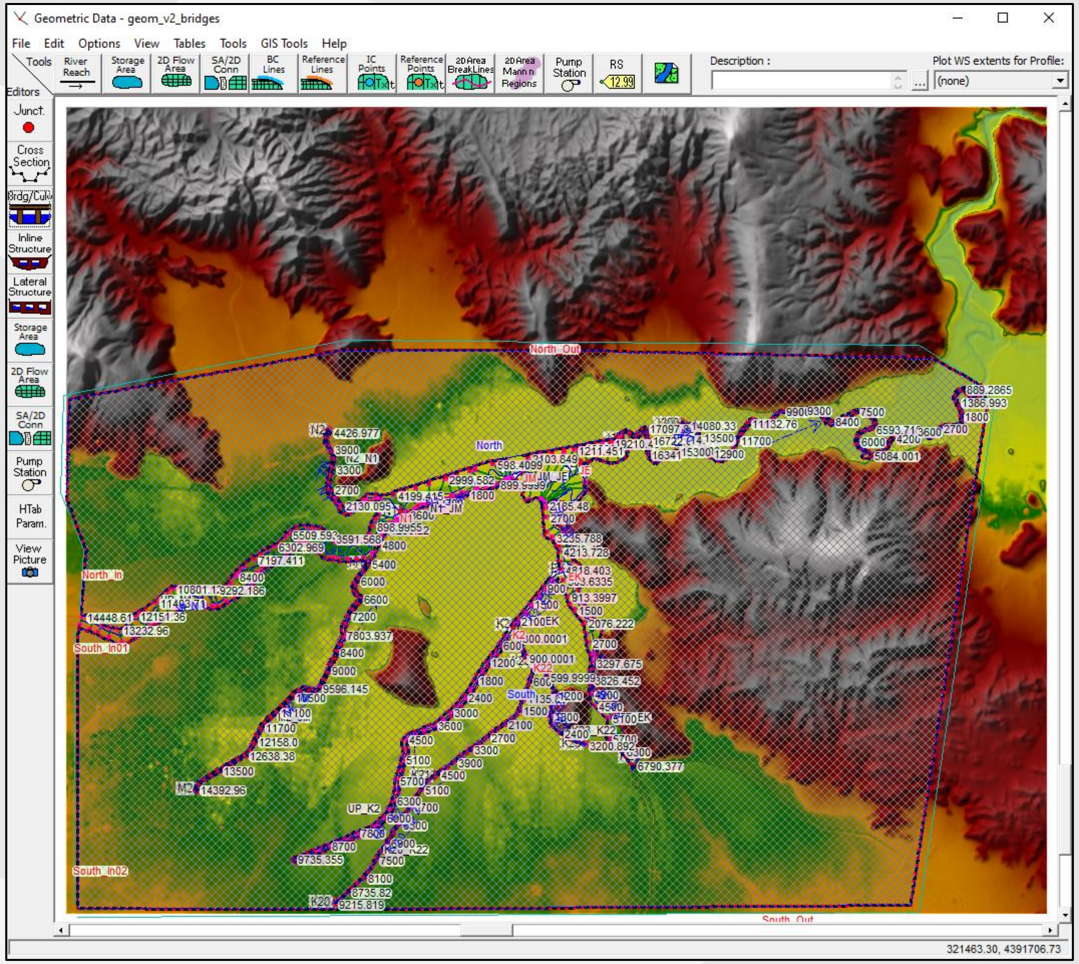
Hydrodynamic simulation of the riverine system (1/2)

- **Coupled 1D-2D** simulations in HEC-RAS.
- Why to choose this type of simulation?
  1. Get the best out of **both** worlds: fast **1D computations** where the flow direction is known beforehand (inside the river banks). **2D computations** in the floodplains where the water path is not known.
  2. **Disclose the water transfer dynamics** between the main river and the floodplains. Allow water to exit and re-enter the riverine system by utilizing **lateral structures in HEC-RAS,** i.e. lateral weirs that control the flow by applying the standard weir equation $Q = C \cdot L \cdot H^{3/2}$



D02 region computational domain

Hydrodynamic simulation of the riverine system (2/2)

Model parameters:

1. **Computational time step,** *Δt* = 10 s
2. **Distance between cross sections (1D domain discretization)**: Δx = 50, 100, 150, 200 or 300 m
3. **2D area computational grid spacing (2D domain discretization):** 50m x 50m or 100m x 100m (Should be proportional to the 1D spacing)
4. **2D flow equations:** diffusion wave approximation
   - Very Stable Computationally.
   - Can handle larger time step Courant C > 2 (C = 5 max).
   - Good for computing rough global estimates, such as flood extent.
5. **Mixed flow regime activated in the 1D domain.**
   - Modeling mixed flow regime (subcritical, supercritical, hydraulic jumps, and draw downs) is quite complex with an unsteady flow model. Most **unsteady flow solution algorithms** become unstable when the flow passes through critical depth.
   - Local Partial Inertia (LPI) Technique. Reduction factor to the two inertia terms in momentum equation.

PART B:

Assessment of the utilized flood protection works

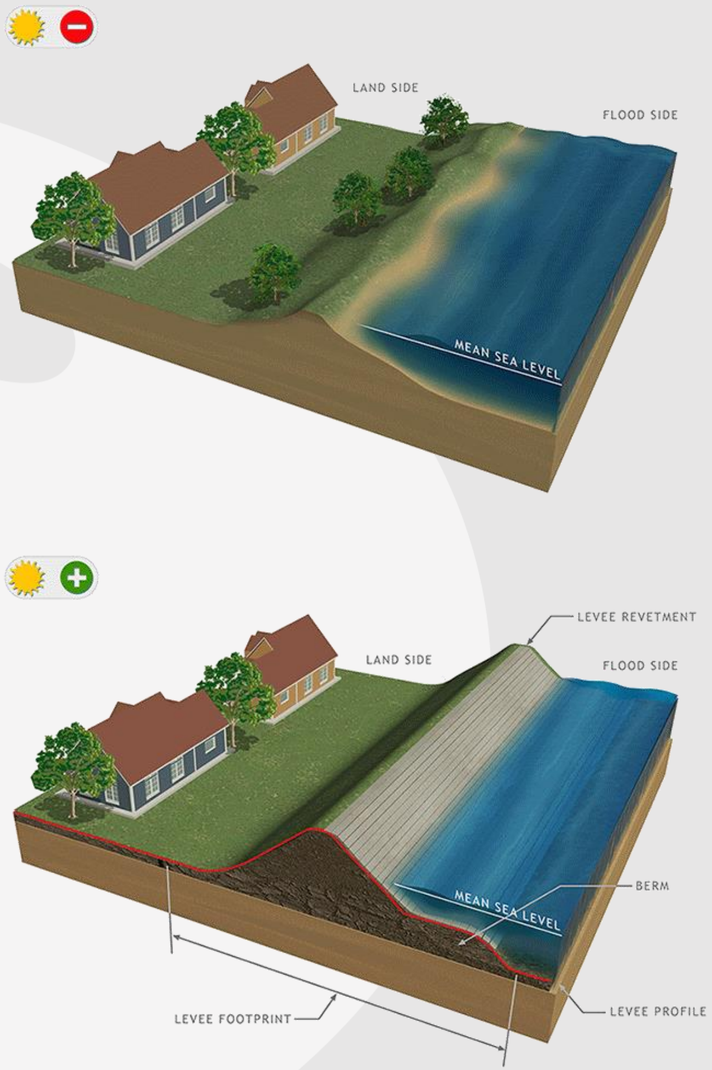
General outline of the proposed works (1/2)

Development of three types of flood mitigation works:

1. **dikes**, along parts of the **lower channel network**
2. **six new** multi-purpose **reservoirs** in **the upstream, mountainous, parts** of the watershed
3. **nine retention basins** in the **middle and downstream** parts (390 km^2 of agrarian land)

Reservoirs

Retention basins



Dikes

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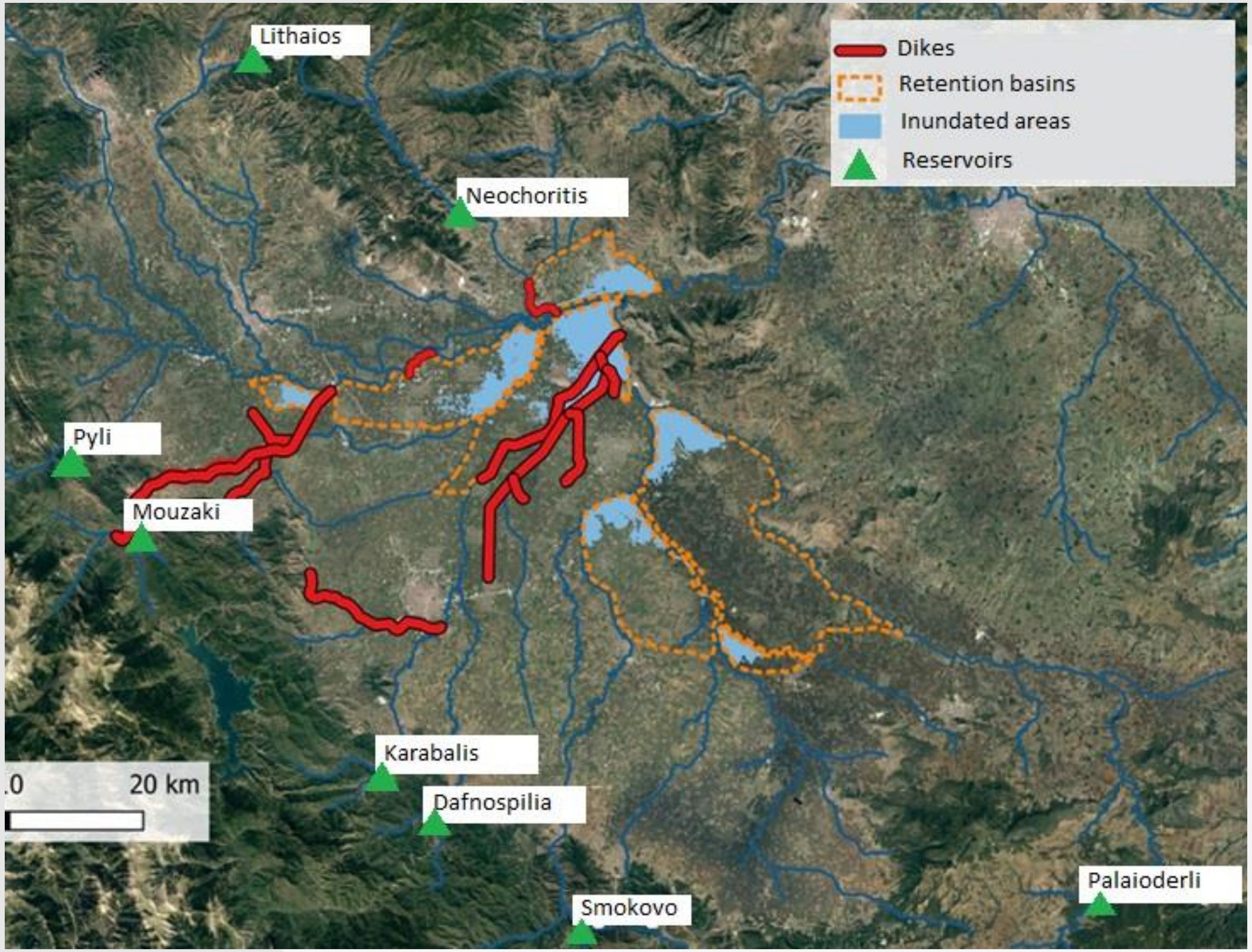
General outline of the proposed works (2/2)



Effect of reservoirs

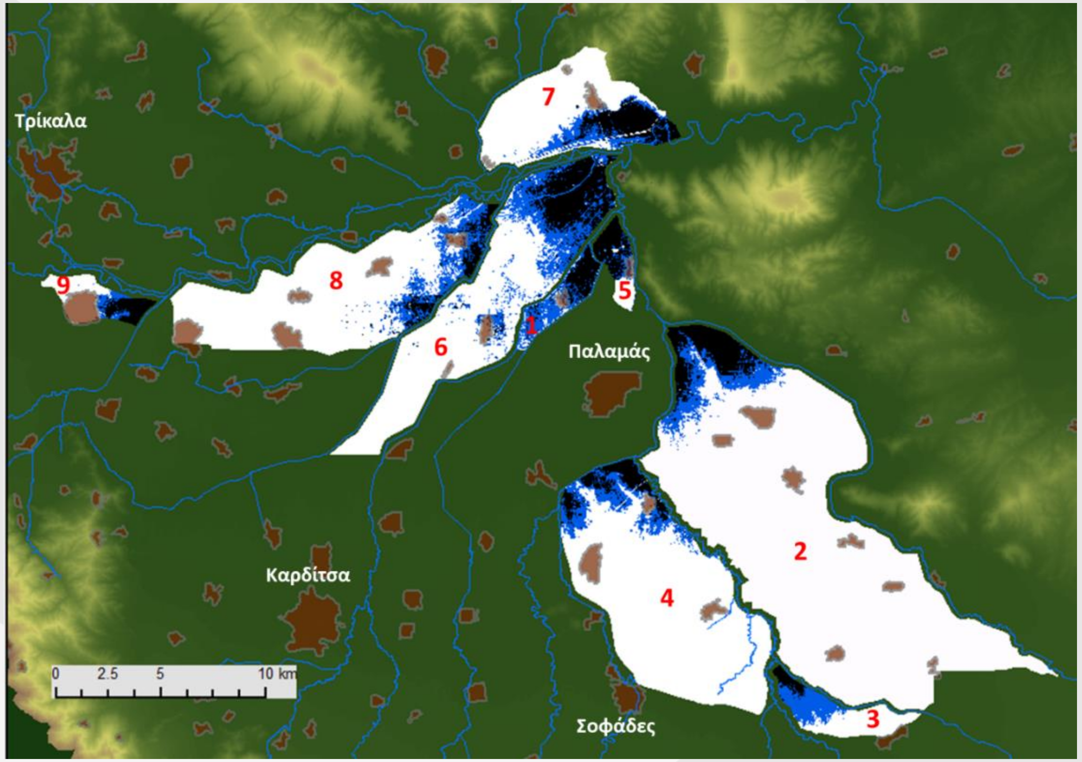
- We examine design storms of a return period ***T= 100 years***
- ***We examine two scenarios:***
  1. **A full reservoir** in the beginning of the simulation**.**
  2. **A semi-full reservoir:** A capacity **(~15%** of the total capacity) is left empty to accommodate the flood volume
- The reservoirs **can store 65 out of 150 hm^3 produced in their upstream sub-basins**, and the larger ones **decrease flood peaks up to 75-95%.**

Reservoir	**Pyli**	**Mouzaki**	**Lithaios**	**Karabalis**	**Dafnospilia**	**Neochoritis**	**Smokovo**	**Palaioderli**
Inflow peak (m^3/s)	839.6	788.1	47.8	261.4	268.7	467.9	759.7	908.6
Outflow peak – full reservoir (m^3/s)	599.6	292.3	38.5	137.4	264.7	337.7	72.9	441.6
Percentage of decrease (%)	29	63	19	47	1	28	90	51
Outflow peak – semi-full reservoir (m^3/s)	474.7	124.5	34.8	86.5	264.7	240.5	8.0	208.8
Percentage of decrease (%)	43	84	27	67	1	49	99	77

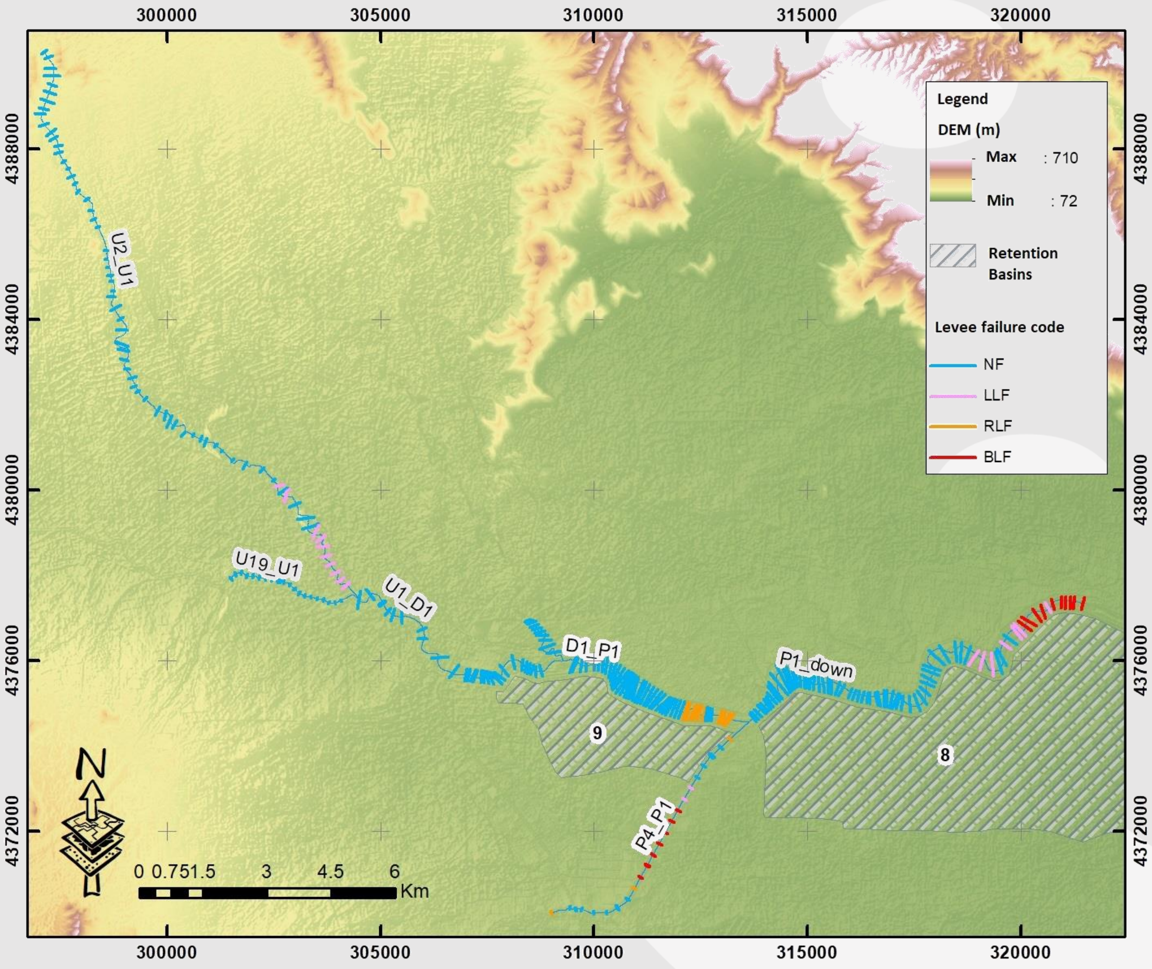
Combined Effect of retention basins and dikes/levees (1/2)

- An important amount of about 56 hm^3 can also be **temporarily retained in the closed basins**, most of which is **diverted from the adjacent channel network**.
- Their performance may also be **further improved** by installing control structures along the dikes (e.g., lateral gates), to better manage the arriving flood flows.

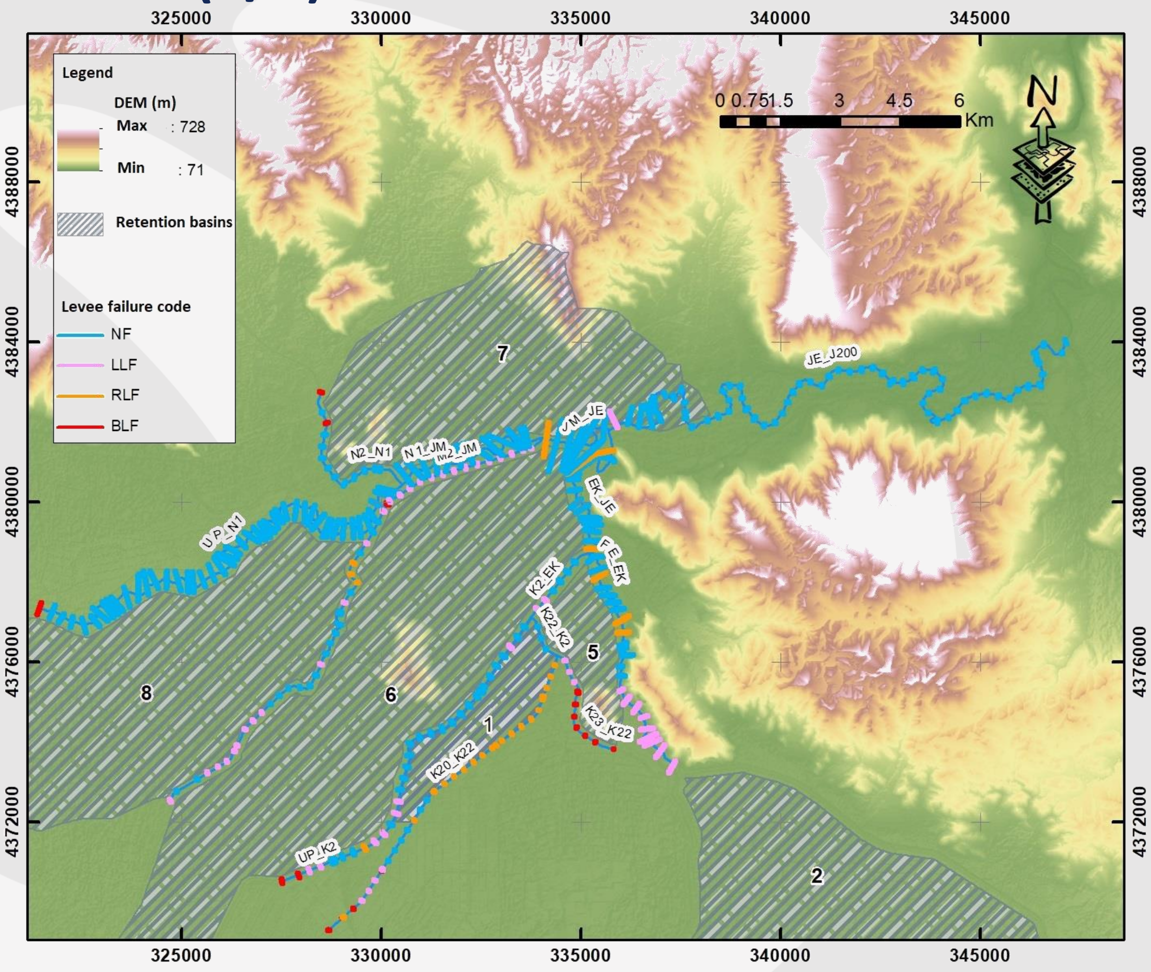
Retention basin	Lateral Structure Codes as modeled in HEC-RAS	Volume overflowing from the channels (hm^3)	Available capacity (hm^3)
1	UP_K2 9735 R, K20_K22 9214 L, K22_K2 899 L	4.0	5.0
2-4	FE_EK 6789 L, FE_EK 6790 R	14.3	20.3
5	K23_K22 3199 R, K23_K22 3200 L, K22_K2 900 R, K2_EK 2098 R	3.9	4.7
6	M2_JM 14392 R, UP_K2 9734 L, K2_EK 2099 L, EK_JE 4818 L, JM_JE 2102 R	6.6	16.2
7	N2_N1 4425 R*, N2_N1 4426 L, M2_JM 14391 L	3.3	10.4
8	P1_down 11459 R, P1_down 11460 L*, M2_JM 14391 L	5.0	4.1
9	P4_P1 7059 L, D1_P1 5297 R	4.7	3.6
Total		**41.9**	**64.3**



Combined Effect of retention basins and dikes/levees (2/2)



D01 region



D02 region

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PART C:

Did we manage to reach our objective ?

Conclusions

- Our analyses reveal the **effectiveness of the combined scheme** of the different flood mitigation works, and particularly the role of good management practices of reservoirs.
- The proposed framework is structured in **a modular way**, allowing to incorporate different modeling techniques or software in the **modeling chain**.
- The effectiveness of upstream storage and retention projects is maximized if they are combined with:

(a) **lateral overflow storage projects in the nine closed basins** proposed in the present study, for which flood-controlled zones are located in their lower reaches, and

(b) **projects to enhance drainage** in targeted sections of the hydrographic network, mainly by **raising embankments.**

References

- Allafta, H., and C. Opp, *GIS-based multi-criteria analysis for flood prone areas mapping in the transboundary Shatt Al-Arab basin, Iraq-Iran*, Geomatics, Natural Hazards and Risk, 12(1), 2087-2116, doi:10.1080/19475705.2021.1955755, 2021.
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- Theochari, A.-P., M. Develekou, and E. Baltas, *GIS-Based multi-criteria approach towards sustainability of flood-susceptible areas in Giofiros river basin, Greece*, Circular Economy and Sustainability, doi:10.1007/s43615-021-00096-z, 2021.

Thank you for your attention!