Flood Mitigation at the Downstream Areas of a Transboundary River

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Abstract: Floods in the basin of Ardas river, a transboundary river that crosses Bulgaria and has its outlet in Greece, have often created havoc and caused millions of damage, especially in downstream Greek areas, which also repeatedly receive unregulated flow from upstream dams. More specifically, Ardas River, a tributary of Evros river, flows for 214 km in Bulgaria and for only 39 km in Greece and its catchment stretches for 5 250 km2 (94% of the total area) in Bulgaria and for 350 km2 (6% of the total area) in Greece. Three large dams along the river have been constructed in Bulgaria (Kardzhaly, Studen Kladenets and Ivaylovgrad), the last one, Ivaylovgrad dam, in short distance (approx. 15 km) from the transnational borders. During heavy rain, excessive flow from the Ivaylovgrad dam is often released downstream, in order to relieve the reservoir that is kept at maximum level for energy production reasons. As a result, the downstream areas, also affected by the same heavy rain events, need to regulate large flows, often with inadequate response time and relevant means. The present study presents an approach to estimate flood water levels in the Greek territory, caused by both rain events and releases from the upstream dam. For this purpose the study area was divided into three subbasins and the corresponding flood volumes were calculated using several methodologies. The paper concludes with a series of structural and non-structural measures that are suggested to be taken to confront and mitigate flood effects.

Key words: Transboundary river, hydrological analysis, hydraulic analysis, flood extent, flood mitigation, structural and non-structural measures

1. INTRODUCTION

Ardas river, a tributary of the river Evros, is a transboundary river that has its sources in Bulgaria and its outlet in Greece. The river springs are located in the north slopes of the Bulgarian Rhodope Mountains. The river flows for 253 km in total before reaching its outlet, out of which 214 km in Bulgarian and 39 km in Greek terrain. Ardas outlet falls in the Evros river, which is the natural Greek – Turkish border. The basin of river Ardas stretches for 5.500 km^2, of which 5.200 km^2 (or 94%) in Bulgaria and 350 km^2 (or 6%) in Greece.

During the decade 1950 – 1960 three large dams were constructed in Bulgaria: Kardzhaly (upstream dam), Studen Kladenets and Ivaylovgrad (downstream dam), with a total storage capacity exceeding 1 billion m^3. These dams, also referred as *Arda hydro power cascade*, were mainly constructed for hydropower production purposes and have total installed capacity equal to 270MW (106 MW, 60MW and 104 MW respectively) and mean annual electricity generation equal to 609 GWh (160 GWh, 244 GWh and 195 GWh respectively) (NEK, 2007). In Greek territory, the Kyprinos dam, a hydropower dam with an installed power capacity equal to 2.6MW that also serves irrigation purposes, was constructed in 1969. Flood protection structures in the downstream areas of the Greek territory, include a natural bank formed just before the Komares bridge and several levees constructed along Ardas river. The structures are adequate only for low intensity flood events, and as a result the area is vulnerable to floods, which are quite frequent. The exact location and the extent of Ardas river basin is presented in Figure 1.

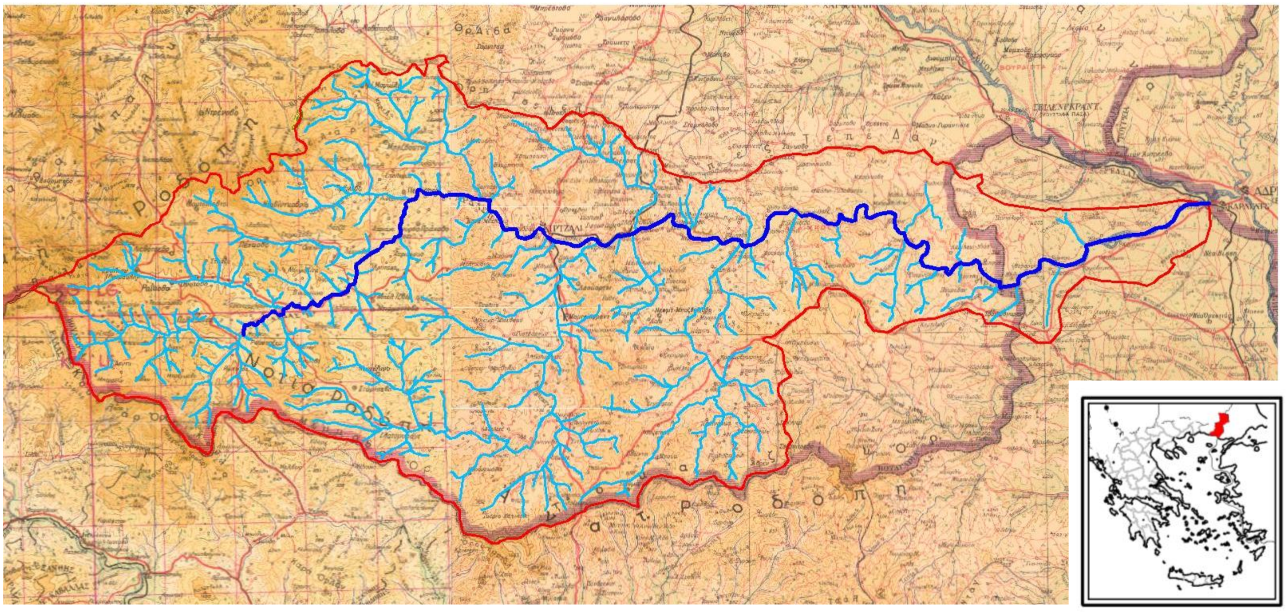

Figure 1: The river basin of the transboundary Ardas river in Bulgaria and Greece.

To maximize potential hydropower, reservoirs in Bulgarian dams are kept at high levels. The adverse impact of this strategy is the fact that during periods of heavy rainfall massive water volumes are released from upstream dams to the downstream areas. These volumes need to be controlled downstream, often with inadequate response time and relevant means. As a result, several downstream areas are flooded causing havoc and millions in damaged property and livestock.

A methodology was applied for the estimation of flood water levels in Greek areas caused by both intense rainfall events and releases from the upstream dam. The results of this estimation are presented in this paper and are further elaborated, considering also structural and non-structural measures that could be adopted in the area, in order to draw useful conclusions for flood mitigation at the downstream areas of Ardas river.

2. METHODOLOGY

The study area includes the area downstream of the Ivaylovgrad dam up to the outlet of the basin to Evros river. Based on topographic information, this area was divided into 3 sub-basins (A, B and C) which are presented in Figure 2, the main characteristics of which are listed in the table 1. Particularly for the hydrographic network the Shreve classification method (Shreve R. L., 1966) was adopted.

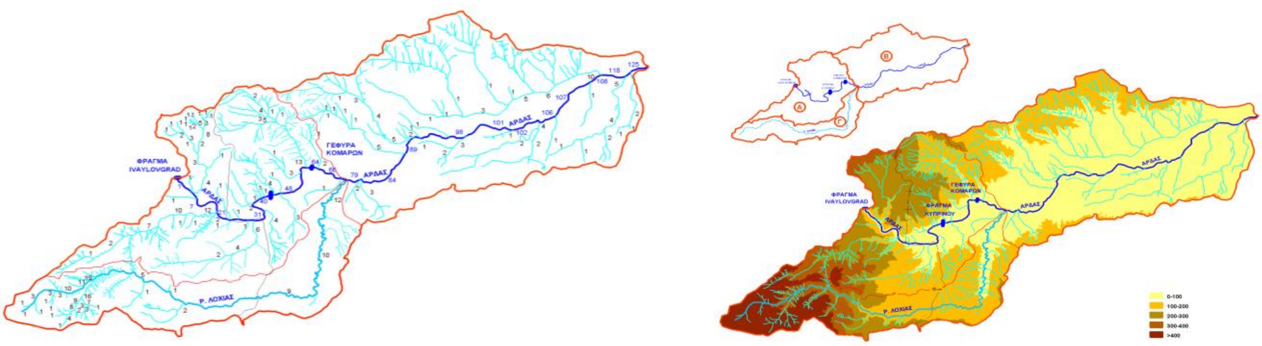

Figure 2: Hydrographic network (a) and altitude map (b) of the study area.

Table 1. Main topographic and hydrographic network characteristics of the 3 sub-basins

Basin characteristics	Total Basin	Sub-basins		
		Ivaylovgrad Dam – Lochias stream	*Lochias stream – Evros River*	*Lochias stream*
		(A)	(B)	(C)
Area (km^2)	495.85	154.03	241.95	99.87
Circunference (km)	131.23	68.86	77.49	72.36
Lenght of main watercourse (km)	44.99	18.69	26.30	38.48
Maximum altitude H (m)	+537	+534	+265	+567
Altitude of basin inlet (m)	+100	+100	+55	+537
Altitude of basin outlet (m)	+35	+55	+35	+55
Stream order (by Shreve)	37	22	15	41
Length (km)	44.99	18.69	26.30	38.48

In order to produce design storms for different return periods for the study area Intensity – Duration – Frequency (IDF) curves had to be constructed. Numerous methods exist in order to carry out this analysis (Chow V. T. et al., 1988). The Gumbel (Extreme Value Type I) Distribution seems to fit best to extreme events (both floods and droughts) and was considered more appropriate for this analysis and was applied. To this end, rainfall datasets were collected for Alexandroupolis station, a meteorological station owned by Hellenic National Meteorological Service (HNMS) that was closer to the study area. The datasets were properly processed and the resulting properties of the Gumbel distribution are shown in the following table.

Table 2. Statistical characteristic of rainfall timeseries available for the study area.

Property	**Value**								
	5 min	10 min	15 min	30 min	1 hr	2 hrs	6 hrs	12 hrs	24 hrs
n	15	15	15	15	15	15	15	15	15
Average $\overline{X}$	84.72	64.32	52.59	36.76	22.77	14.55	6.89	4.10	2.22
Standard Deviation s_x	27.10	26.02	21.10	16.65	8.46	4.33	2.32	1.45	0.88
λ	0.05	0.05	0.06	0.08	0.15	0.30	0.55	0.88	1.46
c	72.53	52.61	43.09	29.27	18.96	12.60	5.85	3.44	1.82

Based on this analysis IDF curves were produced for different return periods, while a regression analysis performed for these curves resulted in the development of a general expression for the IDF curves for any return period in the area (Equation 1). IDF curves are presented in the following.

General IDF expression for any return period.

$$i = 19.79 * T^{0.167} * t^{-0.651} \qquad (1)$$

Table 3. IDF curves developed for different, specific return periods

T	**IDF curves**
2	$i = 19.43 * t^{-0.647}$
5	$i = 26.21 * t^{-0.649}$
10	$i = 30.69 * t^{-0.650}$
20	$i = 34.98 * t^{-0.651}$
50	$i = 40.53 * t^{-0.651}$
100	$i = 44.69 * t^{-0.652}$
200	$i = 48.84 * t^{-0.652}$
500	$i = 54.30 * t^{-0.652}$
1000	$i = 58.43 * t^{-0.652}$

Two methods were applied for the development of synthetic Unit Hydrographs (UH) for each sub-basin, i.e. the Snyder and the British Hydrological Institution methods. The 1 hour UHs that were produced for both cases are presented in Figure 3.

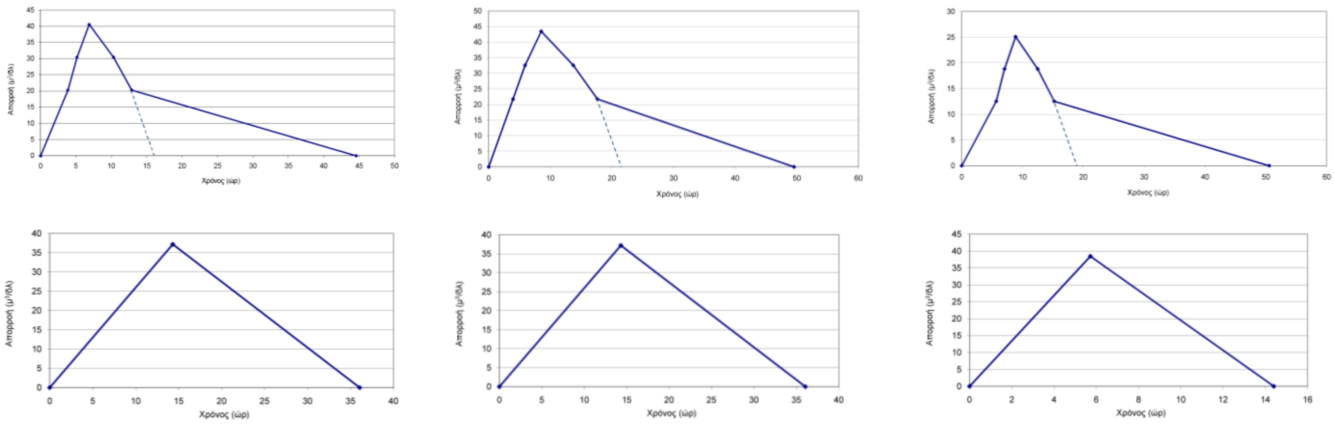

Figure 3: Snyder (top line) and British Institute (bottom line) unit hydrographs for each sub-basin of the study area.

The Snyder UHs seem to describe more accurately the response of the basin and were finally selected for the construction of the design storm. It is assumed that the design storm follows the 2nd distribution pattern defined by Huff (Huff, 1970).

All necessary information for the hydrological study of the area (including inter alia topographic and other characteristic of the sub-basins, values of parameters for Snyder UHs, the design storms etc.) was collected, properly processed and imported in a widely used hydrological model, HEC-HMS and especially the version 3.5 (USACE, 2010a). The hydrological simulation was performed and the outputs of the HEC-HMS model were discharge timeseries for different design storms at the outlets of all 3 sub-basins.

The discharge datasets that were made available during this study were strictly restricted to a timeseries of discharge releases (excessive floods) from Ivaylovgrad dam. These datasets were provided by local authorities and were considered representative of adverse conditions and thus appropriate for the current simulation.

In order to estimate flood levels in the area, the outputs of the hydrological model had to be imported in a hydraulic model. Another HEC model was selected as more appropriate for the hydraulic simulation. More specific, hydraulic modelling was performed using the version 4.1 of the HEC-RAS model (USACE, 2010b). For an accurate hydraulic analysis, the exact geometry of river sections was measured at sections every 50 m along the river. All necessary datasets were properly processed and imported in HEC-RAS model for the hydraulic simulation that was successfully performed and enabled the drawing of flood lines for rainfall events of return period equal to T=50 years. Indicative results of the study are presented in the following section.

Given the extent to which downstream areas are vulnerable to floods, even for low return periods of floods, a list of structural and non-structural measures for flood mitigation, customized to the particularities and the needs of the study area is proposed.

3. RESULTS

A schematic representation of the study area, including the sub-basins with their reaches, their junctions and the outlet, which consists the basin model for HEC-HMS, is presented in Figure 4.

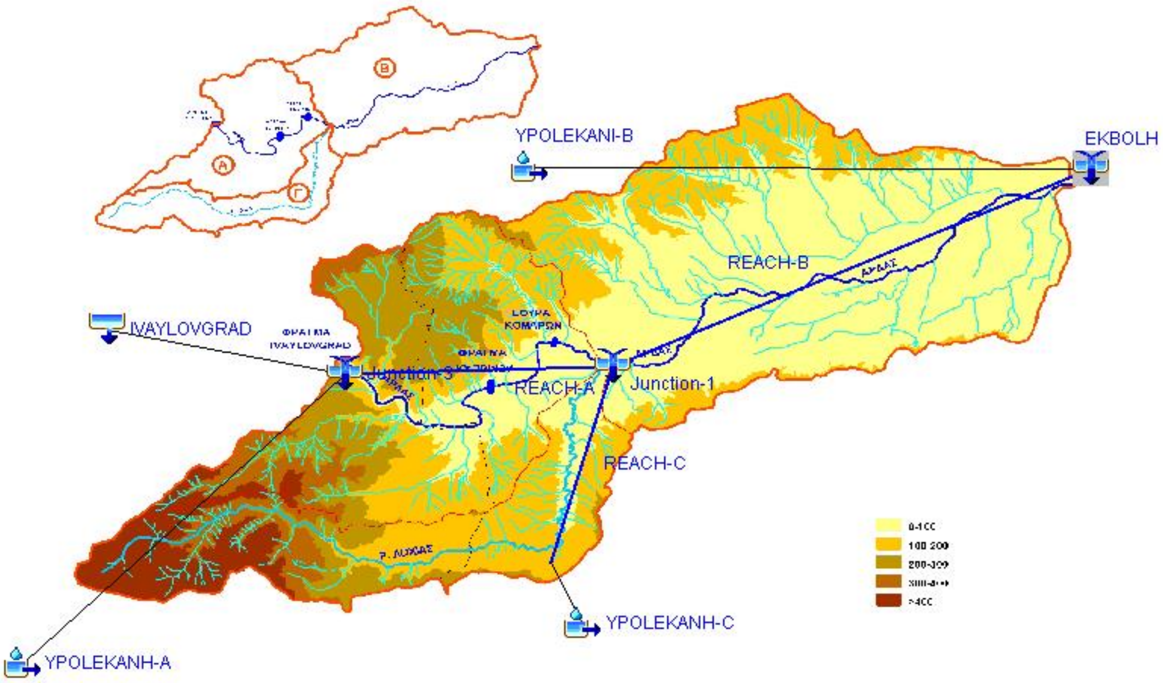

Figure 4. HEC-HMS basin model

The hydrological study was performed for two cases. In the first one, the discharge timeseries from the upstream dam were ignored, while in the second one, these datasets were considered in the analysis. Therefore, two sets of results were produced for each sub-basin. The simulated hydrographs for each case at the outlet of the basin and for different return periods are presented in the following Figures.

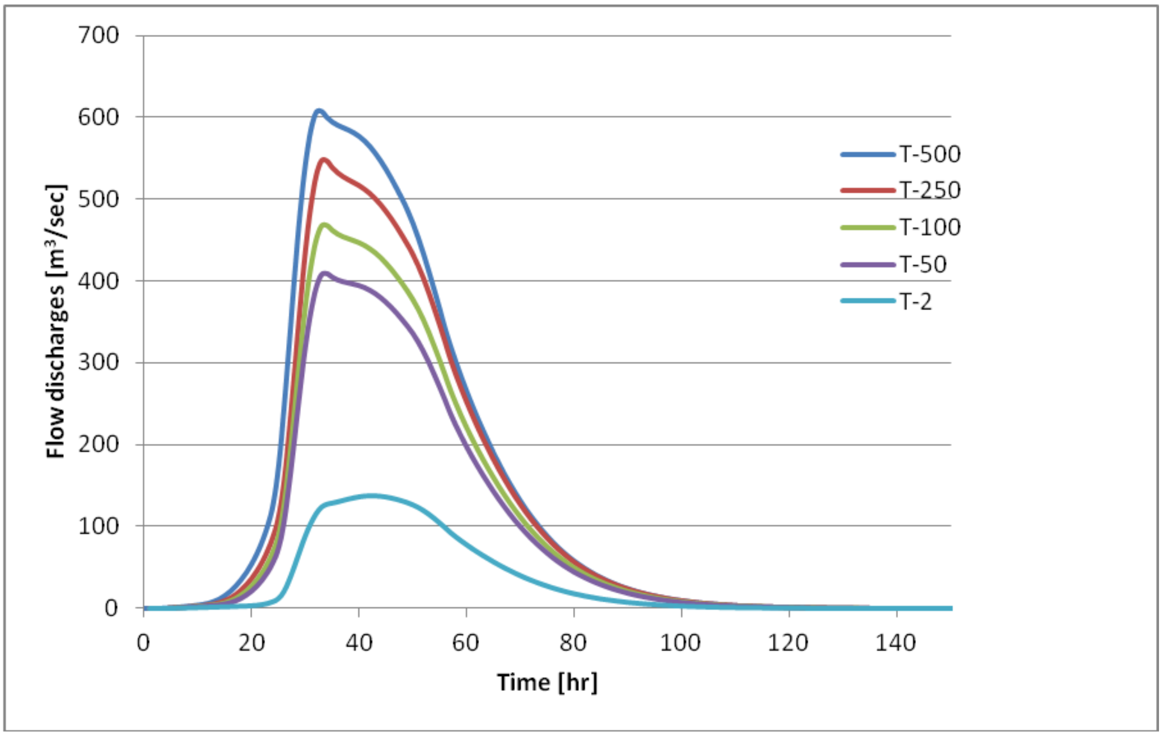

Figure 5. The simulated hydrograph at the outlet of the basin, when releases from Ivaylovgrad dam are ignored.

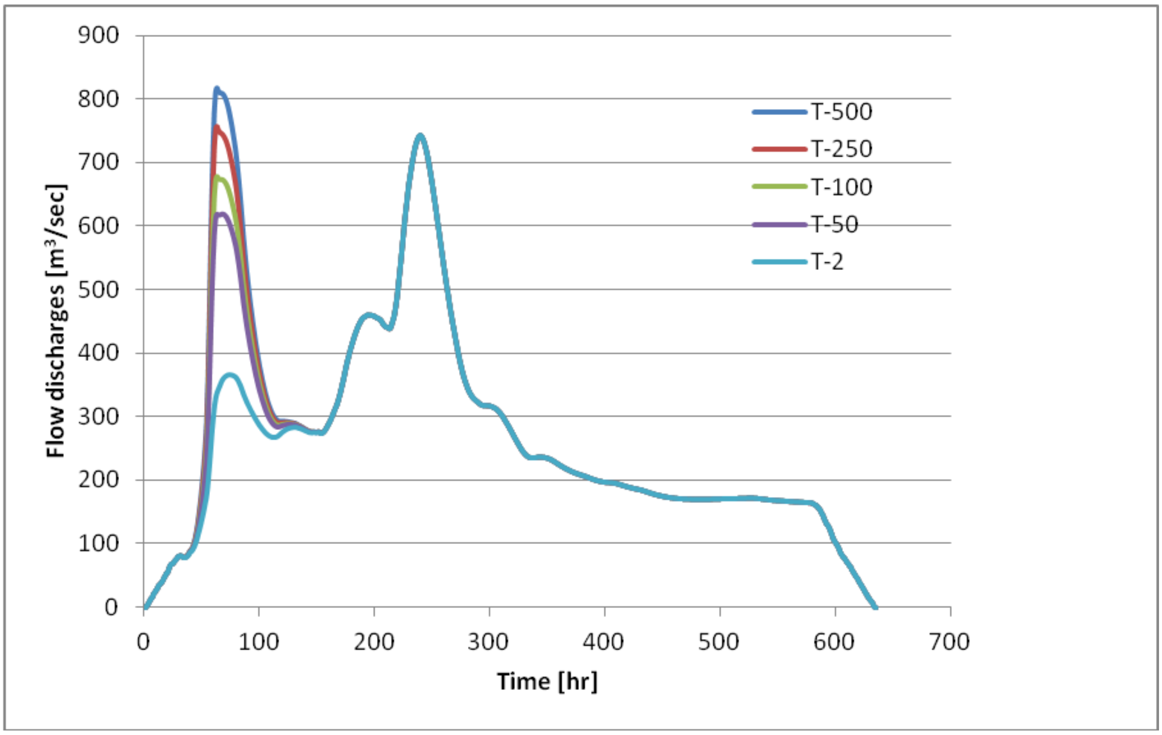

Figure 6. The simulated hydrograph at the outlet of the basin, when releases from Ivaylovgrad dam are taken into consideration.

In the second case, the flood hydropraph has two peaks, the second, lagged one, being attributed to the peak release from Ivaylovgrad dam. In general, as expected, when releases from the upstream dam are taken into account the flood hydropraph represents a more critical situation. Specifically for the 2-year return period, the contribution of the releases from the Ivaylovgrad dam results in an increase in peak flow by ~167% and ~440% for the 1st and the 2nd peak, respectively, when compared with the peak flow estimated when these releases are ignored. Additionally, in the second case, the values of the peak discharges are particularly high, especially for high periods of interval. It also needs to be highlighted that when return periods exceed 250 years the first peak of the hydrograph is more significant than the second one. Even for medium return periods (close to 50 years) both peaks are particularly high and the combined impact of the two successive peaks, the time distance of which is approximately 6 days, is expected to be significant for the unprotected downstream areas.

The peak discharges for every case are summarized in Table 4 below.

Table 4. Peak discharges for the selected return periods, when releases from Ivaylovgrad dam are considered (ALL) and when they are ignored (WITHOUT)

T [years]	ALL		WITHOUT $[m^3/sec]$
	Qpeak I $[m^3/sec]$	Qpeak II $[m^3/sec]$	
2	366,4	743	137,5
50	619,4	743	408,4
100	678,4	743	467,9
250	757,6	743	547,3
500	818	743	607,5

The hydraulic analysis was performed only for the second case considered in the hydrological analysis, i.e. only when discharge timeseries from Ivaylovgrad dam are included (worst case scenario) and only for return period equal to 50 years, which is the design period for most technical works. The HEC-RAS model that was used for the simulation resulted in specific water levels on the banks of the river. The HEC-RAS outputs were transformed to AutoCAD coordinates using a customized routine that was exclusively developed for this purpose. The flood plain was finally projected on 1:5.000 scale maps purchased from the Hellenic Military Geographical Service (HMGS). For reasons of clarity, only selected parts of the total flood plain are presented in the following Figure, and more specifically the parts that concern areas that are close to settlements and cultivated areas.

Figure 7. The flood plain close to Fylakion, Keramos and Elaia settlements (left) and close to Rizia settlement (right), as projected on a 1: 5.000 map of the area.

As it can be concluded from the analysis, when releases from the upstream dam are considered, a flood of T=50 years return period affects significantly both populated and cultivated areas. Of course, the situation becomes even worse in case of greater discharge releases from upstream. As mentioned above, due to the absence of complementary datasets, the sole discharge timeseries that was available for Ivaylovgrad dam was considered typical and adequate for the current hydrological analysis and the conclusions are based on this assumption.

4. DISCUSSION

It is widely accepted that in order to reduce flood risk, the management of transboundary rivers should be organized centrally, i.e. at a river basin basis rather than a national basis. This is also recognized and particularly highlighted in EU Floods Directive 2007/60/EC. The necessity to manage transboundary rivers is neither new, nor rare, since the majority of neighboring countries, at a global scale, seems to share at least one river (Brochmann, 2012). Of course, the difficulties towards such an approach, which include inter alia hydropower, economic, national security, geomorphologic, societal and cultural reasons, and which have been extensively analyzed in the past (Bakker, 2009, El-Swaify et al., 1996) and need not to be ignored.

Particularly for the case study, it can be concluded from the analysis that the international river basin cooperation and management between Greece and Bulgaria in what concerns Ardas discharges and more specifically the releases from the Ivaylovgrad dam, is an issue of priority. It becomes obvious from the analysis that in order to design a strategy of best management practices and measures for flood protection and flood mitigation in Ardas basin downstream of Ivaylovgrad dam, it is critical to take into consideration the discharges released from the upstream dam. For the time being and as also concluded from the analysis, the fortification of downstream areas in the

Greek territory that are prone to floods, especially the ones that are close to settlements and cultivations, emerges as a necessity. Towards such a mitigation of the effects of floods this strategy for flood management needs to be consisted of both structural and non-structural measures.

A series of relevant structural and non-structural measures that need to be undertaken to confront and mitigate flood effects is presented in Table 5. The measures were appropriately selected, based on literature review (TUHH, 2013, Faisal et al., 1999, Tucci et al., 1999) and considering the particularities of the study area in terms of geomorphology, hydrometeorology, as well as current land use in the area. Each one of these measures could also be applied as an independent measure for flood mitigation. However, some of them (especially the non-structural ones) are often inadequate when used exclusively and thus a combination of some of these measures, considering economical, technical, environmental and other criteria, will definitely be more effective.

More specifically, four structural and five non-structural measures are suggested for the study area. The structural measures include river regulation, construction of small berms-dams, and development of rainwater sewer system, construction of retention ponds and bankment construction. The suggested non-structural measures are regulations of land use, flood proofing approaches, development of Early Warning and Flood Forecasting Systems and raising of public awareness.

The main positive and negative aspects of each one of these measures are included in the Table below and are listed following a decreasing priority order for each measure.

Table 5. Positive and negative aspects for each proposed measure

Structural measures		
Measures	**Positive aspects**	**Negative aspects**
Construction of successive small berms – dams for retention of peak discharge during floods	▪ Long-lasting solution ▪ The stored water can be recycled and used also for other purposes (e.g. hydropower production, recreational purposes etc.)	▪ Increased cost ▪ Significant environmental footprint
Construction of retention ponds to temporarily store flood water in reservoirs and release it latter, with a time lag	▪ The stored water can be recycled and used also for other purposes (e.g. used for recreational purposes etc.) ▪ Eco-friendly solution	▪ Increased cost ▪ Maintenance is necessary
Regulation of the parts of the river where the river section is inadequate to carry over flood discharges. Construction of embankments along the stream to confine stream flow	▪ Long-lasting solution ▪ Low uncertainty in flood protection ▪ Concrete embankments prevent bank erosion ▪ Earth embankments provide habitat for flora and fauna	▪ Increased cost ▪ Significant environmental footprint ▪ Possible downstream sedimentation ▪ Impact on biodiversity and natural resources
Sand extraction at areas of interest	▪ Enhances the overall hydraulic operation of the river ▪ The extracted sand could be used as a construction material	▪ Non negligible environmental impact ▪ Needs to be performed regularly ▪ Environmental Impact Assessment studies need to be performed regularly (in accordance to the frequency of applied program for sand extraction)

Non-structural measures		
Measures	**Positive aspects**	**Negative aspects**
Development of a program to regulate discharge releases from Ivaylovgrad dam, mutually agreed between Bulgarian and Greek relevant authorities.	▪ Enhances overall mutual understanding and cooperation between the two neighbouring countries ▪ Measure in agreement to what is foreseen in EU Directive 2007/60/EC.	▪ Inadequate when used alone – needs to be combined with other measures ▪ Requires time to be accomplished
Measures	**Positive aspects**	**Negative aspects**
Land use regulations	▪ Assist environmental preservation (e.g. conservation of ecosystems)	▪ Inadequate when used alone – needs to be combined with other measures ▪ Requires time to be accomplished
Flood proofing (e.g. cleaning of primary and secondary drainage channels prior to the beginning of the flooding season, removal of harmful industrial and agricultural chemicals from flood prone areas)	▪ Prevention of negative impacts on environment (e.g. spread of pollutants) ▪ Low cost	▪ Inadequate when used alone – needs to be combined with other measures ▪ Short term solution, since maintenance is necessary
Development of Early Warning and Flood Forecasting Systems	▪ Can become accessible to stakeholders and also the local society (filtered information) ▪ Permanent facility that allows for real-time monitoring through telecommunication and wireless links	▪ Active collaboration between stakeholders and scientists is needed (SPI) ▪ Reliable datasets are necessary for an efficient calibration of the system
Raising of public awareness on flood risk issues	▪ Contributes to an overall environmental awareness ▪ Makes the environmental problem a “personal” problem and its solution becomes more urgent	▪ Inadequate when used alone – needs to be combined with other measures ▪ Requires time to be accomplished ▪ Awareness campaigns need to be frequent

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