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Flood mitigation at the downstream areas of a transboundary river

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Abstract: Floods in the basin of the Ardas river, a transboundary river that has its springs in Bulgaria and its outlet in Greece, have often created havoc and caused millions of damage, especially in downstream Greek areas, which repeatedly receive unregulated flow from upstream dams. More specifically, the Ardas river, a tributary of the Evros river, flows for 241 km in Bulgaria and for only 49 km in Greece and its catchment stretches for 5.200 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, being in short distance (approx. 15 km) from the transnational borders. During heavy rain, excessive flow from 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 describes an approach to estimate flood water levels in the Greek territory, caused by both intense rain events and increased releases from the upstream dam. For this purpose the study area was divided into three sub-basins and the corresponding flood volumes were calculated using several methodologies. Given the fact that downstream areas are proved to be in high risk in terms of flooding, a series of structural and non-structural measures for the downstream area is examined and the paper concludes with an approach towards the confrontation and mitigation of flood effects in transboundary river basins..

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

1. INTRODUCTION

The 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 290 km in total before reaching its outlet, out of which 241 km in Bulgarian and 49 km in Greek terrain. The Ardas outlet falls in the Evros river, which is the natural Greek – Turkish border. The basin of the river Ardas stretches for appr. 5.550 km^2, out 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 a total installed capacity equal to 270 MW (106 MW, 60 MW and 104 MW respectively) and a mean annual electricity generation equal to 609 GWh (160 GWh, 244 GWh and 195 GWh respectively) (NEK, 2007). In Greek territory, Kyprinos dam, a hydropower dam with an installed power capacity equal to 2.6 MW serving also irrigation purposes, was constructed in 1969. Flood protection structures in the downstream areas include a natural bank formed just before Komares bridge and several levees constructed along the 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 the Ardas river basin are presented in Figure 1.

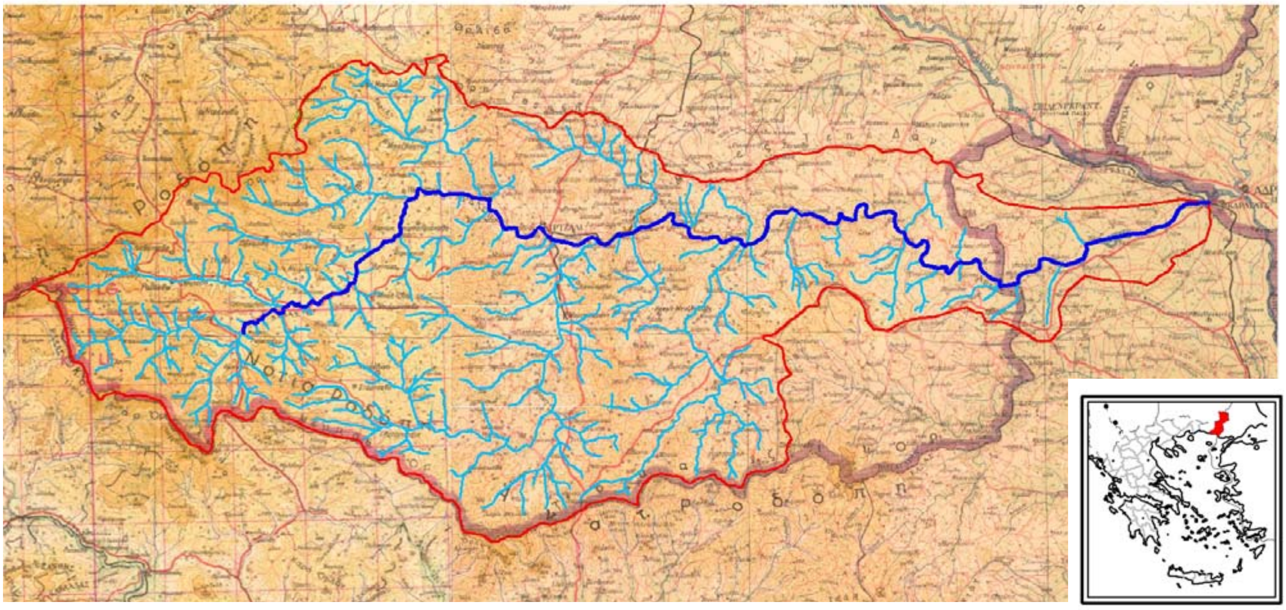

Figure 1: The river basin of the transboundary Ardas river in Bulgaria and Greece.

To maximize potential hydropower, reservoirs in Bulgarian dams are kept at high levels. As a result, massive water volumes are released from upstream dams to the downstream areas during periods of heavy rainfall. These volumes need to be controlled downstream, often with inadequate response time and relevant means. Therefore, 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 increased releases from the upstream dam. The results of this estimation are presented in this paper and highlight the need for adoption of appropriate measures for flood mitigation at the downstream areas of the Ardas river. A list of both structural and non-structural measures that could be adopted in the area is compiled, the positive and negative aspects of each measure are commented and an integrated approach to flood mitigation is suggested.

2. METHODOLOGY

The study area includes the area downstream Ivaylovgrad dam extended until the outlet of the basin to the Evros river. Based on topographic features, 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 Table 1. Particularly for the hydrographic network, the Shreve classification method (Shreve, 1966) was adopted.

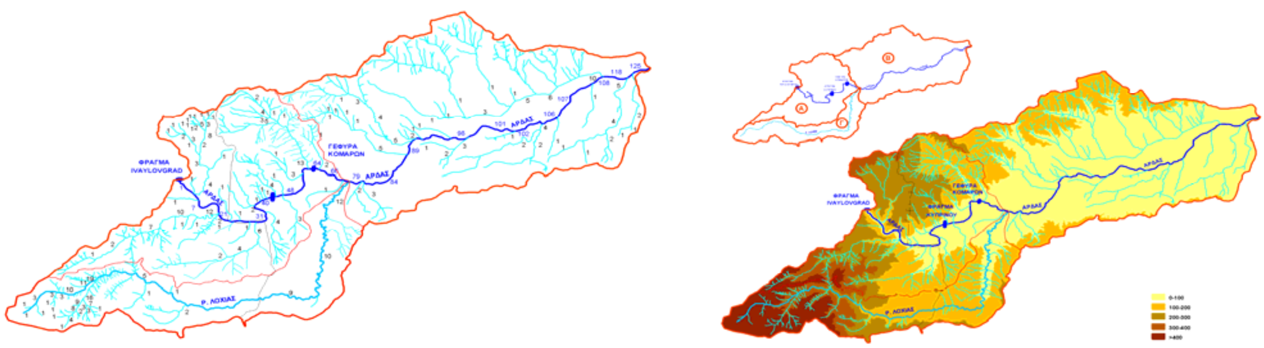

Figure 2: Hydrographic network (a) and altitude map (b) of the study area.

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

Basin characteristics	**Total Basin**	**Sub-basins**		
	Ivaylovgrad Dam – Evros River	*Ivaylovgrad Dam – Lochias stream* (A)	*Lochias stream – Evros River* (B)	*Lochias stream* (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 *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. To this end, rainfall datasets were collected from Alexandroupolis station, a meteorological station owned by the Hellenic National Meteorological Service (HNMS) that is closer to the study area. The datasets were properly processed and the resulting properties of the Gumbel distribution are presented in Table 2.

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 and are presented in Table 3.

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	$i = 58.43 * t^{-0.652}$

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 study area (Equation 1).

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

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.

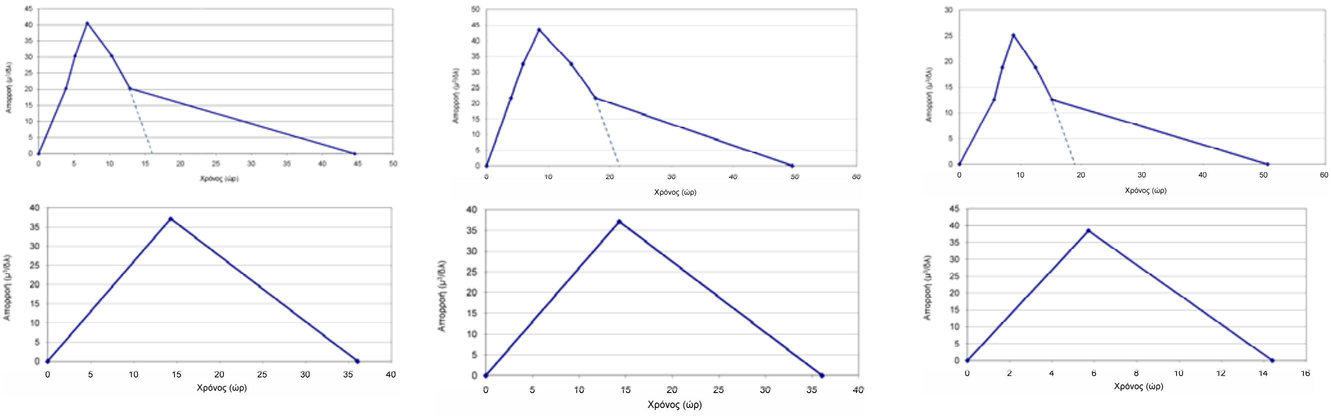

Figure 3: Snyder (top line) and British Institute (bottom line) unit hydrographs for each sub-basin of the study area.

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 second distribution pattern as 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, version 3.5 (USACE, 2010a). The hydrological simulation with HEC-HMS resulted in the generation of 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 limited to a single 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 HEC-RAS model (USACE, 2010b). The exact geometry of the river sections has been measured at 50 m intervals 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 a 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, as developed in HEC-HMS environment, is presented in Figure 4.

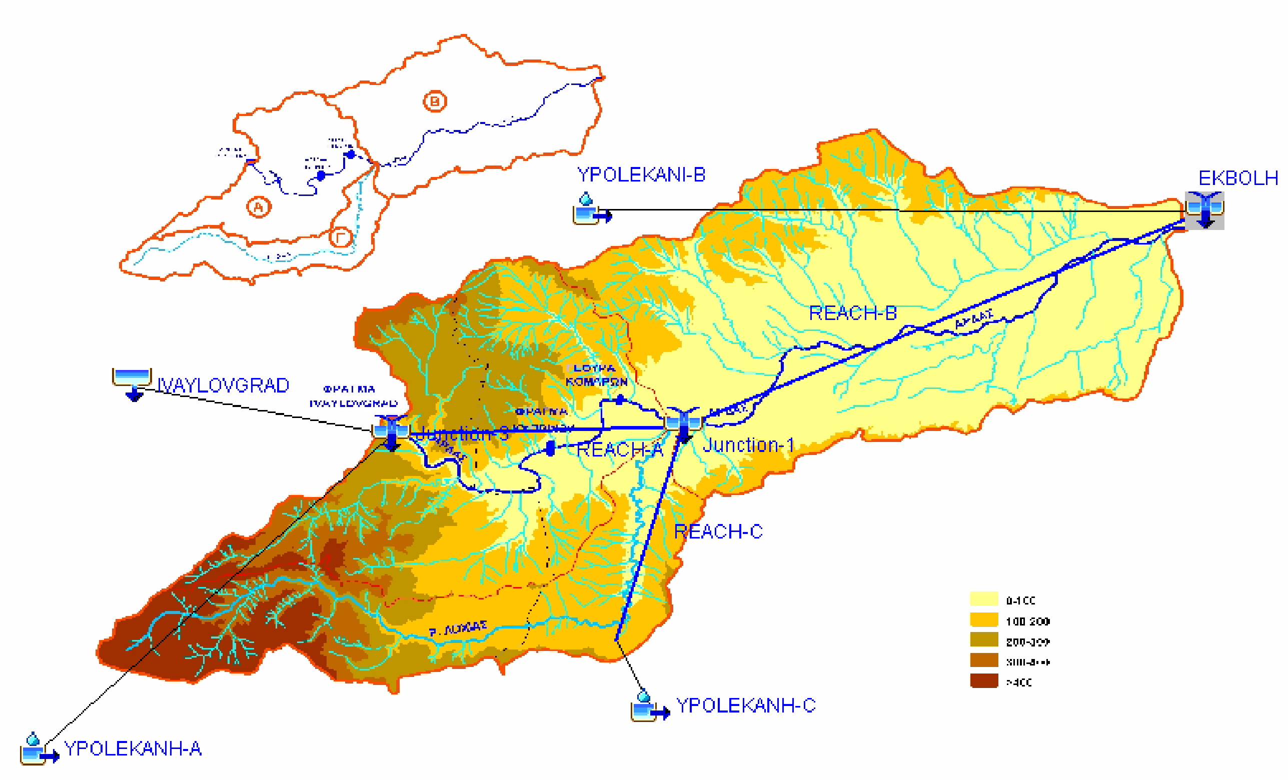

Figure 4. A schematic representation of the elements of the study area, as developed in HEC-HMS environment

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 Figures 5 and 6, respectively.

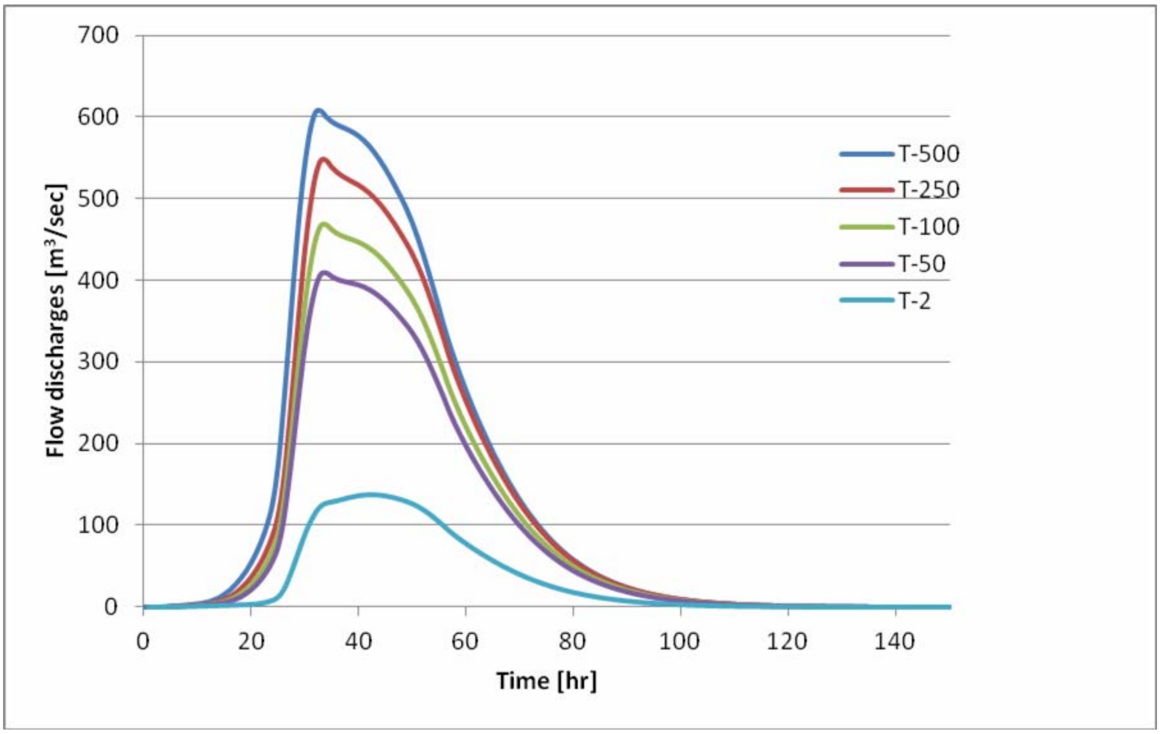

Figure 5. The simulated hydrograph at the outlet of the basin, when releases from Ivaylovgrad dam are ignored.

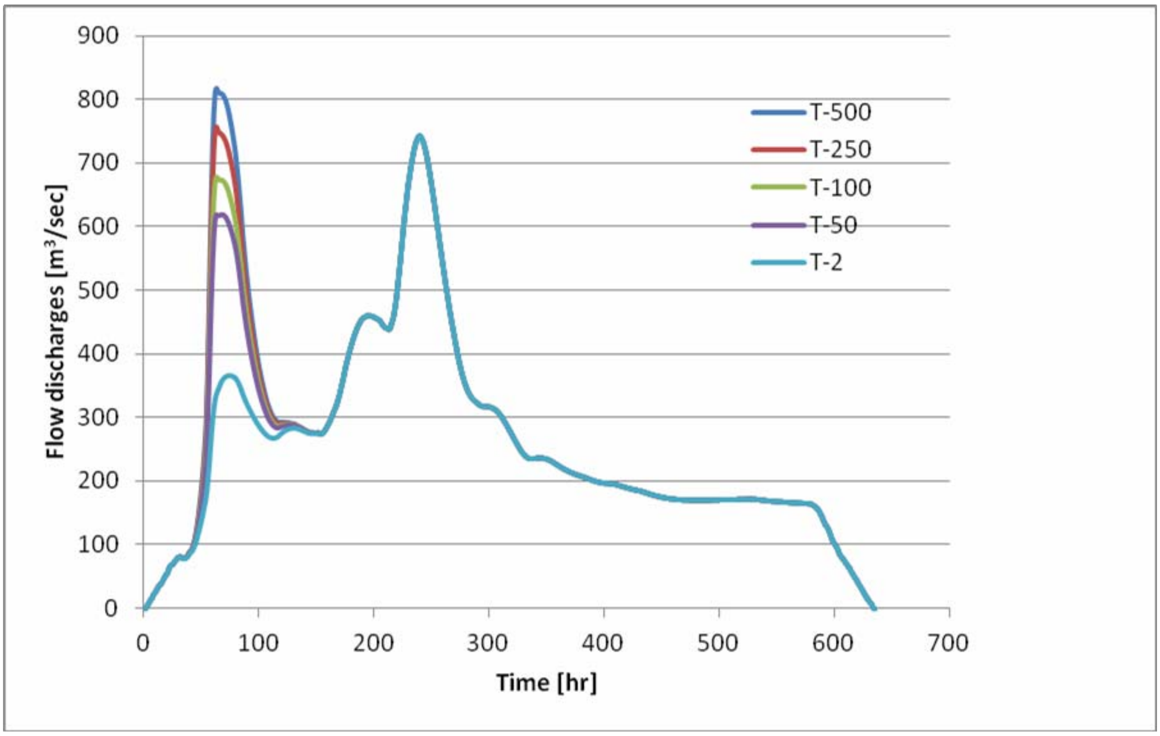

Figure 6. The simulated hydrograph at the outlet of the basin, when releases from Ivaylovgrad dam are taken into consideration.

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 Ivaylovgrad dam results in an increase in peak flow by appr. 167% and appr. 440% for the first and the second peak, respectively, when compared with the peak flow estimated in case these releases are ignored. Additionally, in the second case, the values of the peak discharges are particularly high, especially for high return periods. 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.

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

T [years]	ALL		WITHOUT $[m^3/s]$
	Q_{peak} I $[m^3/s]$	Q_{peak} II $[m^3/s]$	
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 a return period equal to 50 years, which is the design period for most technical works. HEC-RAS model that was used for the simulation resulted in specific water levels on the banks of the river. 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 a 1:5.000 scale map produced by the Hellenic Military Geographical Service (HMGS). For reasons of clarity, only selected parts of the total flood plain are presented in Figure 7, and more specifically the parts that concern areas that are close to settlements and cultivated land.

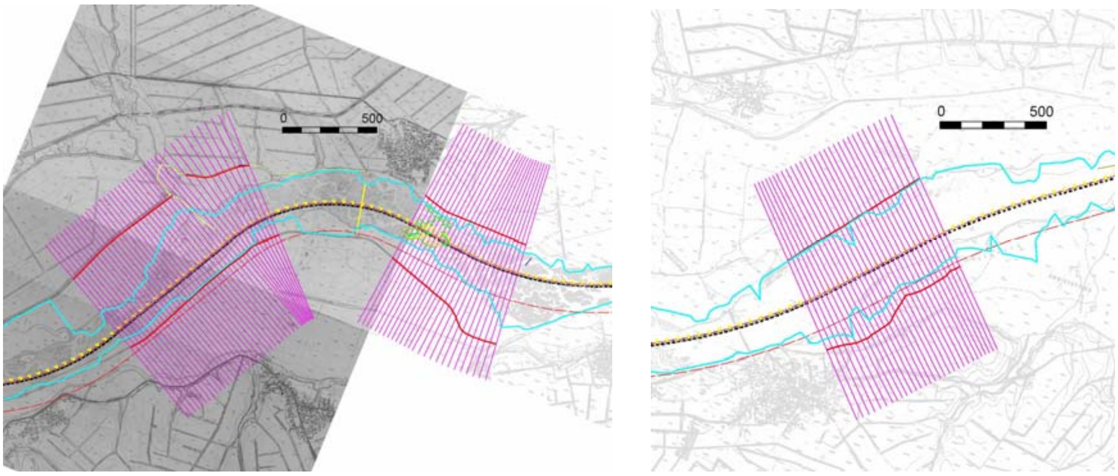

Figure 7. The flood plain close to Fylakion, Keramos and Elaia settlements (left) and close to Rizia settlement (right), as projected on a map of the area (scale in meters).

As it can be concluded from the analysis, releases from the upstream dam during a flood of T=50 years return period affect 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 additional datasets, the single 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

The need to manage transboundary rivers is neither new, nor rare, since the majority of neighboring countries, at a global scale, share at least one river (Brochmann and Gleditsch, 2012). It is widely accepted however 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 a fact recognized and particularly highlighted in EU Floods Directive 2007/60/EC. Of course, one should not ignore the difficulties towards such an approach, which include inter alia economic, national security, hydropower, geomorphologic, societal and cultural issues, many of which have been extensively analyzed in the past (Bakker, 2009; El-Swaify and Hurni, 1996).

Particularly for this case study, it can be concluded from the analysis that the international river basin cooperation and management between Greece and Bulgaria in what concerns the Ardas discharges and more specifically the releases from Ivaylovgrad dam, should be 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 the Ardas basin downstream Ivaylovgrad dam, it is critical to take into consideration the discharges released from the upstream dam. For the time being and as 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. Aiming to mitigate the effects of floods at a planning basis, an approach to flood management that incorporates the adoption of both structural and non-structural measures needs to be developed.

A series of relevant structural and non-structural measures that may be undertaken to confront and mitigate flood effects in the study area is presented in Tables 5 and 6, respectively. The measures were appropriately selected, based on literature review (TUHH, 2013; Faisal *et al.*, 1999; Tucci and Villanueva, 1999) and considering the particularities of the study area in terms of geomorphology, hydrometeorology, as well as current land uses in the area. More specifically, five structural and five non-structural measures are examined for the study area. The structural measures include river regulation, sand extraction and the construction of small berms-dams, retention ponds or embankments. The suggested non-structural measures include the development of a program for discharge regulation mutually agreed between neighboring countries, regulations for land uses, flood proofing approaches, development of Early Warning and Flood Forecasting Systems and campaigns for public awareness raising.

A more detailed presentation of the main positive and negative aspects of each one of the examined measures is included in Table 5 (for structural measures) and Table 6 (for non-structural measures). In general, it can be concluded from Table 5 that most structural measures are long-lasting solutions, the construction of which may serve additional purposes, other than flood protection exclusively, if designed properly. However, structural measures are usually related to increased construction or maintenance costs and are associated with significant environmental footprint. As far as non-structural measures are concerned and as it can be concluded from Table 6, most of them are environment-friendly and from a certain perspective more robust solutions. On the other hand, non-structural measures are usually inadequate when used alone and a fair amount of time is often required before the accomplishment of desired results. The measures are listed following a decreasing priority order, as this turns out from the evaluation of the land uses and the particular geomorphological and hydrometeorological features of the study area.

Table 5. Positive and negative aspects of examined structural measures

Measures	Structural 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 construction 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 construction cost ▪ Maintenance is necessary
Regulation of the parts of the river where the river section is inadequate to carry over flood discharges.	▪ Long-lasting solution ▪ Low uncertainty in flood protection	▪ Increased construction cost ▪ Significant environmental footprint
Construction of embankments along the stream to confine stream flow	▪ Concrete embankments prevent bank erosion ▪ Earth embankments provide habitat for flora and fauna	▪ 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 ▪ Increased maintenance cost (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)

Table 6. Positive and negative aspects of examined non-structural measures

Measures	Non-structural 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
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
Campaigns to raise 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

To sum up, in order to confront and efficiently mitigate flood effects in flood prone areas case-specific measures need to be adopted. Different structural and non-structural measures that take into consideration the particularities of the area need to be examined for each case study. Each one of these measures could be applied as an independent measure for flood mitigation. Nevertheless, given that some of these (especially the non-structural ones) are often inadequate when used exclusively, a combination of some of these measures, considering economical, technical, environmental and other criteria, and often involving both structural and nonstructural measures will definitely be more effective. Papathanasiou *et al*. (2013) suggest a combined application of flood risk management measures both structural and non-structural, each one with case-specific attributed weight, to support an Early Flood Warning System in Attica.

Finally, it needs to be stressed that this latter approach, which engages the examination and adoption of a combination of structural and non-structural measures, may not be restricted to flood management of transboundary river basins; it can be expanded to any case where flood managements is required, even within national borders. For transboundary rivers, it should be emphasized that flood management needs to be organized centrally. Therefore, the seamless cooperation between authorities from neighboring countries, should also involve the setting up of an integrated list of appropriate for the area measures (both structural and non-structural) that will be identified by all involved authorities and the co-evaluation of the identified measures, using economical, technical, environmental and other criteria that cross the narrow geographical boundaries. Especially for the Ardas river, the efficient protection of downstream flood prone areas necessitates the fruitful cooperation between the relevant Greek and Bulgarian authorities and the justified adoption of a properly selected combination of structural and non-structural measures, similar to the ones listed in Tables 5 and 6.

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