

# Flood Routing Simulation and Management in Hydrologic Basins with Artificial Reservoirs—The Case of Arda River

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## Abstract

Major flood events occurred in the Arda River region in the last decades with great economic, social and environmental effects. A specific software package has been developed for the simulation of the flood runoff and routing process of the transboundary Arda River basin. The software package is taking into account the existence of the three cascade Bulgarian reservoirs aiming to flood protection and power optimization. Inflow estimations for duration of five days ahead and initial water levels at the three reservoirs are imported at the beginning of the simulation. The management tool includes all the alternative operation modes of hydropower plants, water released from spillways, and river and reservoir flow characteristics in order to optimize the total system (power generation and flooding costs) during the flood event. The developed software is also an efficient tool for the establishment of a flood warning system.

## Keywords

Reservoirs, Hydropower, Floods, Flood Hydrograph Routing, Software Development, Arda River

## 1. Introduction

The Arda is a 290-kilometre long river in southeastern Europe and crosses two countries, Bulgaria and Greece. The regions along the Arda River (**Figure 1**), situated in both hydrologic basins of the Greek and Bulgaria territories, are often facing flood events. The flood discharges of Arda River contribute considerably to the flood of other regions adjacent to Evros (or Maritsa or Meric) River, since



**Figure 1.** Arda's catchment area.

the first one intersects with the second in the area of the Turkish town Edirne [1]. In the past, several flooding events in the specific area caused serious damages and threatened even human lives. Potential future climate changes might expand the problem increasing the riskiness.

Various flood predicting tools, such as flood warning systems, are very important to preserve lives and infrastructures, as well as to decrease the potential damages [2]. Early flood warning systems are more and more being used to make ready at-risk communities for the purpose of minimizing flood affects [3]. In this context, Bulgaria and Greece cooperated within the “European cross-border cooperation program Greece-Bulgaria 2007-2013” in a common project with title “Flood warning system establishment in Arda River basin for minimizing the risk in the cross border area—ARDAFORECAST”, in order to face together the existence of flooding events in the area. The ARDAFORECAST is a complex system, which integrates scientific research and complex simulation models of natural processes (meteorological, hydrological and hydraulic), and which considers a number of parameters (including the economic dimension of the problem). Its main actions are the following: 1) precipitation forecast, 2) runoff evaluation on the basis of the forecast rainfall, 3) development of a specialized software for dams management and floods avoidance, 4) flood wave routing and inundation maps, 5) early warning system and protection from floods-civil protection, 6) hydro-meteorological system information, and 7) installation of additional hydrometric and meteorological stations. Similar cooperation was achieved in the past between Bulgaria and Turkey for rivers Maritsa and Tundja within the European Commission Cross Border Cooperation Program. Both sides also established stations and good information system, and although their effort proved very useful especially during 2005 and 2006 floods it was not enough [4] [5].

Flood management is a complex issue, and it requires hydrologic, hydraulic,

environmental and economic aspects [6]. Dams on rivers impose permanent effects on natural stream flows and modify the peak discharge, timing and duration of floods and as a result the downstream flooding effects are reduced. Depending on their operating rules, dams with control structures such as spillways, gates, valves may have the ability to further modify flood flows. When operating structures are used to release water during flood episodes, flooding consequences can happen downstream rapidly, which can create negative impacts on downstream communities [7]. Each catchment responds in a different way to rainfall events. So, it is important that all dam operators, and emergency response and support agencies understand the unique behavior of the catchment and operating requirements for each dam within their region.

In the catchment area of the Arda River have become large structural operations with the construction of three cascade dams, which control almost the entire catchment area. Therefore, it is required to be examined the scope of “soft” actions (non-structural interventions) in flood events; for example, the rational management of dams as initially discussed in [8]. The address of floods become more difficult in case of foreign catchment areas, when transboundary floods occur, which may originate in one country and then propagate downstream to another country or countries. In case of Arda River, the catchment area is shared between two countries, Bulgaria, the upstream country and Greece the downstream country, however the discharges of Arda adversely affect Turkey as well. In such a case the transboundary flood management is a long process and typically undergoes different stages. Its success depends mainly on understanding the problems and respecting the needs of transboundary countries and also the causes of these problems taking into account the natural and social processes [9] [10] [11].

The application of system analysis and system dynamics techniques for dams and reservoirs management and operations has been an important issue in water resources engineering during the last decades. A number of models have been developed for evaluating storage capacity and creating release policy, both at the project planning stage and for real-time operations. Many of the developed or adapted techniques to reservoir operations are described in the literature, e.g. [12] [13]. Existing methods for reservoirs’ operation contain optimization techniques, which employ mathematical programming methods such as linear programming [14], non-linear programming [15] and dynamic programming [16] [17] [18].

Because of various limitations of the mentioned classical methods, many evolutionary and meta-heuristic algorithms proposed for reservoir operation, such as genetic algorithm [19] [20], ant colony algorithm [21] [22] [23], particle swarm optimization [24] [25], water cycle algorithm [26], honey-bee mating optimization algorithm [27], cuckoo optimization algorithm [28], harmony search [29] and imperialist competitive algorithm.

Cascade reservoirs optimal operation is a multivariable and complicated

problem, which needs to consider hydraulic and electrical contact between cascade reservoirs, but there are also a lot of constraints [30]. Energy is a fundamental parameter for social and economic development and for that reason the energy demand has increased very much. This causes a rapid growing of greenhouse gas emissions and also increases the need of clean and renewable energy sources such as hydropower [31]. On the other hand, floods are the most common, recurring and devastating natural events [32] between all natural disasters, and flood control is always a basic scope of the reservoirs. The development and application of suitable tools in order to provide fast and accurate predictions for flood management are critical for a mitigation of damages caused by floods [33].

In the present work a part of the above mentioned cooperative project ARDAFORECAST is presented, on the basis of which, studied and proposed the rational management of the Bulgarian dams in conjunction with early prognosis, which possibly result in a significant reduction of flood events or to flood avoidance in Arda region. Existing software packages like HEC-ResSim have been designed to model reservoir operations at one or more reservoirs whose operations are defined by a variety of operational rules and constraints. They are not optimizing water releases, but they are giving a solution satisfying the constraints. The basic idea, which is proposed in the present work, is to drain the reservoirs in order to accommodate the forecasted upcoming inflow. To avoid economic loss, the drain is carried out through the hydroelectric power plants by producing electricity even at a time which is not required. The optimal water releases from each reservoir are the main objective of the developed software, in order to prevent flooding and to maximize the generated power. The benefit of the generated power is evaluated, as well as the cost of potential floods, in order to be achieved a total optimization of the system during the flood episode. Despite the fact that the developed software has been developed for a specific river basin, it can be also implemented in any basin containing cascade artificial reservoirs and the results could be utilized by stakeholders for flood management by integrated reservoir operation.

## 2. Development of a New Software—Management Tool

### 2.1. Study Area

The Arda River, originated from Bulgaria, is a tributary of Evros River that enters the Greek territory and flows through the prefecture of Evros from west to east. Its connection with the Evros River is achieved approximately 6 km downstream to the Turkish town Edirne (Figure 1). The total catchment area of Arda River is 5.600 km<sup>2</sup> and only 345 km<sup>2</sup> are located within the Greek territory, while the rest in Bulgaria. At the Bulgarian side of the river three major dams, Kardzali, St. Kladenets and Ivaylovgrad (Figure 1), constructed about 50 years ago with a total capacity of  $1085 \times 10^6$  m<sup>3</sup>. The three reservoirs are effectively controlling the total runoff, they are multi-purpose and are mostly used for power generation. There is also a fourth dam (Therapio dam) at the beginning of the Greek

basin (**Figure 1**) for irrigation purposes. This dam is very small with a limited capacity of  $3.2 \times 10^6 \text{ m}^3$  and subsequently with a zero ability to regulate the flow. For that reason it is omitted in the analysis of the present work.

The mountainous nature of the greater part of the large catchment area, as well as the climatic conditions in the area, too often cause major floodplain discharges with enormous economic, social and environmental consequences, for the Bulgarian riparian regions, but mostly for Greek and Turkish areas, which are the downstream countries. In the catchment area of Arda River caused most of the time flash and dangerous floods due to the torrential rains and sudden snowmelt, as a result of the composite Continental-Mediterranean climate of the region [34] [35]. The recorded historical observations of the last 50 years show that the floods usually occur toward the end of the winter, however flood events occurred relatively often in summer as well as in other seasons [5]. Despite the existence of three major reservoirs in the Bulgarian side mainly for power generation [36], major flood events frequently occurred close to the Greek-Bulgarian border.

## 2.2. Initial Approach and Main Concept of the Problem

Current technology allows for reliable weather forecasts (including rainfall) of several days. With the use of modern meteorological methods, the Bulgarian partners (National Institute of Meteorology and Hydrology, NIMH) achieved the forecast of 5-days rainfall, with output data results of 3-hours, in space grid cells of  $8 \times 8 \text{ km}$ . The simulation of the surface and subsurface runoff in the computational grids or the subbasins, as well as the surface runoff routing through the stream is achieved with the use of hydrologic models [37].

The main feature of the Arda catchment area is the three cascade large dams, the management of which is very important for multiple purposes such as water supply, irrigation, power generation and flood protection. The basic idea which is proposed in this work is based on the consensus view that the five days time of rainfall and runoff forecast is very important and crucial for flood control. Therefore, by estimating the rain height and subsequently the inflow into each reservoir for the next five days the drain of reservoirs is becoming feasible in order to accommodate the upcoming inflow. To avoid economic loss, the drain of reservoirs is carried out through the hydroelectric power plants by producing electricity even at a time which is not required (e.g. 24 hours), in order to achieve the best water management. But how much water needs to be drained from each reservoir and in what period of time? The answer is not simple, because it depends on several parameters, such as:

- What is the expected inflow, to each reservoir, from the corresponded catchment area and in what temporal distribution?
- What is the initial level of each reservoir? Is it capable to hold the upcoming inflow?
- What quantity may overflow from each reservoir, in what time and how will

it affect the downstream reservoirs?

- How long will it take an outflow from an upstream reservoir to reach the downstream reservoirs? This time is not constant but varies depending on the flow conditions.
- How fast the water level of the reservoir is increased or decreased due to inflow or outflow?
- What is the financial loss or gain?

The answer to the above questions is not simple neither easy. For this reason, a new software (management tool) was developed in order to continuously simulate the flow through the reservoirs and the river for the next (at least) ten days (five days rainfall forecast and at least five days for runoff completion). The simulation includes all alternative modes of hydropower plants in conjunction with overflows through the spillways and the flow routing through the river and the reservoirs in order to maximize the generated power and prevent flooding.

### 3. Hydrologic and Hydraulic Characteristics of the Developed Software ARDAFLOODS

#### 3.1. Hydrologic Simulation

Due to the kind of the available data, the catchment area of the Arda River was treated differently for the Bulgarian section than for the Greek. In the Bulgarian catchment area there are available forecasted hydrographs input in the three reservoirs of Kardzaly, Studen-Kladenets and Ivaylovgrad, produced by the National Institute of Meteorology and Hydrology of Bulgaria (NIMH). So, for this part of the catchment area, the developed software ARDAFLOODS routes the specific hydrographs through the streams and the three reservoirs.

The Greek part of the catchment area has been divided into eight subbasins (Figure 2). For this area rainfall prediction, derived from NIMH is inserted for the next five days with a time step of three hours in space cells of  $8 \times 8$  km. Thus, it is calculated the rainfall of the eight subbasins in relation to the time. The transformation of rainfall into direct runoff is made using the method of Snyder's Synthetic Unit Hydrograph in conjunction with the Horton's method for the calculation of infiltration losses. These hydrographs are synthesized by the runoff hydrograph derived from the Bulgarian section and routed to the confluence of the Arda with the Evros River near the town of Edirne.



**Figure 2.** Division of the Greek part of Arda's catchment area in individual subbasins.

### 3.2. Routing Hydrographs through Streams

The routing of hydrographs through streams is achieved with the discretization and the numerical solve of the “kinematic wave” equations. The describing equations of this one-dimensional model are derived from Saint-Venant equations, which can be used to describe such flows [8] [38] [39]. The basic assumptions made in the development of the basic differential equations of one-dimensional unsteady flow are: 1) the slope of the stream is small (less than 1:10), 2) streamlines are essentially straight, 3) the pressure distribution is approximately hydrostatic, 4) resistance to flow may be described by empirical resistance equations such as the Manning equation, and 5) momentum carried to the fluid from lateral inflow is negligible. Under these conditions, the mechanics of unsteady open channel flow may be expressed mathematically in terms of the St. Venant equations:

Continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L \quad (1)$$

Momentum equation (channels of unit width):

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial y}{\partial x} = g(S_0 - S_f) - q_o \frac{(u - v)}{y} \quad (2)$$

where:

$x$  = distance measured in downstream flow direction (m),

$t$  = time (sec),

$A$  = cross-sectional area (m<sup>2</sup>),

$Q$  = discharge at the section (m<sup>3</sup>/sec),

$q_L$  = total lateral inflow per unit length of channel (m<sup>2</sup>/sec),

$y$  = water depth (m),

$u$  = x-component of mean velocity (m/sec),

$v$  = y-component of velocity for lateral inflow (m/sec),

$g$  = acceleration of gravity (m/sec<sup>2</sup>),

$S_0$  = average bottom slope (m/m),

$S_f$  = friction slope defined by the Manning equation,

$q_o$  = lateral inflow per unit length of channel of unit width (m/sec).

An order of magnitude analysis shows that inertia and pressure terms are not important in the momentum equation—“kinematic waves approximation”—which is then reduced to the well-known relation for steady, uniform flow in a “channel” (neglecting also the momentum carried to the fluid from lateral inflow):

$$S_0 = S_f \quad (3)$$

*i.e.*, the bed slope is approximately equal to the friction slope. We calculate the volume flux  $Q$  at any point in the “channel” from Manning’s formula:

$$Q = \frac{1}{n} S_0^{1/2} R_h^{2/3} A = aA^m \quad (4)$$

where  $R_h$  is hydraulic radius,  $n$  is Manning's resistance factor, and  $a$  and  $m$  are kinematic wave routing parameters and are related to flow geometry and surface roughness [38].

Combining the Equations (1) and (4) we find:

$$\frac{\partial A}{\partial t} + amA^{m-1} \frac{\partial A}{\partial x} = q_L. \quad (5)$$

We use finite difference method for approximating the governing partial differential Equation (5) with simple difference equation for an array of stationary grid points located in the space-time ( $x - t$ ) plane. The governing equation in terms of finite differences ( $i$  for space,  $j$  for time), is given by:

$$\begin{aligned} & \frac{A(i, j) - A(i, j-1)}{\Delta t} + am \left[ \frac{A(i, j-1) + A(i-1, j-1)}{2} \right]^{m-1} \left[ \frac{A(i, j-1) - A(i-1, j-1)}{\Delta x} \right] \\ & = \frac{q_L(i, j) + q_L(i, j-1)}{2} \end{aligned} \quad (6)$$

The above finite difference equation applies if the wave celerity  $c$ , is less than the ratio of the space to time step, e.g.,  $c < (\Delta x / \Delta t)$  (where  $c$  is computed as the average change of flow divided by the average flow area for a particular routing reach). If  $c > (\Delta x / \Delta t)$ , then the following finite difference equation was used:

$$\frac{A(i-1, j) - A(i-1, j-1)}{\Delta t} + \left[ \frac{Q(i, j) - Q(i-1, j)}{\Delta x} \right] = \frac{q_L(i, j) + q_L(i, j-1)}{2}. \quad (7)$$

### 3.3. Routing Hydrographs through Reservoirs

For routing hydrographs through reservoirs, the developed software used the method of water balance, that based on the temporal discretization of the problem at time intervals  $dt$ . For the implementation of the method, the relation "water level"- "water volume" of the reservoir is required and also the relation between "outflow discharge" and "water level". The equation of the water balance is as follows:

$$\frac{dS}{dt} = I - Q \quad (8)$$

where:

$dS/dt$  = the change in the stored water in time interval  $dt$  ( $m^3/s$ ),

$I$  = the water inflow in the reservoir ( $m^3/s$ ),

$Q$  = the water outflow from the reservoir either through the spillway of the dam or through the turbines of the hydroelectric plant ( $m^3/s$ ).

The water outflow from the spillway is calculated using the following relation:

$$Q_\varepsilon = CBdH^{1.5} \quad (9)$$

where:

$Q_\varepsilon$  = the discharge from the spillway ( $m^3/s$ ),

$C$  = supply rate ( $m^{1/2}/s$ ),

$B$  = the effective width of the spillway crest (m),

$dH$  = the water level above the spillway crest (m).

Applying finite differences in the above Equation (8) with specific time step  $\Delta t$  we get:

$$\frac{S_{i+1} - S_i}{\Delta t} = \frac{I_{i+1} + I_i}{2} - \frac{Q_{i+1} + Q_i}{2} \quad (10)$$

where values with  $i$  indicator refer to  $t_i$  time, while values with indicator  $i + 1$  refer to  $t_{i+1} = t_i + \Delta t$  time, and  $\Delta t$  is the time increment.

The outflow from the turbines derived from the operational characteristics of the hydroelectric plants. Furthermore, in case of a high rainfall and runoff forecast for the next five days, the standard operation scheduling of the turbines needs to be modified in order to drain the reservoirs providing space to upcoming inflow. But what is the optimal functioning time period for each power plant in order to avoid floods with little or without economic loss? The simulation of the turbines performance for specific operational hours and not for 24 hours performance was achieved using the Utilization Factor (UF), who takes values from 0% (for zero function) up to 100% (for 24 hours performance). The Utilization Factor of each power plant is the unknown-under definition variable and it is calculated from the developed software, when the optimum solution is aimed.

## 4. Economic Evaluation of Alternative Management Operations of the Developed Software ARDAFLOODS

### 4.1. Power Generation by Each Hydropower Plant

During a flood event the generated power consists an important evaluation factor for management scenario and calculated by the ARDAFLOODS software for each time-step  $dt$  according to the released water discharge and the water level of each reservoir. The operation of a hydroelectric power plant during a flood event lowers the reservoir water level while providing flood protection in an economically advantageous manner.

The generated power at various times of 24 hours does not always yield the same economic benefit. Depending on the time and the season the generated power is usually priced differently. This variation is considered in the developed software, which includes time zones, where the generated power has a different commercial price. For example, usually the price of energy produced at night is smaller than the produced one during the day. So, defining as basic the energy produced in a certain season and time zone we can convert every other produced energy to equivalent to the basic using a weight factor, which equals to the rate of the two energy prices. Thus, the generated power, for each time-step, is multiplied by the appropriate weight factor, depending on the time and the month and the equivalent weighted energy is calculated.

### 4.2. Remaining Energy

An important factor in the economic evaluation is also the final level, and there-

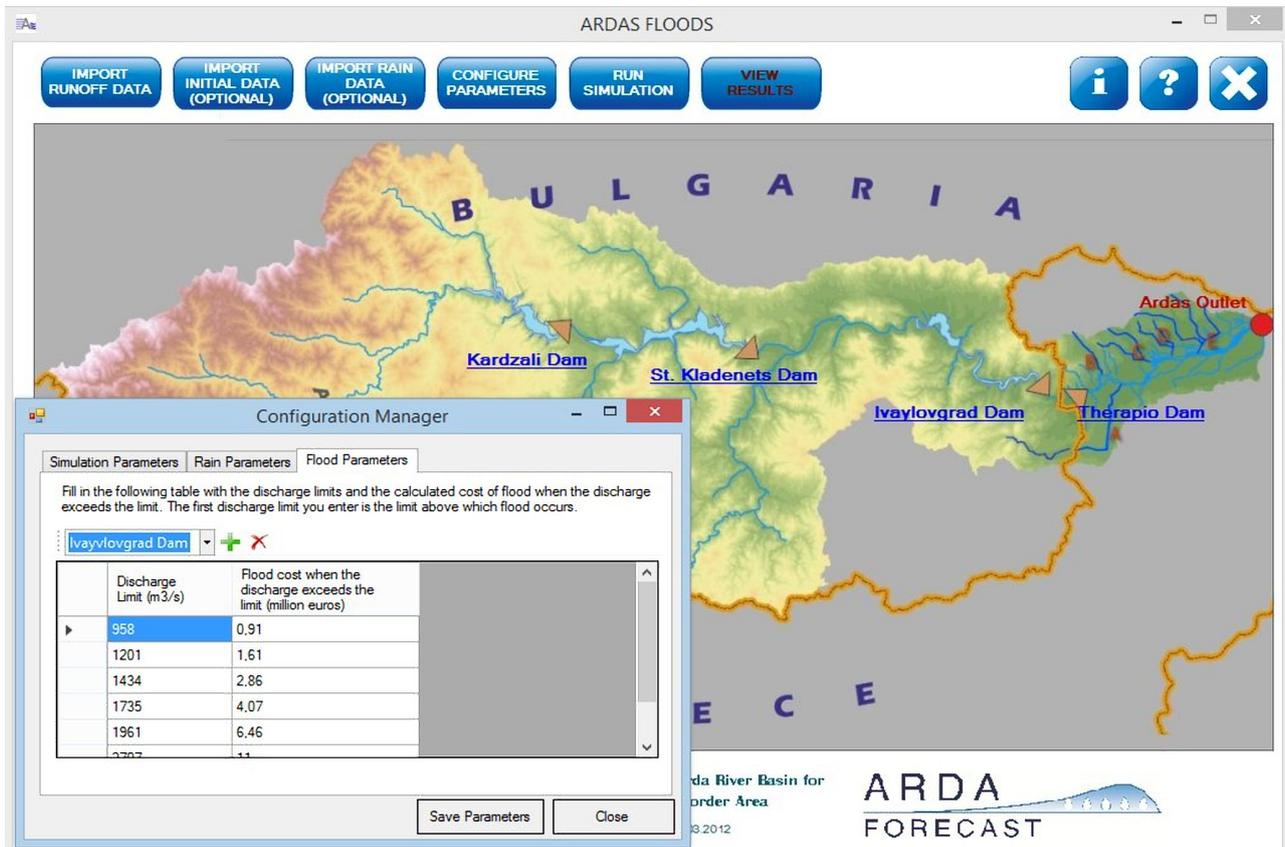
fore the final volume of water stored in each reservoir at the end of a flood event, as a result of each alternative management scenario. For example, it is possible during the implementation of a management scenario to produce not very much energy for the flood event period, but at the completion of this event the reservoir may have a raised water level. This offers the possibility of high energy production in the future, whenever required, using this extra water volume which was stored in the reservoir as a result of the management scenario. For this reason, the developed ARDAFLOODS software calculates for each of the three reservoirs the remaining energy, *i.e.* the energy that can be produced in the future by the stored water volume, which is located between the elevation of the free water surface at the end of a flood event and the minimum operating level. Since there are three successive reservoirs in Arda River, the stored water volume at the upstream reservoir of Kardzali will be used as well for the next reservoir of Studen Kladents in addition with the already stored volume of water at the last one. Also, the above sum will be used for power generation in the most downstream reservoir of Ivaylovgrad in addition to the already available there. It is supposed that the remaining energy is produced during time periods with high energy demand and therefore it returns a premium profit.

### 4.3. Economic Evaluation

For the economic evaluation of alternative management actions the developed software applies the concepts of the energy profit and flood cost. The energy profit is calculated by multiplying the total equivalent weighted generated power plus the remaining energy from the three reservoirs by the benefit per unit generated power (€/kWh). For the calculation of the flood cost three tables used by the developed software, corresponding to the three riparian areas downstream of the three reservoirs, which are covered by floodplain discharges. Each table contains two columns with different values of peak discharge rates and the corresponding cash flood costs as indicatively shown in **Figure 3** for the area downstream of the reservoir of Ivaylovgrad.

Using detailed hydraulic simulations of flood routing hydrographs, the inundation areas are estimated near the Arda River, for various flood peaks. These areas are mainly agricultural and at first approach historical data used for the period 2002-2012 from the state agency compensation for assessing an average flood cost per acre. This average cost per acre multiplied each time with the flooded acres to assess the flood cost and is a fairly conservative estimate, as it does not include infrastructure costs, costs due to the reduction of economic activity, etc.

On both sides of the Arda River, levees were constructed for the protection of the riparian areas, spaced up to 800 m in some sections. The flood cost is generated when the peak discharge exceeds a critical value  $Q_{\text{critical}}$  and the water overflows the levees, which are acting as lateral weirs. In the example illustrated in **Figure 3**, the flood cost is up to 0.91 million Euros when the flow discharge of



**Figure 3.** Table of expected flooding losses (in million Euros) downstream of the dam when the created peak of the hydrograph exceeds the critical discharge value.

the Arda river downstream the dam of Ivaylovgrad exceeds the critical value of  $958 \text{ m}^3/\text{s}$ . If the peak flow discharge is slightly lower, the flood cost will be zero. But, the behavior of nature is not usually so “sharp”. For that reason, the ARDAFLOODS supposes that, as the max flow approaches the critical discharge  $Q_{\text{critical}}$  for levees overtopping or failure, then the probability of flood increases. So, the normal distribution has been selected to calculate the probability of flooding and to allocate a possible cost as we approaching the critical discharge value. We used a ratio (Standard Deviation/mean) = 10%, so that only when the peak discharge is very close to the critical value, flood cost is generated.

## 5. Results of the Developed Software

As previously mentioned, the basic concept used for the system’s optimization during a flood event is the suitable relegation of the reservoirs water level in order to hold the upcoming runoff from the catchment area. The draining of the reservoirs is proposed to be achieved in a beneficial manner, *i.e.* through the power generation by the hydroelectric plants. Therefore, the unknown and under determination variables are the utilization factors (UF) of the three power plants, who receive values from 0% (for zero function) up to 100% (for 24 hours performance).

The simulation starts with the rain forecast for the next five days and covers a time period of at least ten days until the completion of the runoff. Given the water levels of the reservoirs at the start of the simulation the software examines all the alternative modes of operation of the three hydropower plants, *i.e.* different combinations of the utilization factors. For each management scenario the model ARDAFLOODS simulates the routing in waterways and reservoirs, which accept as inflow the predicted runoff of their catchments as well as the provision of upstream waterways and as outflow the discharge through the hydroelectric plants and through the spillways. For each time step the generated hydroelectric power is calculated during the flood event as well as the capability of power generation by the stored water in the reservoirs at the end of the episode.

The optimum solution can be achieved in two options. In the first option, the management scenarios are ranked in a descending order in relation to the generated power. At the same time, on the basis of the flood peaks, which are formed downstream of the three reservoirs, those scripts that cause floods are excluded. Therefore, as a best option proposed that management scenario, where the maximum power is generated (from the list presented in descending order), but at the same time it is not producing a flood downstream of the reservoirs.

The second option in the selection of the optimal management plan is based on a synthetic evaluation criterion, aiming to the system optimization, defined as follows: economic evaluation of the generated power and in the meanwhile economic evaluation of the (potential) damage due to flooding from the routing of the flood waves in Arda River through the three reservoirs. Thus, the assessment and classification of all management scenarios of the reservoirs is made on the basis of the benefit from power generation minus the corresponding flood costs derived from the released amounts of water from the three reservoirs.

The answer to the question of which is the best way for selecting the optimal management plan is immediately determined once a realistic data is entered in the software. Both options lead to the same result since the flood cost is usually orders of magnitude higher than the extra benefit from the generated power with the use of different operations during the flooding crisis. Therefore, the use of real data leads to the maximization of the generated power and to the avoidance of a flood event, since the added benefit from the generated power is estimated at around a couple of thousands of euro, while the flood costs amounting to tens or hundreds millions of euro.

**Figure 4** illustrates the results of the software for a hypothetical flood event. At the top of the figure is the ranking list of various alternative management plans which are classified on the basis of the overall benefit in euro (column 5). The overall benefit results from the energy benefit (column 6) minus the flood costs (column 7). As it is observed, the optimal management plan for these conditions for the operation of hydroelectric plants of Kardzali, Studen-Kladenets and Ivaylovgrad are 100%/100%/100% (column 1) respectively. In column 2 is given the peak discharge that is created after the last (downstream) dam of Ivaylovgrad

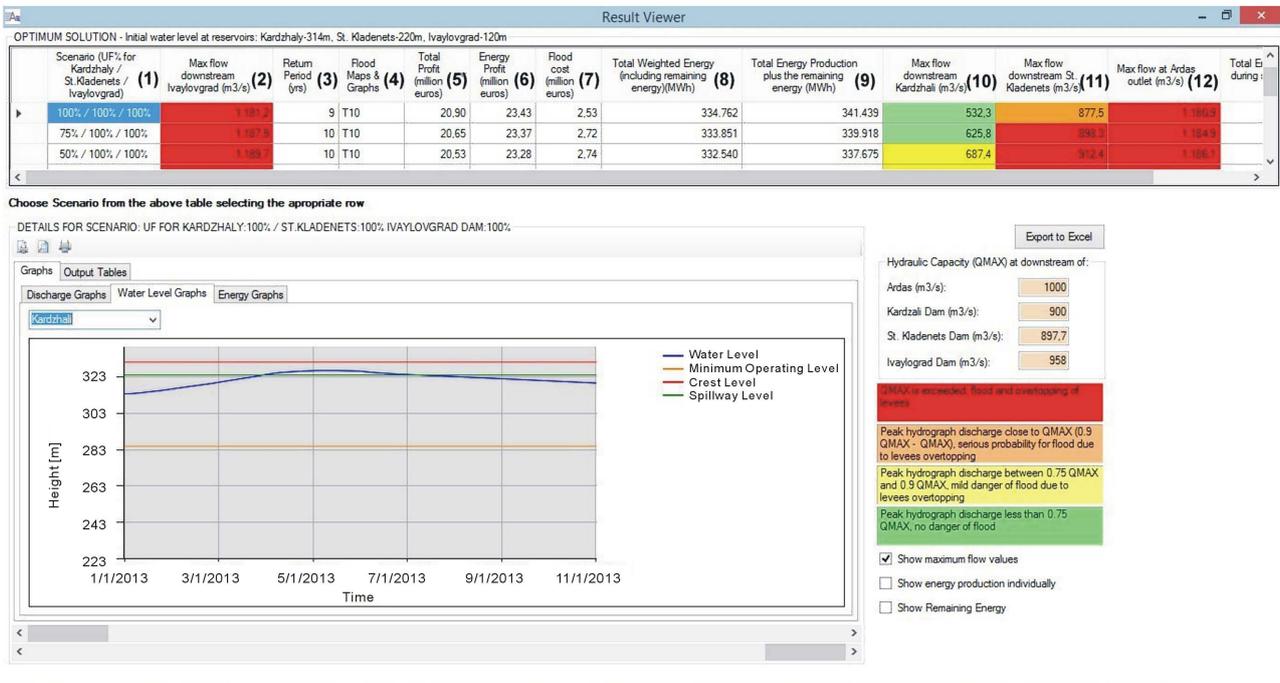
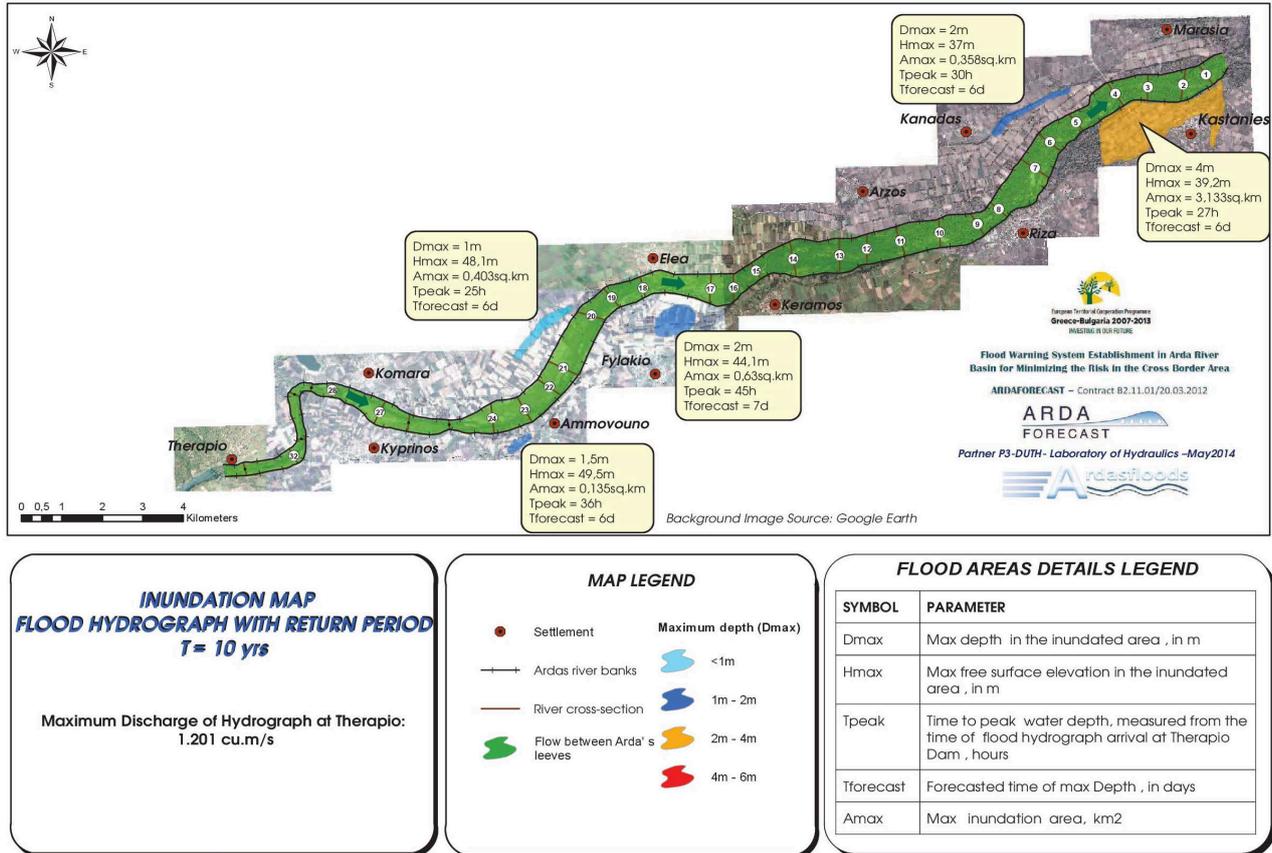


Figure 4. Table of selection of optimal management plan and indicative information diagrams of the developed software.

and the red coloration indicates the exceeded limit discharge above which floods will be caused. In column 3, this peak discharge is assigned to the return period and the inundation map is appeared as well as a series of hydraulic information (*i.e.* flow depths, water elevations, flow velocity, travel times, overflows) by selecting column 4, see Figure 5.

Because of the fact, that the generated power during the 24-hours period does not have the same pricing value, the software calculates the total energy in MWh, as it is presented in column 9, which will be produced during the flood event as well as with the water that will remain in the reservoirs. In column 8 is calculated the equivalent weighted energy. In columns 10 and 11 are given the peak discharges downstream of dams Kardzali and Studen-Kladenets, while in column 12 the peak discharge at the confluence of Arda and Evros rivers is given. These discharges have been colored with criterion the risk according to the following assumptions:

- 1) with red color when the created peak discharge exceeds the critical discharge  $Q_{critical}$  overflow of the levees,
- 2) with brown color when the peak discharge is between 90% - 100% of the critical discharge  $Q_{critical}$  so there is a serious possibility of overflowing or failure of the levees,
- 3) with yellow color when the peak discharge is between 75% - 90% of the critical discharge  $Q_{critical}$  so there is a medium risk of overflowing or failure of the levees and,
- 4) with green color when there is no risk and the peak discharge rate is less than 75% of the critical discharge  $Q_{critical}$ .

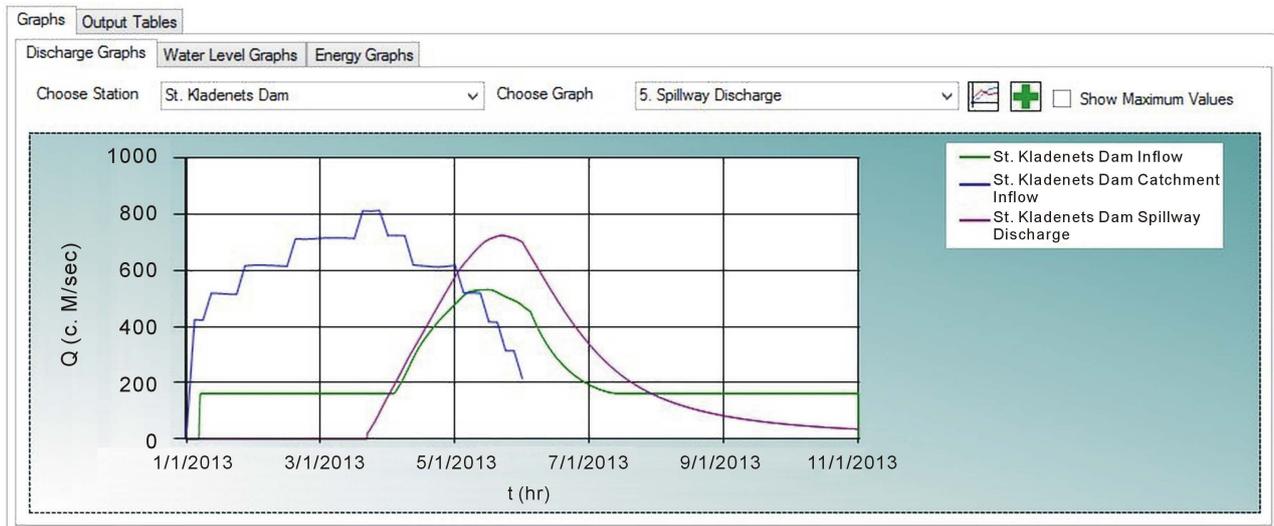


**Figure 5.** Inundation map of the near the Arda River area downstream the last dam and until the confluence of Arda and Evros Rivers.

The table of results in **Figure 4** is extended to the right by providing additional information and downwards by presenting the evaluation results of the different management plans. Moreover, the software is capable of producing a variety of graphs and tables *i.e.* hydrographs of the inflow and outflow at the reservoirs and the waterways (**Figure 6**).

### 6. Conclusions

A new computer software program has been developed for the simulation of the rainfall-runoff and flood routing processes of the transboundary Arda River basin. It is taking into account the existence of the three cascade dams and is suitable for crises periods, when significant precipitation is forecasted. The basic idea is the early lowering of the reservoirs' water level in an economically advantageous manner, in order to accommodate the upcoming runoff. Existing software packages usually model reservoir operations on the basis of predefined rules and constrains, while our new software is based on a synthetic evaluation criterion, which is the economic evaluation of the generated power minus the flooding cost. Despite the fact that the developed software has been developed for a specific river basin, it can be also utilized in any basin containing cascade artificial reservoirs.



**Figure 6.** Typical diagram of the inflow in a reservoir from the catchment area and from the upstream waterway and outflow through the hydropower plant and the spillway.

We studied and proposed the rational management of the dams in conjunction with early prognosis, in order to be achieved a total optimization of the system during the flood episode. To avoid economic loss, the drain of the reservoirs is carried out through the hydroelectric power plants by producing electricity even at a time which is not required. The optimal water releases from each reservoir are the main objective of the developed software. The software finds the best releases through the hydropower plants in order to maximize the total profit, *i.e.* energy profit minus flooding costs. It is also a useful tool of floods forecasting and constitutes the basis of an early warning system.

As shown by the present investigation the flood costs are usually much larger than the economic profits of hydroelectric energy production during a flood crises period. Searching for the best management scenario, we noticed that the additional benefit from the power generation with various management ways assesses a few thousand euro, while the flood costs amounting to tens or hundreds millions of euro. For that reason, the optimum solution is usually located at the maximization of the generated power, but at the same time with the avoidance of a flood event in any case.

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