ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
СОФИЯ

Том Volume 52 | 2019 | Брой Issue S1

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY
SOFIA

*Получена: 03.06.2019 г.*
*Приета: 17.06.2019 г.*

# IMPROVEMENTS OF THE HYDROLOGICAL MODELLING, SOFTWARE APPLICATIONS AND DAM OVERFLOW COMPUTING IN ARDAFORECAST PROJECT FOR ARDA RIVER BASIN

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***Keywords:*** *hydro forecasting, ARDAFORECAST, SURFEX*

## ABSTRACT

ARDAFORECAST project (AFP) was designed and accomplished within EU INTERREG program within two years and the flood forecasting started to operate in April 2014. After 5 years of operation we estimate the project efficiency in terms of statistical scores of streamflow forecast and achieved public awareness. It appears that the system is successful enough but has to be updated in several directions. In this paper we present the improvements made during the past 5 years as well as the next planned ones. The software platform being based on a scientific common code, the National Institute of Meteorology and Hydrology – Bulgaria (NIMH), as main project partner and responsible for the maintenance of the AFP, implemented the recent advances accomplished by the international team developing the SURFEX platform at Météo-France. New calibration of model parameters was performed using river catchments where automatic stations were installed. The software between the hydrological model and the hydro-meteorological database was optimized and an important update was performed in the computing of dam overflowing rate during floods. Further improvements are expected to be included in the FLOODGUARD project starting in May 2019. The latter is supported by the Ministry of Internal Affairs – General Directorate Fire Safety and Civil Protection and will be founded by INTERREG V-A program.

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## 1. Introduction

AFP was implemented between March 2012 and April 2014 with a total budget of 823k€ including 123k€ national co-financing. The project was funded within the INTERREG III program and was performed by four partners from Bulgaria and Greece under the title “Flood Warning System Establishment in the Arda River Basin for Minimizing the Risk in the Cross Border Area” and acronym ARDAFORECAST. It is implemented in the cross-border region between Bulgaria and Greece and is devoted to the creation of a flood warning system. Thus the project supports the implementation of flood mitigation measures and reduces the adverse consequences of flood events for human health, environment, cultural heritage and economic activity in cross-border area [1]. The core of the project was the development of automated flood forecasting system for riverside settlements in the Arda River basin (Fig. 1) in Bulgaria and at the border with Greece. The system was built on the basis of a Soil-Vegetation-Atmosphere Transfer (SVAT) model – SURFEX coupled with TOPODYN hydrological model [2]. The former is using several physically founded schemes including water balance equations to compute the evapo-transpiration, drainage water and surface runoff. Then a variant of the hydrological model TOPMODEL is used to compute the route of water to river reaches [2]. Input forcing data for the computing system is mostly based on measured precipitations, air temperature, relative humidity etc., but for the 5 days of the forecasting period such data is available from meteorological high-resolution atmospheric models ALADIN-BG and ECMWF deterministic model, whose resolution and quality was further improved in 2016 [3]. Important part of the forecast is dedicated to Arda Reservoirs inflow and overflow prediction. The latter is based on separate software realized in Excel VBA [4]. In October 2015 AFP received an award from the Ministry of Regional Development as the best example into priority axis “Quality of Life – Protection, Management & Promotion of the Environment Resources” for the European program period 2007 – 2013 [5].

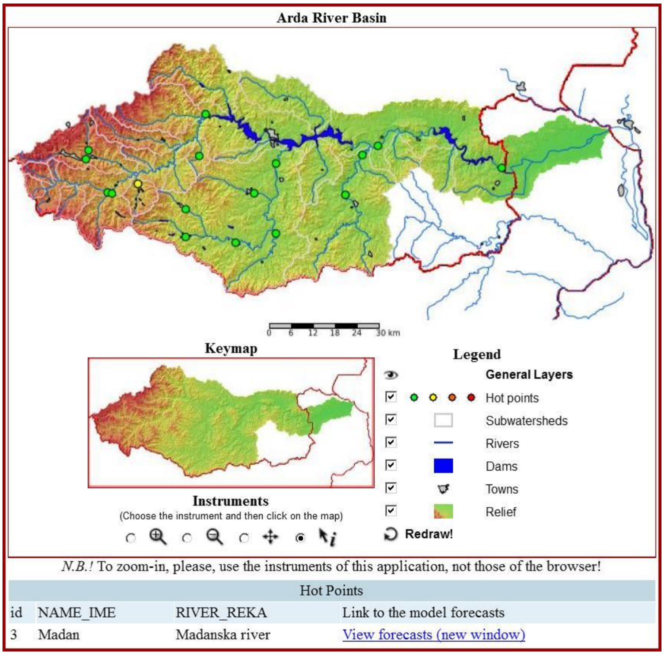


**Figure 1. Map of settlements with provided on-line flood forecast information**

## 2. Short Description of the Modeling System and of the Dam Overflow Forecasting

The hydrological model usually deals with predefined amounts of runoff and drainage water that it routes through the river network until it reaches a river cross-section of interest (that we call “hotpoint”) for which we compute the forecasted discharges. The computing of surface runoff and drainage per-unit area here is made by the surface scheme ISBA (Interface Soil Biosphere Atmosphere) [6]. ISBA as other specific models is built into SURFEX – the Land and Ocean Surface Platform for the simulation of earth surface variables and fluxes developed by the scientific community lead by CNRM – Météo-France. The hydrological model coupled with ISBA is a version of TOPMODEL that is based on the basin topography. The coupling was firstly developed for the simulation of fast floods in Mediterranean region in France [7]. That makes the models suitable for the ARDAFORECAST project dealing with the Mediterranean rivers, too.

When a hydrological model is fed with data coming from a forecasting meteorological model we can predict to some extend the streamflow corresponding to the forecasted precipitation intensity and location. In this project we combine precipitation and air temperature data from the following weather forecast models: A. Regional scale short range ALADIN-BG model – 3 days ahead forecast; B. Global scale model – European Centre for Medium Range Forecast (ECMWF) – 5 days ahead forecast.

The overflow estimate of the dam is performed by a fully automated application, with a cascade simulation of the high wave transition in the dams from the Lower Arda cascade. All three dams are treated and a result of a hydrological model for the streamflow discharge from owns catchment is included [8]. Additional flow for the cascade dams includes the flow of the forecasted outlet of the upper dam. The specificities of the overflow & release facilities for each of the dams are reflected in the transitions curves, account is taken of historical information on the operation of the relief facilities at the high wave transition (HPP, main exhaust, overflow valves). The application reads from the database latest current dam levels and the newest forecasted inflow for 5 days ahead. Data is processed by calculating free volume, time to overflow, and a number of checks based on future scenarios are performed. The application is autonomous and runs every hour, reflecting the latest changes (new forecast, new current levels). As a result, the data is recorded in a text file with an estimate of water quantities every three hours as a streamflow discharge after each dam.

### 2.1. Main Problems to Solve

The main problem in hydrological forecasting is firstly to achieve a good simulation of series of streamflow discharges (or water levels) using measured (not forecasted) precipitation data. Quality is assessed after comparison of simulated series to daily average streamflow discharge series computed by hydrologists. That means that quality of measured precipitation field is directly reflecting in the hydrological model set-up, calibration and statistical results. In Arda River basin the source of precipitation data are 24h accumulated measures of NIMH network and the automatic stations of the project in the area (Fig. 2). Estimation of snowfall, which is important for the snow accumulation & melting process, depends on air temperature measuring stations at the locations of automatic stations. It can be seen that some mountain parts are not covered enough by such information. Forcing fields of liquid and solid precipitation and air temperature are prepared following the procedures described in [9].

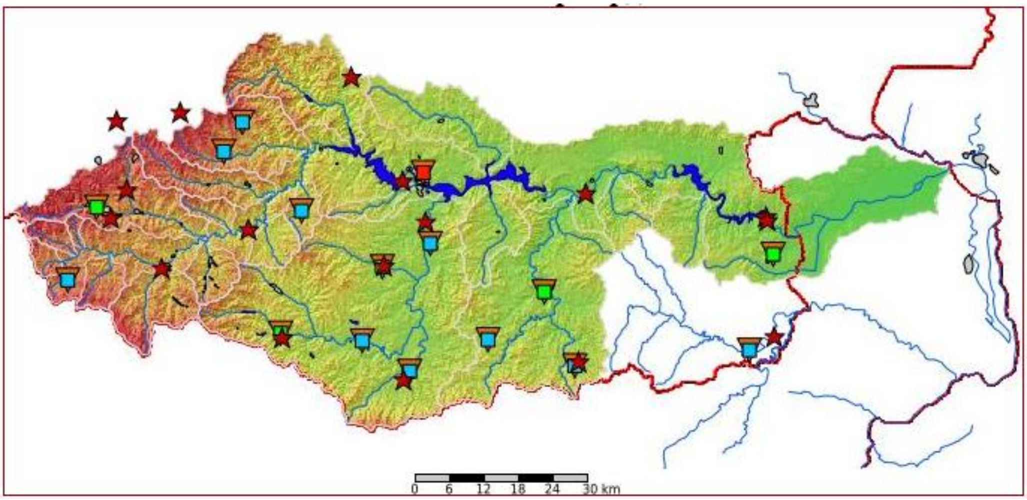


**Figure 2. Precipitation measuring stations in Arda River Basin. Stars show the automatic gauges and boxes show the conventional stations**

## 2.2. Prediction of an Overflow

The overflow forecast is made using a fully automated Excel VBA application. The base of the application is cascading simulation of the passing of the wave trough the dams of the Arda River. All three reservoirs are handled in the add-on and the result of the hydrological model for each own watershed is included. As additional inflow to each dam is added the predicted from the application outflow from the upper dam.

The specifications of the spillways, gates, outlets and HPP for each of the reservoirs are used including rating curves of the reservoirs (levels in reservoir against volume & overflow). Beside that historical information about the operation of the gates, outlets and HPP during the high waves were analysed and included.

The application reads from a database the most recent values of the water levels in the dams and the newest forecast of the inflow for each dam computed by the hydrological model. The data are processed by computing water volume, free volume, time to the overflow and overflow height with iterative calculations and automatic checks based on future and past scenarios. The application is self-contained and runs on a schedule, reflecting the latest changes (current forecast of own inflow and actual water levels). Resulting data series are stored in a text file containing forecasted streamflow discharge quantities after each dam for the next five-day period with 3h step.

### 2.2.1. Prediction of an Overflow – Kardzhali Reservoir

When the level is expected to reach 323,00 m, elevation is increasing ≥ 4 cm per hour and the forecasted inflow exceeds the capacity of the turbines of the Kardzhali HPP, a "High Wave Transition Personnel Action" is activated. At the point when the water level reaches the elevation of 324,30 m, overflowing is forecasted.

The spillway of the Kardzhali reservoir includes 4 spill gates. Each of them, upon reaching the normal upper storage level and maximum opening, has a discharge capacity 220 $m^3/s$. The spillway of the Kardzhali dam is designed for total discharge of all four opened gates corresponding to 3100 $m^3/s$ when the water level in the reservoir is at the absolute maximum permissible level. The main outlet consists of 2 pipes with a total capacity 880 $m^3/s$. There is also an additional tunnel outlet with capacity of 1680 $m^3/s$ at normal upper storage level. The Kardzhali HPP includes four turbines designed to conduct in total 162 $m^3/s$.

### 2.2.2. Prediction of an Overflow – Studen Kladenets Reservoir

The rules of the “Instruction for the Activities of the Personnel During the High Wave Passing Through the Studen Kladenets Reservoir” are integrated in the flood forecast. When the level is expected to reach 224,0 m, elevation is increasing ≥ 4 cm per hour and the forecasted inflow exceeds the capacity of the turbines of the Studen Kladenets HPP at the point of water level reaching the elevation 225,0 m, overflowing is forecasted. The number of open valves is determined according to the forecasted inflow, predicted water level and overflowing height. The forecasted end of the overflow is corresponding to the time when the water level in the reservoir becomes identical to the “maximum working water level”.

The spillway of the Studen Kladenets Dam includes 9 spill gates, each of which, upon reaching the normal upper storage level and maximum opening, has a discharge capacity of 230 $m^3/s$. The total discharge for all spillway gates is 3600 $m^3/s$ when the water in the reservoir is at the absolute maximum permissible level. The main outlet consists of 2 outlets with a total throughput of 180 $m^3/s$. The HPP includes five Francis turbines designed to process a total of 150 $m^3/s$.

### 2.2.3. Prediction of an Overflow – Ivailovgrad Reservoir

Overflowing is forecasted when the level is expected to reach 120,20 m and the forecasted inflow exceeds the water quantity through the turbines of HPP. With the given dam construction, the manipulations are possible only with the main outlets. They are manipulated similar to the gates of Studen Kladenets – the total outflow through the outlets and through the turbines of HPP has to be equal to the incoming water quantity, i.e. the level in the reservoir remain stationary.

The overflow of the dam is without gates and is designed for a discharge of 5250 $m^3/s$ that corresponds to 0,1% statistical probability. The main outlet consists of two pipes with a total discharge of 270 $m^3/s$. The HPP includes 3 turbines, which are designed to process a total of 279 $m^3/s$.

### 2.2.4. Calculation of the Overflowing Water Quantity

The forecasted overflow is calculated based on the basic hydraulic formula for overflow discharge like “practical” profile and is presented according to [10]:

$$Q = m_k b \sqrt{2g}\, H^{3/2}, \tag{1}$$

$m_k$ is Coefficient of discharge;

$b$ – Effective spillway length;

$H$ – Total height over the spillway.

For the needs of the forecast the equation is used to determine the Coefficient of discharge for typical discharges.

$$m_k = \frac{Q_k}{b\sqrt{2g}\, H^{3/2}}. \tag{2}$$

### 2.3. Forecast Data Analysis

An analysis of the observed and projected data for the period from 2019-02-04 to 2019-04-16 has been carried out on the water volumes in the dams listed in Tab. 1, taking into account forecasts started respectively 3h, 6h, 12h, 24h, 48h, 72h and 96h before the newest actual data from automatic water level stations of the reservoirs.

Fig. 4 shows the temporary curves of reservoir water volumes. Dark colour indicates the measured values, while shades of grey indicate the forecasts depending on the time to measure the actual volumes.

Accuracy evaluation of the model's predictions is performed with the Nash–Sutcliffe efficiency ***E*** [11] and percent bias (PBIAS).

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than the observed counterpart.

The percent PBIAS is calculated as:

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n} Q_{obs,i} - Q_{\mathrm{mod}el,i}}{\sum_{i=1}^{n} Q_{obs,i}} 100\,. \tag{3}$$

Nash–Sutcliffe efficiency can range from −∞ to 1. An efficiency of 1 ($E$ = 1) corresponds to a perfect match of modelled discharge to the observed data. In case of $E \le 0$ the model is considered ineffective.

According to values of $E$ and PBIAS, Moriasi et al. in [12] introduce the following criteria for assessing the accuracy of the model data:

$E > 0{,}80$ and PBIAS $\le \pm 5$ the results are very good;

$0{,}70 \le E \le 0{,}80$ and $\pm 5 <$ PBIAS $< \pm 10$ results are good;

$0{,}50 < E < 0{,}70$ and $\pm 10 \le$ PBIAS $\le \pm 15$ results are satisfactory;

$E \le 0{,}50$ and PBIAS $> \pm 15$ the results are not satisfactory.

**Table 1. Automated stations whose data was analysed**

| Reservoir | ID | Analysed data |
|---|---|---|
| Kardzhali | 61751 | volume |
| Studen Kladenets | 61801 | volume |
| Ivailovgrad | 61901 | volume |
| outflow Ivailovgrad | 61900 | water quantity |

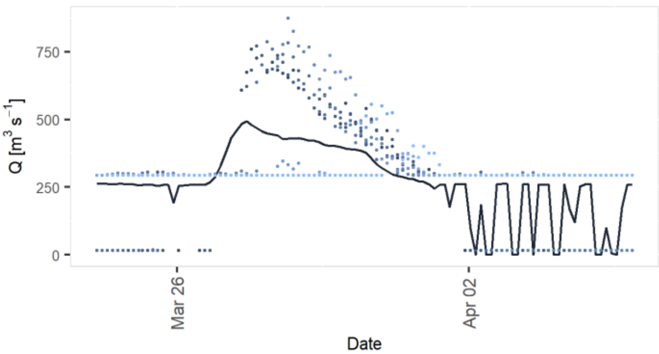


**Figure. 3. Measured and forecasted discharge after Ivailovgrad reservoir 26.03 – 02.04.2018**

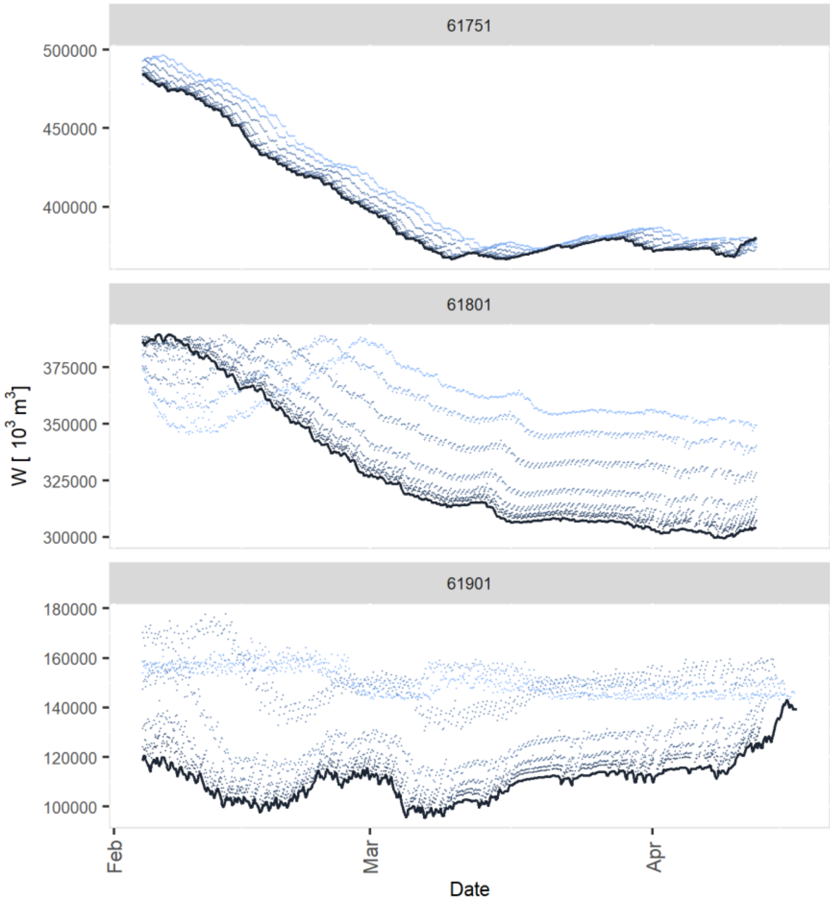


**Figure. 4. Measured and predicted water volumes in reservoirs**

## 3. Improvements after the Projects Implementation Period

During projects development the extensive works were directed towards establishment of a stable river flow forecasting platform for the Arda River basin. However, for some river stations (Byala-Smolyan, Elhovska-Rudozem and Arda-Kitnitsa) the lack of data series with high quality didn't allow acceptable calibration of parameters. Moreover, in August 2017 the dataflow of five hydrological and 18 precipitation stations was interrupted as they were the property of an independent state-owned enterprise. Thus NIMH had to re-establish hydrological and precipitation measurements at many locations. Beside the flood damage mitigation, an important aim of the project was to serve as a basis for scientific development. Here a short list of achievements is following and more explanations are given in the next chapters:

- Quality assessment and further development of the reservoir inflow simulation, water storage and overflowing computation scheme;
- Quality assessment of streamflow simulations and integration of novel model developments;

- Enhancing the public awareness about the flood-forecast information systems at NIMH.

### 3.1. Improvements Performed Within the Dam Overflow Computing System

The cubic equation for calculating the overflow height was giving inaccurate results leading to an increase in the outflowing water quantities from Ivaylovgrad reservoir. New rating curves *Q-H* were prepared achieving more accurate determination of the outflow.

Optimizations were worked out of the way and changes to the conditions for the number of open gates of Studen Kladenets reservoir according to an emergency plan for conducting a peak flow through the dam.

A number of automatic checks were introduced, in case of absence of actual volumes from the automatic stations, for calculating the volume in relation to the dam rating curve. An overflow check for *H* and *Q* was added, as well as an overflow limitation introduced, the discharge from the dam being equal to the inflow with reflection of the water retention capacity of the reservoir.

### 3.2. Statistical Scores of the Streamflow Discharge Simulation Compared to the Measured Data Series

Achieving satisfactory simulation with measured meteorological input is needed firstly to initialize the forecasting model and secondly to assess the model's efficiency itself without interfering with the forecasting precipitation efficiency. After AFP implementation, since 2014 to 2019, the hydrological model was used as a basis of scientific development. Novel options developed within the SURFEX community were tested. One of them is the "multi-layer soil diffusion" (DIF) scheme [13] and the other is the "multiple energy balance" (MEB) [14]. We tested the above schemes combined with DT92 [15] subgrid runoff against the former ISBA 3L scheme combined with TOPD subgrid runoff [16]. Validation results for the year 2018 are shown in Tab. 2. Used statistical coefficients are Nash coefficient – $\boldsymbol{E}$ and $\boldsymbol{R^2}$ – determination coefficient. At Tab. 2 best results (higher values) are emphasized with red color. For most of the stations combined ISBA DIF–MEB option outperforms ISBA 3-L combined with TOPD subgrid runoff. It is important to note that these results were obtained after a new calibration of SURFEX-TOP (ISBA 3L+TOPD) model parameters performed for a period of one year [17].

**Table 2. Comparison of simulated against measured streamflow for 2018 year**

| River-Station | ISBA 3-L+TOPD runoff | | ISBA DIF-MEB+DT92 runoff | |
|---|---|---|---|---|
| | $E$ | $R^2$ | $E$ | $R^2$ |
| Byala River-Smolyan | -0,427 | 0,513 | **0,653** | **0,788** |
| Arda-Rudozem | 0,070 | 0,302 | **0,628** | **0,693** |
| Elhovska-Rudozem | 0,242 | 0,304 | **0,339** | **0,527** |
| Cherna-Taran | 0,596 | **0,707** | **0,632** | 0,677 |
| Arda-Vehtino | 0,252 | **0,705** | **0,563** | 0,632 |
| Arda-Kitnitsa | 0,602 | 0,614 | **0,722** | **0,724** |
| Varbitsa-VarliDol | **0,823** | **0,831** | 0,509 | 0,798 |
| Varbitsa-Dzhebel | -0,970 | 0,723 | **0,363** | **0,781** |
| Krumovitsa-G.Kula | 0,766 | 0,773 | **0,877** | **0,877** |

**Table 3. Estimate of predicted data compared to measured values**

| | | Forecast time before actual events | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Reservoir/Station** | **Statistics** | **3 h.** | **6 h.** | **12 h.** | **24 h.** | **48 h.** | **72 h.** | **96 h.** |
| "Kardzhali" | PBIAS | 0,200 | 0,300 | 0,500 | 0,900 | 1,700 | 2,700 | 3,400 |
| "Kardzhali" | E | 0,999 | 0,998 | 0,995 | 0,985 | 0,946 | 0,880 | 0,812 |
| "Studen Kladenets" | PBIAS | 0,700 | 1,100 | 1,900 | 3,600 | 6,500 | 8,700 | 9,700 |
| "Studen Kladenets" | E | 0,992 | 0,982 | 0,944 | 0,785 | 0,215 | -0,622 | -1,380 |
| "Ivailovgrad" | PBIAS | 3,100 | 4,700 | 8,000 | 16,100 | 37,200 | 38,900 | 35,300 |
| "Ivailovgrad" | E | 0,653 | 0,262 | -1,050 | -6,890 | -34,200 | -31,100 | -22,200 |
| Arda R. – 61900 | PBIAS | 10,900 | 7,470 | -2,020 | -18,800 | -25,100 | -16,500 | -10,800 |
| Arda R. – 61900 | E | 0,989 | 0,724 | 0,550 | 0,368 | 0,292 | 0,173 | 0,078 |

### 3.3. Achieved Public Awareness

One of the aims of the project was to disseminate and emphasize the value of flood-forecasting systems to the large public. This was achieved by all project partners during the project implementation [4] and after that by East Aegean River Basin Directorate (EARBD) in the towns of Smolyan, Kardzhaly and Haskovo through the organization of several meetings in the concerned municipalities. At these meetings, where most of the participants were from local communities, civil defence staff and media representatives, the functioning of the flood-forecast systems, the best way to interpret the visualized data but also some issues and the need of future development were presented in detail. Gathered statistics on the number of accessed AFP web site pages for IP addresses of neighbor countries are presented in Tab. 1. Monthly history (Fig. 5) shows that in autumn-winter months when floods in Arda River basin are frequent, visited pages and bandwidth are increasing by 30%.

**Table 4. Visits of the ARDAFORECAST web site**

| Country | Period | Pages | Bandwidth [KB] |
|---|---|---|---|
| Bulgaria | Jun-Dec 2018 | 1120 | 674 |
| Greece | Jun-Dec 2018 | 133 | 76 |
| Turkey | Jun-Dec 2018 | 217 | 115 |
| Bulgaria | Jan-Apr 2019 | 1080 | 7260 |
| Greece | Jan-Apr 2019 | 89 | 456 |
| Turkey | Jan-Apr 2019 | 437 | 398 |

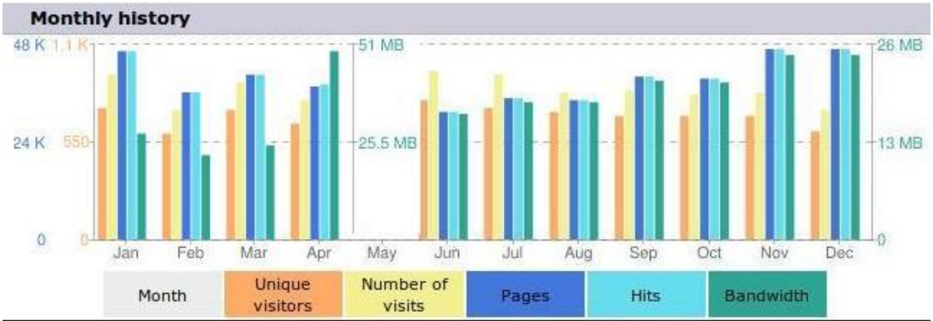


**Figure 5. Monthly history of visited pages of ARDAFORECAST web site for 2019 – 2018**

### 3.4. Next Steps for the Flood Forecasting System Improvement

Further development of the Arda River flood forecasting system is needed for several reasons. NIMH is the state organization that is in charge by the Water Act art. 171 paragraph 6 [18] for the development of such systems. After 5 years of exploitation and maintenance we found some possible enhancement directions and are planning further development steps. Such enhancements are:

- To increment the surface scheme spatial resolution from 8 to 4 km. This will bring more details in the forcing fields, also because of the more detailed orography, and corresponds to the enhanced resolution of ALADIN-BG weather forecasting model whose new resolution is about 5 km.
- To transform the time step of forcing input fields and computed streamflow forecasting series from 3h to 1h. This action is directed towards more precise simulations and forecasts.
- Set-up of new sub-catchments to be included in the simulations and forecasting. Such example is the Malka Arda River at the village of Banite.
- Installation of new hydrological, precipitation and air temperature stations and replacement of outdated measurement sensors. This is needed in relation with the spatial resolution change but also because some sensors have shown limited capacity against the real measured scale. An example is the snow scale sensor installed in the Rhodope Mountains at 1960 a.s.l. The sensor that measures snow water equivalent (SWE) up-to 500 kg/m$^2$ was installed in autumn of 2013. Since then we experienced two winters (2014 – 2015 and 2018 – 2019) with long periods of SWE higher than the sensor's capacity (Fig. 6). Snow water equivalent scale is not able to measure more than 500 mm/m$^2$ and need to be replaced.

Some of these actions will be performed by NIMH as project partner within the starting FLOODGUARD project funded by EU INTERREG V-A program. The project is led by Chief Directorate Fire Safety and Civil Protection [19] (CDFSCP) under the Ministry of Internal Affairs. Seven partners from Bulgaria and Greece are involved in the implementation that is planned to last from May 2019 to December 2021 with a total accepted budget of 4.48€ E6.

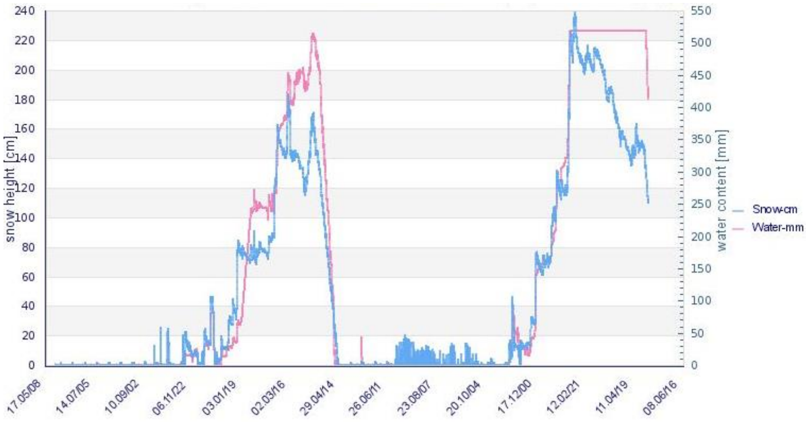


**Figure 6. Snow parameter records of the Rhodope Mountains station at 1960 m during 2017 – 18 and 2018 – 19 winter seasons. Snow height [cm] is given in blue color. SWE in red [mm/m$^2$]**

## 4. Discussion

### 4.1. Hydrological Parameters Calibration Issues and Solutions

Although models for many gauged cross-sections show acceptable statistical scores, there are some discrepancies regarding the calibration and validation procedure: we use the daily average streamflow discharge series computed by the NIMH department of hydrology. However, it would be more precise to obtain and to use hourly data series for the calibration and validation of the model parameters. In order to use hourly discharge series, they must be prepared as an additional data set that seems complicated at this moment.

There are some visible discrepancies in the comparison of simulated to measured river flow. The analysis of river flow data series and the underlying water balance components show that physics of water freezing in soil and melting in spring months might be optimized to produce more smooth drainage and runoff.

A novel option in SURFEX-TOP system permits to simulate river flow of nested river basins that was not possible until now. At the moment this issue is solved by launching in parallel several model runs for each nested sub-catchment. The new version of SURFEX – 9 is expected to be released in 2020.

### 4.2. Scientific Development

Usually national and regional projects directed to enhancement of flood protection and mitigation measures over specific watershed are using already established somewhere else set of measures and proprietary software. The later is less appropriate for scientific development as the user is able to change the parameters and the input files but not the inner behavior of the model. In our case we used the SURFEX platform [20] that comes with CeCILL-C free software license agreement – the French equivalent to the L-GPL license. The later permits to explore and to change the software code in order to obtain better physical process representation and possibly better statistical scores when comparing model results to the real data. This was made by us suggesting a "variable river speed" for the hydrological model [2]. Other aspects of the scientific development are that the flow forecasting system of AFP might be continuously updated including the new developments realized by the community [14].

## 5. Conclusion

The overall analysis shows that ARDAFORECAST is an important regional project for Bulgaria and Greece for which NIMH contributed with a performing Flood Forecasting System (FFS). This system is maintained and further developed by NIMH within its scientific program and the assigned obligations but also as basis for upcoming projects as FLOODGUARD.

## Acknowledgements

We would like to acknowledge all our colleagues that had worked on the ARDAFORECAST project and specially Prof. Dobri Dimitrov who was the initiator, scientific advisor and administrative leader during the project implementation.

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