DOI: 10.31577/ahs-2021-0022.02.0030

ACTA HYDROLOGICA SLOVACA

Volume 22, No. 2, 2021, 264 – 275

Improvement of the operational HEC-HMS hydrological model embedded in the Flood Forecasting and Warning System of the Sava River Basin

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In 2017 the HEC-HMS model for the Sava River Basin was embedded under the Flood Forecasting and Warning System in the Sava River Basin (Sava FFWS) and coupled with many hydraulic models. Since the model was initially calibrated as the event-based model, a lack of accuracy has been recognized during the continuous simulations within the Sava FFWS operational use. Therefore, the Sava FFWS users organizations: ten forecasting organizations from five Sava countries, agreed to upgrade and improve this hydrological model. The activities of the model improvement were performed in period January 2019 till June 2020. It was implemented by the national experts from the Sava FFWS users' organizations as a true joint action and coordinated by the Secretariat of the International Sava River Basin Commission. This paper presents the results of the Sava HEC-HMS model improvements and updated parameters, including a comparison of results of initial and improved models within the operational forecasting system. The paper also discusses the potentials of the remote sensing and radar- and satellite-based data that will be used for the future model improvements.

KEY WORDS: forecasting, modelling, calibration, Sava River Basin

Introduction

The Sava River is the third longest and the largest by discharge tributary of the Danube River. The length of the Sava River from its main source in western Slovenian mountains to its mouth to Danube in Belgrade is about 945 km. The Sava River runs through four countries (Slovenia, Croatia, Bosnia and Herzegovina, and Serbia). The Sava River Basin has a surface area of about 97700 km^2 and covers considerable parts of Bosnia and Herzegovina, Croatia, Montenegro, Serbia, Slovenia and a small part of the Albanian territory. The objectives of transboundary flood risk management in the Sava River Basin are regulated with the Framework Agreement on the Sava River Basin (FASRB) and the accompanying Protocol on Flood Protection to FASRB (Protocol). With respect to an efficient flood awareness and preparedness, the Protocol has committed all Sava countries to establish a joint flood forecasting system for the entire Sava River Basin under the coordination of the International Sava River Basin Commission (ISRBC). The Flood Forecasting and Warning System in the Sava River Basin (Sava FFWS) was established in October 2018 and represents a comprehensive and versatile system that combines data and models of individual countries, as well as common models, making it a unique example of cross-border cooperation in flood forecasting even globally. Sava FFWS currently has ten users, i.e. national organizations responsible for the flood forecasting and it is hosted at five locations: primary and three backup server modules that are installed in the four Sava countries, while archive and web server in ISRBC.

One of hydrological models integrated in Sava FFWS is the HEC-HMS model for the Sava River Basin (Sava HEC-HMS) which represents the backbone of system. The model was initially calibrated as event-based hydrological model on several selected periods, up to a six-month long. Calibration periods were mainly from the winter seasons characterized by average to high flow conditions while dry and low flow periods were not included. In the operational mode within Sava FFWS the lower reliability of Sava HEC-HMS was recognized during the continuous simulations. It was suspected that the way of the initial calibration was one of the reasons for less accurate simulations of the state of the model and forecasts. Given that Sava FFWS currently collects real-time data from many meteorological stations that were not included into the initial Sava HEC-HMS model it was reasonable to expect that the improved density of the meteorological stations would result with the improved hydrological model. Sava HEC-HMS calibration, as the process of estimating model parameters by comparing model outputs for a given set of assumed conditions with observed data for the same conditions, was performed. Validation involved running a model using input parameters measured or determined during the calibration process. According to Refsgaard (1997), model validation is the process of demonstrating that a given site-specific model is capable of making "sufficiently accurate" simulations, although "sufficiently accurate" can vary based on project goals (Moriasi et al., 2007). A number of publications have addressed model evaluation statistics (Willmott, 1981; ASCE, 1993; Legates and McCabe, 1999) as well as some recently developed statistics that were used within the study.

In this study the Sava HEC-HMS model was updated without interventions on the hydrological modelling processes while the number of the measuring locations was significantly increased and the model parameters were assigned in the process of the calibration suitable for the continuous models. The process was jointly performed by the users of the Sava FFWS under coordination of ISRBC.

Flood Forecasting and Warning System in the Sava River Basin

Sava FFWS is operating as an open shell platform for managing the data handling and forecasting processes trough the integration of the wide range of external data and models (Deltares, 2018). This concept is particularly important for the cooperating countries, taking into account that the Sava River basin is shared by five countries where each country is using its own models, monitoring systems, forecasting systems, water authorities and interests.

Sava FFWS integrates the Hydrological Informational System for Sava River Basin (Sava HIS) – data hub for the collection of real-time observed hydrological and meteorological data (precipitation, air temperature, snow, water levels, discharges); various Numerical Weather Prediction (NWP) models; available weather radar and satellite imagery; outputs of existing national forecasting systems and different hydrological and hydraulic models (Fig. 1), including the Sava HEC-HMS model as the backbone of system.

The system is in use simultaneously by several organizationally independent forecasting teams (Table 1). Given the open nature of the Sava FFWS environment, responsibilities for the output and the forecast dissemination within each country are very clearly defined in accordance with the national legislation.

An effective Sava FFWS has aim to bridge differences and supports collaboration in the field of hydrological

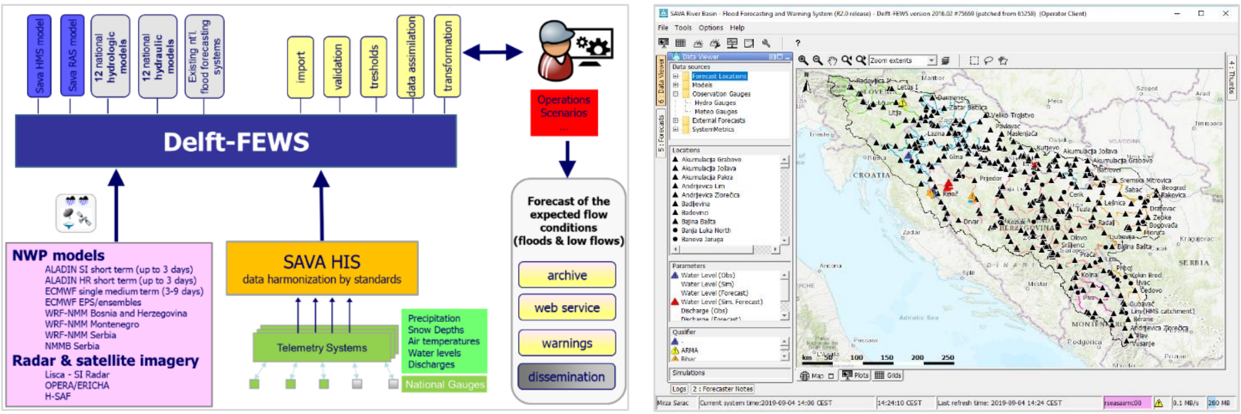

Fig. 1. Schematic overview of the Sava FFWS and screen of the operator client (forecasting locations).

Table 1. List of the Sava FFWS users and hosting organizations

Country	Institution	Note
Slovenia (SI)	Slovenian Environment Agency	Central server and User
Croatia (HR)	Croatian Meteorological and Hydrological Service	User
	Croatian Waters	3rd backup and User
Bosnia and Hercegovina (BA)	Federal Hydrometeorological Service	User
	Sava River Watershed Agency	2nd backup and User
	Republika Srpska Hydro-Meteorological Service	User
	Public Institution "Vode Srpske"	User
Serbia (RS)	Republic Hydrometeorological Service of Serbia	1st backup / test system and User
	Public Water Management Company "Srbijavode"	User
Montenegro (ME)	Institute of Hydrometeorology and Seismology	User
	International Sava River Basin Commission	Archive / web server and Coordinator

forecasting keeping the countries own autonomy in monitoring, modelling and forecasting and remain open to developing its own models and supplementary forecasting initiatives. The system is assessed as added value to existing or developing systems, expecting that a common forecasting platform with well trained staff should provide better preparedness and optimized mitigation measures to significantly help reduce adverse consequences from floods, in future from droughts, ice hazards.

Models setup within the forecasting platform

The setup of Sava FFWS is modular where the combination of a numerical weather prediction and observations of precipitation and temperature, a hydrological model converting precipitation and temperature to discharge and, in most cases, a hydraulic model routing discharge downstream and computing water levels, define a unique forecast workflows (Deltares, 2018). Due to the number of hydrological models, hydraulic models and numerical weather prediction models available for the Sava River basin, several forecast workflows are configured in Sava FFWS. In case there was no hydrological model connected to a hydraulic model, the Sava HEC-HMS model covering entire basin is connected to deliver lateral flows.
In this moment 13 hydrological models are included in Sava FFWS where some of them are integrated models including hydraulic component. Some cover complete basin or a large area, others just small local river basins. HEC-HMS for the Sava River Basin and WFlow (BA, ME, RS) are models representing hydrological processes on the complete or the major part of the Sava basin. While Mike-NAM Sava (HR), Mike-NAM Una (BA/HR), Mike-NAM Vrbas (BA), HBV-light Bosna (BA), WFlow (ME), HEC-HMS Kolubara, HBV Kolubara and HBV Jadar (RS) are models with the local or national coverage.
Regarding hydrological modelling, the backbone of the Sava FFWS forecasting system represents the Sava HEC-HMS model, as the only hydrological model that covers the entire Sava River Basin. The model was developed by the U.S. Army Corps of Engineers (USACE), in close collaboration with ISRBC and national experts and initially calibrated as event-based model.

Development and update of the HEC-HMS model of the Sava River Basin (Sava HEC-HMS)

Initial Sava HEC-HMS model (version 1.0)

Sava HEC-HMS model consists of 235 subbasins, carefully selected to take the local hydrology into account, 174 junctions mainly located at the hydrological stations locations or locations of confluences and 158 river sections as well as 20 reservoirs. Sava HEC-HMS simulates hydrological processes through the meteorological and basin model working together to define the rainfall-runoff processes within the watershed. The meteorological model provides precipitation in the form of rain or snow as input to the basin model, while the basin model uses input loss parameters to calculate precipitation lost to storage in the watershed, precipitation infiltrating into the soils, and the subsequent amount of excess runoff precipitation. Excess precipitation is routed to the subbasin outlet as overland flow using a unit hydrograph transform (Clark Unit Hydrograph) method. Precipitation infiltrating into the soil is routed to the subbasin outlet using the recession baseflow method. Overland flow and baseflow are combined at each subbasin outlet before entering the reach network. As the combined flow is routed down through the river reach network of the basin, flow is aggregated from additional subbasins and routing reaches in hydrological order (USACE and ISRBC, 2017).
Evapotranspiration rates are also defined within the meteorological model where the Monthly Average method was utilized to represent evapotranspiration rates in the basin but also considering that the evapotranspiration is not a critical component for short-term simulations.
Hourly precipitation and temperature data at all available meteorological stations in period of the initial model development were integrated, 74 meteorological stations in total (rainfall and air temperature).
In addition to the relatively modest number of meteorological stations, within the Sava River Basin existed areas where precipitation input was very sparse. In an attempt to rectify the lack of observed precipitation in these areas, the Inverse Distance Weighting precipitation method (IDW) was applied. The IDW method calculates subbasin average precipitation by applying and inverse distance squared weighting all available precipitation gages in the user-specified search radius (Feldman, 2000).
A dense coverage of stations exists in the headwaters of the Sava River Basin, mainly in Slovenia while there is a relative lack of stations in the middle and far downstream portions of the basin. Fig. 2 illustrates the areas of the Sava River Basin with less meteorological station coverage showing every station with a 25-km radius buffer overlaying the basin delineation, and 50-km radius that was at the end used as a necessity. This was one of the main gaps of the initial model but a result of the real precipitation stations network coverage in the period of the model development.
In addition to precipitation in the form of rainfall, the meteorological model is configured to compute the snowmelt and for that purpose the temperature index method was used. The meteorological model, at every time step, whether the precipitation falling is rainfall or snowfall based on the temperature data at nearby meteorological stations. The temperature index approach considers snowmelt as a mass-balanced process (Feldman, 2000).
Available snow-related data in the Sava River Basin are very limited, therefore the most parameters for the snowmelt method were established from the related studies and the consultation of the USACE snow experts.

Initial snow-water-equivalent (SWE) values and elevation band parameters were developed through GIS processes on available data. Daily Advanced Microwave Scanning Radiometer (AMSR-E)/Aqua Level 3 global snow water equivalent grids were compiled from the National Aeronautics and Space Administration's (NASA) National Snow and Ice Data Center (NSIDC) in Boulder, Colorado USA (Tedesco et al., 2004). Due to the large grid size of the SWE grids, the accuracy of this method is uncertain. However, the satellite-based SWE grids were the best available data at the time of model development.

Elevation bands, which are input into the meteorological model to account for the differences in snowfall and snowpack across the range of elevations in each subbasin, were developed as the elevation-area relationships using the SRTM DEM digital elevation map with 30 meter resolution (Rodriguez et al. 2005). These elevation-area relationships were segmented at natural breakpoints in the topography to define the elevation bands for each subbasin. For each defined elevation band, initial snowpack parameters were required to define any snowpack that may be present at the beginning of the hydrological model simulation. The aforementioned AMSR-E SWE grids were used to define the initial SWE for each elevation band within each subbasin.

The Sava HEC-HMS basin model consists of 235 analytical units carefully selected to take the local hydrology into account (Fig. 3). A unique local characteristic in Sava River basin is the presence of karst which affects the subbasins boundaries and the parameterization of the subbasins. For some specific areas like karst geology, levees, and canals especially in the flatter areas of the basin SRTM DEM needed to be manually manipulated.

SRTM DEM and the GIS module of the HEC-HMS were also used to generate the physical parameters of the Sava River basin such as drainage area, stream lengths, basin slopes, etc. From these physical parameters, initial estimates of unit hydrograph parameters, time of concentration and storage coefficient were developed for each subbasin. Reach routing parameters, such as reach slope and length, were also extracted.

The Sava HEC-HMS implements various methods to represent the rainfall-runoff processes of the basin of interest. Various factors contributed to the decision for each of the modeling component methods Sava River Basin such as applicability of the method based on specific basin characteristics (such as terrain and urbanization) and availability of data supporting a specific method.

25 km radius　　　　50 km radius

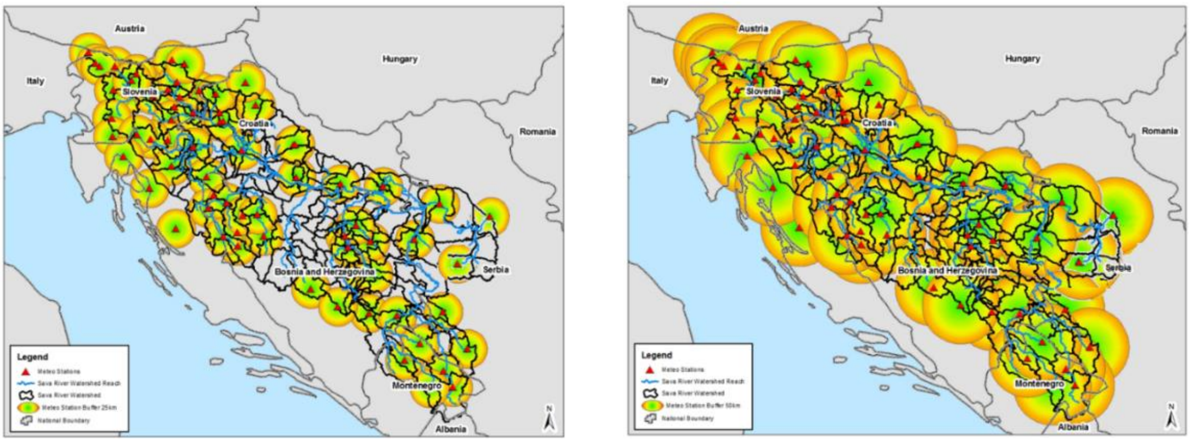

Fig. 2. Precipitation gauge coverage (Sava HEC-HMS v1.0).

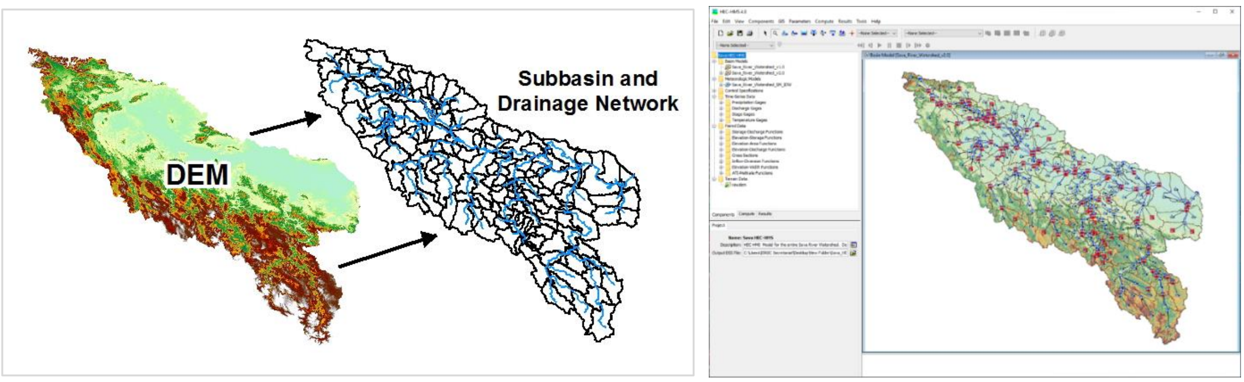

Fig. 3. Illustration of the SRTM DEM conversion to subbasin and river network and the final model structure.

The decision to use these methods were based on:

- Simple Canopy Method – chosen for its simplicity due to a lack of available data defining the canopy.
- Deficit-Constant Soil Loss Method – chosen based on the success of this method for large basin studies such as the Sava River Basin. The method provides the ability to simulate soil moisture characteristics throughout an event using easily derived and calibrated parameters. In addition, is the method used for most major flood forecasting models within USACE.
- Clark Unit Hydrograph Transformation Method – chosen based on its ability to be estimated using available terrain data and the successful implementation of this method across modeling studies within USACE. The parameters for this method are also fairly easy to calibrate especially in situations where discharge stations are relatively abundant such as in the Sava River Basin. In addition, this method has shown to be very effective in representing the timing and shape of flow hydrographs through varying magnitudes and volumes of floods.
- Recession Baseflow – chosen for its simplicity and its ease of application.
- Muskingum-Cunge Reach Routing Method – chosen because it primarily based on physical characteristics of the routing reaches which can be attained from the available information. This method has been widely used within USACE and provides the ability to represent the flow hydrograph translation and attenuation in situations with varying levels of floodplain storage.

The parameters used to define the hydrological model are described in more detail below and a summary of the various basin parameters is provided along with the basin modeling methods developed within the Sava HEC-HMS (Table 2). These parameters were the subject of the model calibration.

Updated Sava HEC-HMS (version 2.0)

Since the Sava HEC-HMS was initially calibrated as event-based model using hourly data values, the lower reliability was recognized during the continuous simulations in the operational mode within the Sava FFWS. Regularly performed simulations of the Sava HEC-HMS model coupled with NWP data in Sava FFWS shows that the model has a strong reaction to moderate

Table 2. Number of stations with the hourly (real-time) data exchange available in the Sava HIS / Sava FFWS

Modeling Method		**Parameter**	**Description and representative values in the model v1.0**	
Canopy Storage	Canopy	Initial Storage	Initial storage in canopy	100 %
		Max Storage	Maximum storage in canopy	2–50 mm
Soil Losses	Deficit Constant	Initial Deficit	Initial condition for the soil layer. Amount of water required to saturate the soil layer	0–35 mm
		Maximum Deficit	Maximum amount of water the soil layer can hold (30–75mm)	
		Constant Loss	Percolation rate of the soil layer	0.1–2.25 mm/hr
		Percent Impervious Area	Percent of the subbasin that is covered by directly connected impenetrable surfaces such as concrete, rooftops, and urban development	0–53.8 %
Hydrograph transformation	Clark Unit Hydrograph	Time of Concentration	Travel time from the most hydrologically remote point in the subbasin to the watershed outlet	0.2–50 hr
		Storage Coefficient	Conceptual parameter representing basin's storage capacity	0.7–160 hr
Baseflow	Recession Baseflow	Initial Baseflow	Baseflow at the beginning of the simulation	0.001–0.621 $m^3 s^{-1} km^{-2}$
		Recession Ratio	Rate at which baseflow recedes between events	0.72–0.98
		Threshold Ratio	Flow at which the baseflow is reset	ratio to the peak
Reach routing	Muskingum-Cunge Routing	Length	Length of reach	0.22–106.16 km
		Slope	Slope of reach	0.00001–0.0196 $m\ m^{-1}$
		Manning's n-Values	Roughness coefficient for the channel, left overbank, and right overbank	0.02–0.05
		Shape	Shape of the routing reach cross section	8-point or trapezoidal

amounts of rain and produce untimely and overestimated forecasts. Reasons for a such behavior of the model are the modelling methods initially selected (Table 2) e.g., soil loss method which is not capable of long-term soil moisture accounting, but also due to meteorological data availability and coverage, snow data availability as well as the reservoirs regulation at various dam.

Any intervention on the robust and complex model like Sava HEC-HMS, which is in use by many experts per different institutions and countries, has to be done in well organized and coordinated way. After a joint agreement of the expert team that the initial model needs to be updated with the new information, the action plan has been made to upgrade the model with new measuring locations and to perform the recalibration of the model parameters. The expected goal was that the new precipitation and air temperature data would complement the existing spatial and temporal accuracy of the meteorological component of the model.

Meteorological inputs are typically the greatest limitation in any hydrological model because meteorology is such a random and natural phenomenon. The IDW method, used to model precipitation in the Sava HEC-HMS, relies heavily on the location and density of stations because the precipitation applied at any given subbasin is computed by interpolating between measured precipitation values at these stations. If the spacing between stations is too great, a storm could pass between two stations and not be recorded at either station, which means that the Sava HEC-HMS would not register this event and apply the improper precipitation to the subbasins between the stations. In addition, if a rainfall event does not pass over enough stations to capture the shape and volume of the rainfall, the model will not accurately apply precipitation to the adjacent subbasins (Feldman, 2000). These inherent limitations exist for all meteorological models relying on point stations, which is why acquiring the best available data and quality controlling this data is critical to the performance of the Sava HEC-HMS model as well.

The two immediate solutions are increasing the density of stations in areas with limited or insufficient coverage and/or incorporating radar-based gridded precipitation data into the model. For a robust flood forecasting system such as Sava FFWS, incorporating both gauge- and radar-based precipitation is the best solution to create redundant data sources and to protect against one of the source data feeds failing.

Radar-based precipitation has become a standard data source for hydrological models across the world because it solves the issue of spatial coverage of precipitation data that exists with readings at meteorological stations. As with any measurement, raw radar-based data possesses some level of uncertainty and must be verified and corrected to measurements made at standard single-point meteorological stations further emphasizing the need for ground stations. In spite of this uncertainty, radar-based data, when processed through proper quality controls, provides the spatial and temporal distribution of precipitation data necessary for large, complex hydrological models such as the Sava HEC-HMS. The European National Meteorological Services Network (EUMETNET), with members from the European Union and Balkans, collaborate and produce network-wide radar mosaics through the Operational Program for Exchange of Weather Radar Information (OPERA), which could provide a source of radar-based nowcasting information for the Sava River Basin. As mentioned in the Chapter 2, along with NWP data, Sava FFWS is prepared to extrapolate radar or satellite imagery in order to provide a very accurate short-term hydrological forecast (nowcasting) for several hours in advance based on measured values. Nowcasting products are currently not available within the Sava basin and the existing radars are currently still not able to produce accurate rainfall images. Considering the importance of providing a such input and raising the awareness of experts to this type of precipitation data, the Lisca radar data (Slovenia) are implemented Sava FFWS, next to Opera radar composite images and H-SAF satellite images (Fig. 4).

However, considering that radar- and satellite-based images are only displayed within the system but are not connected to any of hydrological models neither to Sava HEC-HMS, it was decided to update the model in this stage to include the new hydrological and meteorological inputs and recalibrate Sava HEC-HMS without changing the structure of the model. Challenging work resulted with an improved Sava HEC-HMS model more suitable for continuous hydrological simulations needed for accurate process of the flood forecasting in Sava FFWS. Important step, beside technical interventions on

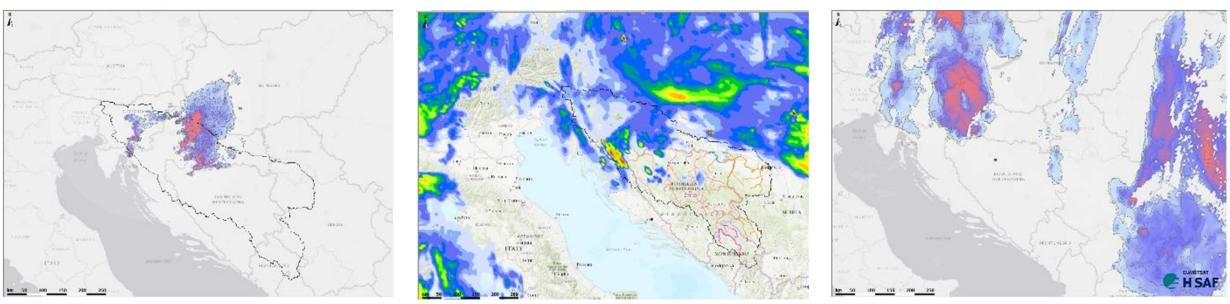

Fig. 4. Available radar and satellite images in the Sava River Basin integrated under Sava FFWS.

the model, was managing and coordination of all activities and application of a consistent methodology since many Sava countries experts were involved in this process. The applied methodological approach consisted of the following steps: (1) preparation of the necessary technical documentation and time plan for the work of national experts; (2) inclusion of the new hydrological and meteorological stations to the model; (3) collection of historical hydrological and meteorological hourly data for the period from 2010 to 2018; (4) uploading of the collected data to Sava HIS/Sava FFWS Archive module; (5) enhance the model components; (6) calibration and validation the new model setup and (7) hindcast analysis and validation of the operability performances of the model through the Sava FFWS testing module including comparison of different model versions.

A first step of the model enhancement was related to increase of the number of precipitation and temperature data inputs at all available meteorological stations. In total 258 meteorological stations for precipitation and temperature data inputs are currently available in the Sava HEC-HMS v2.0 as well as 151 hydrological stations for the observed discharge data presentation and the purpose of comparison with the simulated runoff. However, from the total number of stations integrated in the model, data were collected for a part of stations that have regular and hourly measurements of precipitation, air temperature and discharge (Table 3), representing an increase of 125 meteorological and 41 hydrological stations compared to the initial setting of the model.

The greatest number of the new meteorological stations integrated under Sava HEC-HMS v2.0 are located in the central part of the basin while the number of the stations in the upper and lower parts was not changed significantly. Following the model configuration enhancements along with integration of the new measuring locations and their historical data the model was recalibrated. Different approach to the calibration was mainly dependent on the calibration skills of the expert team members. The calibration of the parameters in the initial Sava HEC-HMS v1.0 model was performed for the six short periods related to the flood events between 2009 and 2015. The updated v2.0 model has been calibrated and primarily validated using different periods per subbasins while additional two validations of the model were performed for period 01 Jan 2014–31 Dec 2014 and 01 Jan 2016–31 Dec 2016. Work performed on calibration and validation of the Sava HEC-HMS model v2.0 was jointly agreed and distributed among the team members considering responsibility of each organization but also the model structure, capacities and expertise of individuals and a rule of equivalence as well, so activities were divided per subbasins and countries. Most of data and information used for model improvement was provided by the national organizations involved in the activity. Each organization has provided input time-series data for the stations in its responsibility despite the distribution of work related to calibration and validation of the model. A substantial amount of data was collected as part of the initial model development efforts. The period from 2010 to 2018 was divided into sub-periods where one was used for the calibration and others for the validation of the Sava HEC-HMS v2.0 model. In the end three validation procedures were performed given that the calibration and first validation were done per subbasins while additional two validations were performed for the entire model.

The model calibration was performed at 107 calibration points i.e., 32 more compared to the initial model.

For the determination of the model parameters two approaches were used: trial-and-error method and the built-in automatic calibration procedure of HEC-HMS software (Zhang et al., 2013). For both calibration approaches the hydrograph volume, peak discharge and timing of the peak were also monitored. In order to ensure the model's ability to represent these characteristics, three metrics were analyzed during the calibration simulations at various locations: Nash-Sutcliffe Coefficient (NSE), Root mean square error to Standard deviation of observations Ratio (RSR=RMSE/Std), Coefficient of determination (R^2). The goodness of fit for each model parameter was evaluated based on NSE, while other coefficients where continuously monitored.

These metrics provided an overall measure of the numerical performance of the model's ability to capture all characteristics of the outflow discharge hydrographs, which incorporates peak, volume, timing, and shape.

In addition to these three metrics, calibration plots depicting the time series discharge hydrograph output versus the observed discharge hydrograph were also analyzed. The calibration plots provided an effective visual illustration of the performance of the model and were monitored using HEC-HMS, as well as the graphical user interfaces of Sava FFWS.

Results and discussion

The main improvements of the Sava HEC-HMS calibration process included: (1) improvements of the meteorological inputs with higher spatial and temporal data coverage for precipitation and air temperature; (2) some corrections of the meteorological

Table 3. Number of stations per countries available in Sava HEC-HMS v2.0

Type of the station / parameter		**BA**	**HR**	**ME**	**RS**	**SI**	**Totals**
Hydrological stations	Discharge	54	35	9	17	19	**134**
Meteorological stations	Precipitation	41	49	3	10	96	**199**
	Air temperature	41	27	3	8	18	**97**

model of snow melting; (3) increased number of calibration points; (4) increased number of calibrated sub-basins, up to 98 from initial 66; (5) longer time series of discharge observations; (6) new version of the Sava HEC-HMS model integrated under the Sava FFWS testing module.

The model skill was evaluated using NSE on the period from 2010 to 2018 and about 50% of stations score a NSE greater than 0.55 (rates: good and very good), while a higher percentage of stations score a NSE greater than 0.40 (rate: satisfactory). The higher NSE scoring was achieved in the upstream parts of the basin and along the Sava river. The new model accuracy and NSE increased in comparison to the initial model.

During the calibration process, it was noticed that the change of the model parameters would not necessarily lead to the better performance of the updated model, therefore the parameters for some computation points and accompanying subbasins have not been changed. This was the case on the parts of basin where new input data have not been changed. The changes were needed on areas where new input data were available and mainly in the module for the direct runoff transformation to decelerate and attenuate the simulated hydrographs. In the baseflow module change has been made on the recession constant that needed to be increased together with the ratio to peak parameter. In the karstic area e.g., the upstream part of the Bosna River subbasins, it was necessary to increase the soil percolation rate and initial loss. All these changes were expected having in mind a transition from the event-based to the continuous model. Statistical analysis of the performance metrics, from the initial and the updated model achieved on 87 locations, where two models were possible to compare, has been done using one and two-tailed t-test and Mann-Whitney test (Table 4). The test results are showing that there is no significant statistical difference between NSE values for the two models and that the NSE value for the updated value is greater than the initial model. In the case of root mean square error-observations standard deviation ratio (RSR=RMSE/Stdev), the p-values are indicating that statistical difference between the two models exists and that the RSR for the updated model is lower than for the initial model. R^2 is not showing a clear signal whether the updated model is better than the initial one.

Following the statistics, a comparison between the initial and updated model has been performed. The Nash-Sutcliffe efficiency coefficient values, used for evaluation of the numerical model performance were greater than 0.55 for more than 50% of locations classifying the model as good and very good in the calibration period. Most of the rest of NSE values are greater than 0.4 meaning that the model is in the class of the satisfactory models.

In this paper 11 selected location (Table 5) were used for an analysis of the numerical goodness of fit for two periods. For the basin parts where, new meteorological stations have been installed the model performance has increased while the other subbasins record the same or

Table 4. Statistics for the performed one-tailed and two-tailed t-test and Mann-Whitney test based on simulations of the two models versions

Model performance metrics	t-test (α=0.050)		Mann-Whitney test (α=0.050)	
	one tailed	two tailed	one tailed	two tailed
NSE	0.046	0.092	0.002	0.004
RSR	0.009	0.019	0.001	0.003
R^2	0.292	0.584	0.244	0.489

Table 5. Performance metrics of the initial (v1.0) and updated (v2.0) Sava HEC-HMS model for two periods using the general performance ratings: Very Good; Good; Satisfactory; Unsatisfactory (Moriasi et al., 2007)

Up to downstrem	Computation point (hydrological station)	01 Jan 2014–31 Dec 2014				01 Jan 2016–31 Dec 2016			
		Model v1.0		Model v2.0		Model v1.0		Model v2.0	
		NSE	RSR	NSE	RSR	NSE	RSR	NSE	RSR
10	J_01_08_03_Laško	-0.03	1.01	0.57	0.65	-0.39	1.18	0.71	0.54
16	J_01_13_11_Jesenice	0.65	0.59	0.76	0.49	0.69	0.56	0.80	0.45
18	J_04_02_05_Kupljenovo	0.41	0.77	0.43	0.76	0.28	0.85	0.33	0.82
31	J_06_10_06_Farkašić	0.61	0.62	0.65	0.59	0.67	0.58	0.68	0.57
39	J_12_02_04_Kralje	0.45	0.74	0.55	0.67	0.68	0.56	0.79	0.46
48	J_14_01_02_Daljan	-1.02	1.42	-0.18	1.08	-3.38	2.09	-0.04	1.02
67	J_20_19_06_Maglaj	0.82	0.43	0.70	0.55	0.56	0.66	0.46	0.74
75	J_24_01_02_Bijelo Polje	-1.50	1.58	0.06	0.97	-0.22	1.10	0.67	0.57
82	J_27_01_04_Sr. Mitrovica	0.74	0.51	0.72	0.53	0.77	0.48	0.80	0.45
85	J_28_03_01_Beli Brod	0.59	0.64	0.59	0.64	0.28	0.85	0.15	0.92
87	J_28_03_05_Draževac	0.03	0.98	-0.58	1.26	0.39	0.78	0.51	0.70

lower values of NSE. In addition to analysis of the numerical model performance the calibration plots, as an effective visual illustration of the model performance, depicting the simulated discharge hydrograph versus the observed discharge hydrograph, were also monitored (Fig. 5). Analyzing results at the selected computation points an improvement in the matching of the simulated and observed hydrograph was obvious although parameters during the recalibration for some locations have not changed significantly (Farkašić). Also for some locations (Bijelo Polje) the initial model was not able to perform the simulated hydrograph at all, while the Sava HEC-HMS v2.0 compute it successfully. The overall hydrograph matching is also slightly better, as a result of the model inputs improvements and calibration that was carried out for a long-term period, unlike the initial model. The added value in the updated model was recognized in the better fitting of timing of the peak and the peak value itself but also in the better fitting of low and mean flows. A good example of the peak fitting can be seen at the computation point: J_20_19_06_Maglaj (Fig. 6) and where peaks are better simulated in the updated model. Another good example of the peak but also low and mean flows fitting can be seen at the computation point: J_01_13_11_Jesenice (Fig. 7) showing that data are better simulated in the updated model. Due to the lack of in-situ measurements of stream discharges there is always a doubt whether the rating curve (discharge vs stage) of observed data is properly developed in the high flow range and the observed flow is over or underestimated and whether comparison of the simulated and observed values is reliable.

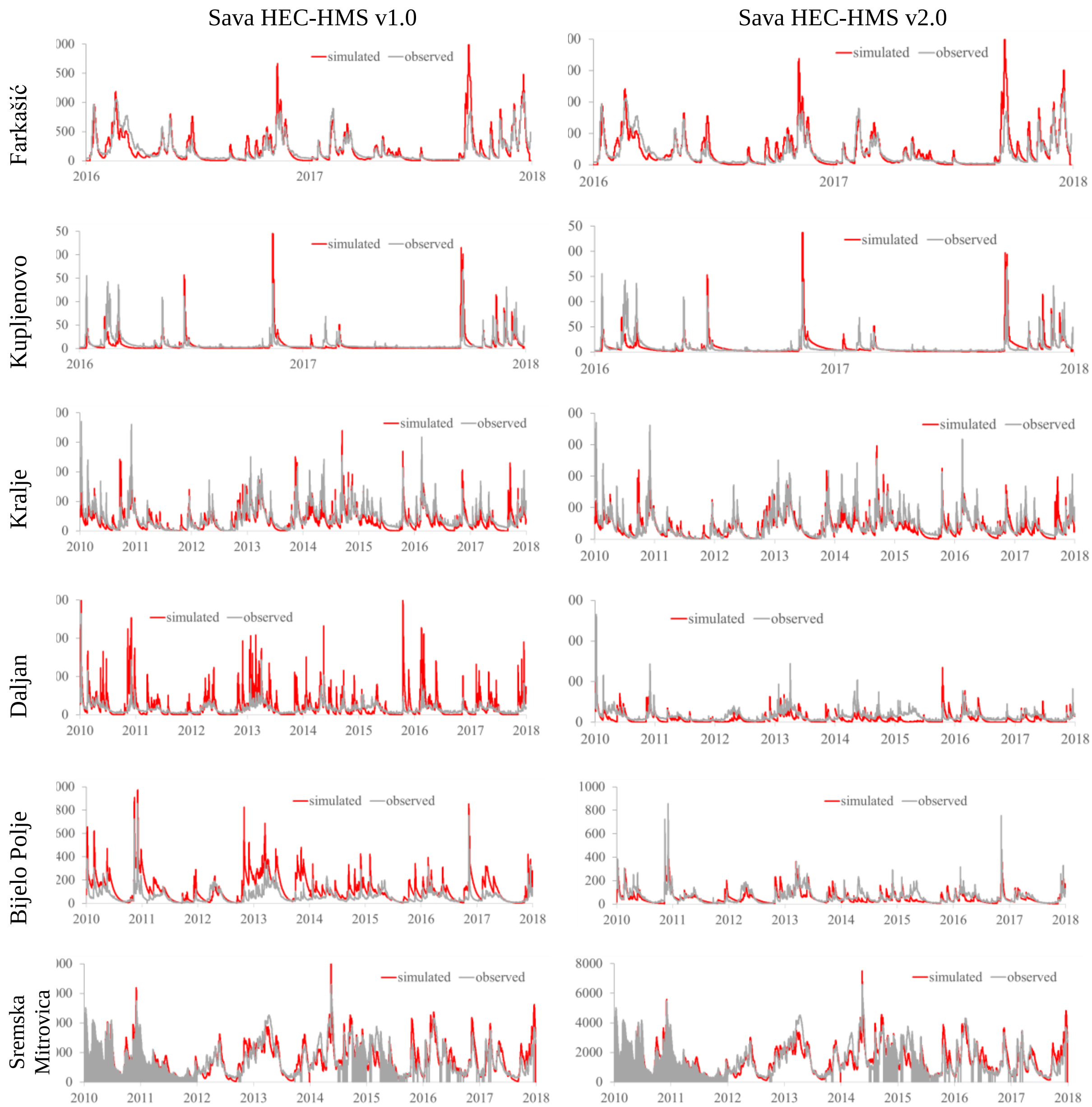

Fig. 5. Comparison of the simulated and observed flow at the selected locations.

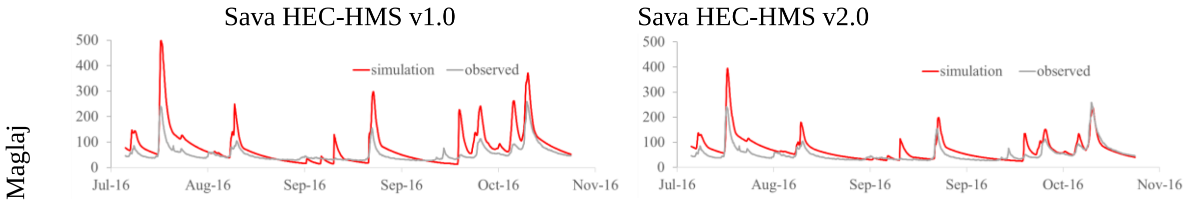

Fig. 6. Comparison of the simulated and observed flow at the location Maglaj.

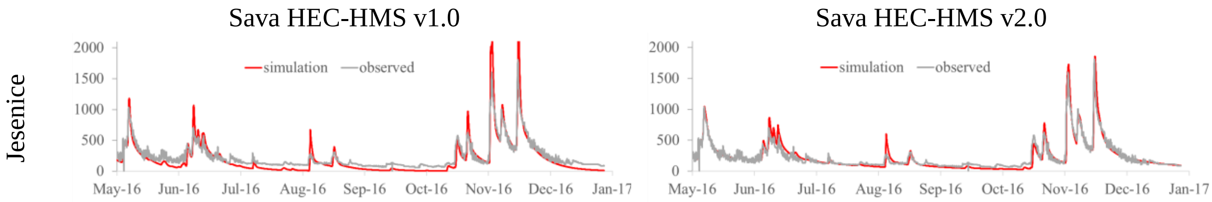

Fig. 7. Comparison of the simulated and observed flow at the location Jesenice na Dolenjskem.

Conclusions and recommendations

The hydrological simulations were conducted for the period 2010–2018 including extreme May 2014 flood and several smaller floods, with evaluation of daily mean hydrological conditions and processes. The main findings are as follows: (i) performance and forecast accuracy of the existing Sava HEC-HMS model was significantly improved; (ii) the model was (re)calibrated for both high flows (for accuracy) and low flows (for stability and model performance); (iii) data sources for further developments were improved; (iv) a solid background for an international team of experts was established.

Considering that the Sava FFWS users have access to all data and workflows as well as managing the functioning and further developments of the system, it was very important that the national experts were fully involved in the study. Therefore, joint work and close cooperation of the national experts (duty forecasters) should be emphasized as an additional achievement, as follows: (i) experts deeply familiarized with the HEC-HMS software capabilities as well as with methods and techniques implemented into the Sava HEC-HMS model; (ii) upgraded own knowledge how to calibrate a such model; (iii) recognized all benefits of the model, its limitations and possible future applications; (iv) much more prepared for using this model under the Sava FFWS.

After performed activities and obtained results, the following recommendations are suggested: (i) development of a more complex soil loss method capable of long-term soil moisture accounting; (ii) a more detailed analysis of snowmelt within the model necessary (snow data availability); (iii) reservoir regulations at dams through the incorporation of a reservoir regulation model component (HEC-RESSIM). The future updates should utilize remote sensing data inputs for the soil moisture accounting, snow melting, reservoir regulating as well as other specific applications in the Sava HEC-HMS. For future recommendations, the incorporation of high-resolution grid-based snow water equivalent and precipitation data, as well as the placement of additional meteorological stations in areas currently lacking observed data, will serve to improve performance of the model. Application of available products of missions like Sentinel, Landsat, AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer), AMSR-E (Advanced Microwave Scanning Radiometer-Earth Observing System), DMSP (Defense Meteorological Satellite Program) in the Sava HEC-HMS will be explored. The great potential of remote sensing data application is in general evident, both for the calibration of hydrological models and for operational hydrological forecasting, as well as for filling the data in catchments without observations or with an insufficient network of measuring stations and therefore will be used in the further Sava HEC-HMS model and Sava FFWS improvements including the related adaption of the modelling methods especially related to a rapid work of HEC and all latest developments of the software.

Acknowledgement

This research is supported by the International Sava River Basin Commission and responsible authorities from the Sava River Basin: Sava River Watershed Agency, Federal Hydrometeorological Institute, Republic Hydrometeorological Service of the Republika Srpska, Public Institution "Vode Srpske", Croatian Meteorological and Hydrological Service, Institute of Hydrometeorology and Seismology, Republic Hydrometeorological Service of Serbia, Slovenian Environment Agency. The authors also thank Dragan

Zeljko, Secretary of the ISRBC, Brantley A. Thames, U.S. Army Corps of Engineers, Matthijs Lemans, Deltares and Damir Bekić, University of Zagreb for their constructive advice and immense help to improve this study.

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