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SETTING THE REAL-TIME FLOOD FORECASTING MODELS IN UKRINA, TINJA AND BRKA UNGAUGED BASINS

Abstract

Flood forecasting (FF) is one of the most challenging problems in Hydraulic Engineering. It is also most important due to tremendous contribution in reducing economic and life losses that usually occurs during flooding. Major part of the FF system is hydrologic and hydraulic model that simulate runoff and corresponding water levels in rivers, based on the input data that are results from the meteorologic forecasting model. Major uncertainty of the FF systems that operates in real time usually stems from combined hydrologic-hydraulic model, apart from the large uncertainty that comes from the meteorological model. This uncertainty significantly rises when the catchments of interests are ungauged. In this paper, methodology of setting hydrological and hydraulic model that operates in real time FF and early warning system is presented. Case study are ungauged basins of Ukrina, Tinja and Brka, tributaries of Sava River.

Keywords: flood forecasting system, hydrologic model, hydraulic model, ungauged basins

УСПОСТАВЉАЊЕ МОДЕЛА ЗА ПРОГНОЗУ ПОПЛАВА У РЕАЛНОМ ВРЕМЕНУ НА НЕИЗУЧЕНИМ СЛИВОВИМА УКРИНЕ, ТИЊЕ И БРКЕ

Сажетак

Прогноза поплава је један од најзахтјевнијих задатака у хидротехници, али и најважнијих обзиром на велику улогу у смањењу материјалне штете и губитака људских живота који обично прате феномен поплава. Главни дио прогнозних модела у реалном времену чине хидролошки и хидраулички модел који дају симулације отицаја и одговарајућих нивоа воде у водотоцима на основу резултата симулација метеоролошког прогнозног модела. Највећа неизвјесност резултата прогнозних модела потиче управо од комбинованог хидролошко-хидрауличког модела. Ова неизвјесност постаје већа уколико се ради о хидролошки неизученим сливовима. У овом раду приказана је методологија успостављања хидролошког и хидрауличког модела за потребе система за рану најаву и прогнозу поплава у реалном времену на примјеру неизучених сливова Укрине, Тиње и Брке које су директне притоке ријеке Саве.

Кључне ријечи: систем за прогнозу поплава, хидролошки модел, хидраулички модел, неизучени сливови

1. INTRODUCTION

Floods are the most impacting natural disaster in terms of economic damages [1]. Floods also result in thousands of casualties globally each year (4500 in 2019 for example). Flood early warning systems are one of the most efficient measures to reduce the impact of floods, especially when time and budget is limited. Research by JRC[2] illustrates a damage reduction of about 25% for European countries when early warning systems are in place. Besides providing timely warning to the public, flood early warning systems also provide flood managers insights and tools to better understand the water system and communicate in an objective science based manner with other experts and disaster managers.

After the devastating floods in the Sava basin heavily affecting amongst others Bosnia and Herzegovina, several flood early warning systems were developed to timely warn people about potential floods. One of these systems covers the Bosna, Ukrina, Brka and Tinja river catchment in Bosnia and Herzegovina. While Bosna River catchment covers many hydrological and meteorological stations to calibrate and run models that feed the forecasting system, hydrological and meteorological stations on Ukrina, Brka and Tinja basins are sparser. Especially hydrological stations and historical observations are missing essentially making these basins ungauged.

In the flood forecasting systems, hydrological and hydraulic models are vital tool for forecasting current flood condition. These models are usually calibrated upon observed meteorological and hydrological data. When basins do not have any monitoring system, establishing reliable FF system becomes extremely challenging. One of the solutions include regionalization of model parameters [3] with certain basin classification [4] included to consider similarity of two or more basins [5], [6]. Other authors rely on physically based hydrological models [7] but even for them, some kind of calibration/adjustment of model parameters is needed.

This paper presents methodology used in setting up the flood forecasting and early warning system for ungauged basins Ukrina, Tinja and Brka (UTB) in Bosnia and Herzegovina. Integral part of this FF system was Bosna basin also, which is gauged. Data from Bosna subbasins are used to calibrate hydrological NAM model parameters and establish a regression models between calibrated parameters and certain physical and morphological basin' characteristics. Using these regression models, values of NAM parameters are determined for ungauged basins of UTB. Resulting simulation data are compared with regional flow duration curves in order to validate the methodology. Proxy data collected on site during flood in 2010. are also used to check results of combined simulation od hydrologic and hydraulics models. This data served for models' re-calibration, where observed water levels didn't agree with simulated one.

2. MIKE MODELS

2.1. GENERAL RAINFALL-RUNOFF MODEL

The NAM model [8] is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in up to four different storages: (1) surface storage, (2) lower ground layer – storage of vegetation roots zone, (3) storage of underground water and (4) snow. Different components of rainfall-runoff process continually calculate amounts of water in those storages that are different but intercommunicating vertical components of ground [9].

Surface reservoir is a cultivated top layer of soil with vegetation and surface depressions that hold water. Amount of water in this layer changes in dependence of evapotranspiration, surface runoff and interflow, i.e. water offset from surface into lower layers. In this layer parameter U_{max} (mm) plays a role of maximum amount of water that can be held in this layer. Root zone is next storage in vertical direction in which water comes from the surface layer and offsets to transpiration, interflow to groundwater reservoir, amount of water for filling up groundwater and also smaller part for shallow subsurface runoff. Maximum amount of water in this layer is defined with parameter L_{max} (mm). Underground reservoir is deepest layer of ground in which amount of water comes from previous layer, root zone. Amount of water fulfilling these resources depends on amounts of water in root zone and is regulated with parameter TG (-). NAM has a possibility of adding next, deeper layer whose capacity is controlled by two additional parameters but this addition increase number of model free parameters which usually does not improve model performance [10]. Snow module in NAM model behaves as another storage, in which precipitation (snow) is stored during cold days and gradually discharged in form of melted water during warmer days. For snow module NAM requires just temperatures in same resolution as given precipitation. There are two ways of snow calculation: general - averaged on whole basin and distributed in vertical direction (height zones).

Aside from above mentioned components of model and belonging parameters, there are also parameters which control surface flow as well as amounts of water that set off into lower layers i.e. interflow. Complete list of NAM parameters is shown in Table 1.

Table 1. NAM model parameters

Parameter	Description	Measure unit	Typical values
Surface layer and root zone			
Umax	Maximum capacity of soil humidity in surface layer	mm	10-20
Lmax	Maximum capacity in root zone	mm	50-150
CQOF	Coefficient of surface flow – divides surface water capacity on surface runoff and lower layer infiltration.	-	0,1-0,99
CKIF	Time constant for mid-runoff, runoff between surface layer and root zone. It defines amount of surface water setting off in mid-	hours	200-1000
CK1,2	Time constant for surface and mid-runoff. Defines the shape of hydrograph.	hours	3-48
TOF	Threshold value for surface flow – there is no surface flow if relative humidity of lower soil layer is smaller than this value.	-	0-0,7
TIF	Threshold value for mid-runoff, similar as previous, regarding surface layer.	-	0-0,99
Underground layer			
CKBF	Time constant of basic runoff – defines shape of hydrograph in periods without precipitation.	hours	500-5000
TG	Threshold value in root zone for growth of runoff in underground (similar as TOF)	-	0-0,99
CQLOW	Growth in lower underground layers – defines growth in underground reservoir that goes into lower layers by	-	
CKLOW	Time constant of linear reservoir that is used to model basic runoff.	hours	
Carea	Part of basin that contributes to neighboring basin or part of neighboring basin that seeps into modelled basin.	-	n/a
GWLbf0	Maximum depth to underground water level – measured from average basin height to minimal recipient level	m	10
Sy	Specific growth in underground water	-	0,1
GWLfl1	Depth to the level of underground water that defines capillary ascend from lower to higher ground layers upon humidity of	m	
Snow storage			
Csnow	Snow meltdown coefficient	mm/C/day	2-4
T0	Basic temperature that defines precipitation as snow or rain	C	0
Crain	Rain coefficient – defines snow meltdown speed	mm/mm/C/day	

2.2. HYDRAULIC MODEL MIKE 11

For all three tributaries of Sava River, MIKE 11 hydrodynamic models are used to predict water levels and discharges along the river courses during the simulated flood events. The MIKE11 software solves “full” 1D unsteady flow equations but quasi 2D approach can be used by connecting 1D river reaches (parallel branches) [11]. The mass transfer between main channels and floodplains are modelled using so called link channels (Link structure in Figure 1). The link channel is a short branch that usually represents embankment geometry but can also be a model object that represents imaginary (“arbitrary” defined) boundaries between main river and inundations (Figure 2) or even the boundaries inside floodplains when more than one (parallel) river branches represent flow along the same floodplain. The parameters that “control” the dynamic of water mass exchange between main river and floodplains are width-depth relationship, length, slope and Manning *n* value for link structure.

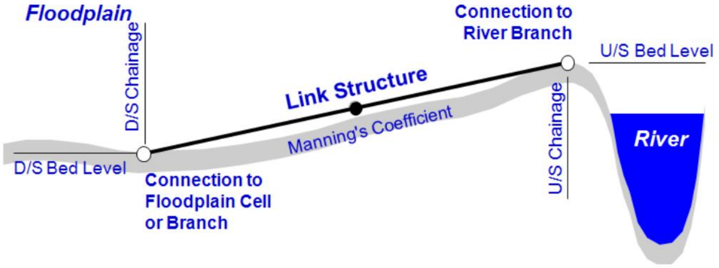


Figure 1. *Representation of a Link Channel* [12]

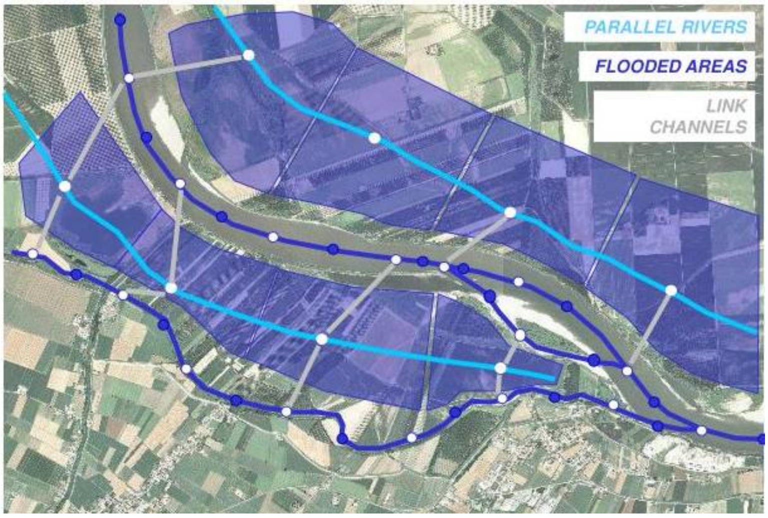


Figure 2. *Quazi 2D schematization of river flow* [13]

A numerous type of boundary and interior conditions can be set in the hydrodynamic model. User can define hydrographs, stage/discharge relationships or other relationships (or values of their parameters) that represents flow conditions at the outer boundaries or inner parts of the computational domain. The influence of different type of inline or lateral structures (weirs, culverts, sills, etc.) or “outer” water bodies (tributaries and main rivers, storage areas, etc.) on the river flow conditions can be taken into account in 1D flow simulations.

3. BASINS AND DATA

The real-time FF system comprises of the four basins, namely Bosna River Basin, Ukrina, Tinja and Brka (Figure 3). Bosna basin is not in focus in this paper, only the results of hydrological model calibration of Bosna sub-catchments, more specifically the optimized parameters for regionalization. Ukrina, Tinja and Brka (UTB) are right tributaries of Sava River, all three located in BiH. The total areas of UTB are 1500km^2, 950 km^2 and 233.2 km^2, respectively.

Hydrometeorological data collected for the area are mainly precipitation values. Analyzing positions of the stations over the study area with Thiessen polygons it is concluded that polygons around five stations cover the basins area providing dominant areas of point data distribution (see Figure 4). Available data for those stations are summarized in Table 2.

For the basins of Ukrina and Brka, there were no recent observations from monitoring hydrological stations. On Ukrina, daily flows for Derventa station are available only in period between 1964-1983, with gaps. However, those data were used to develop flow duration curves and compare them with simulated ones after the calibration.

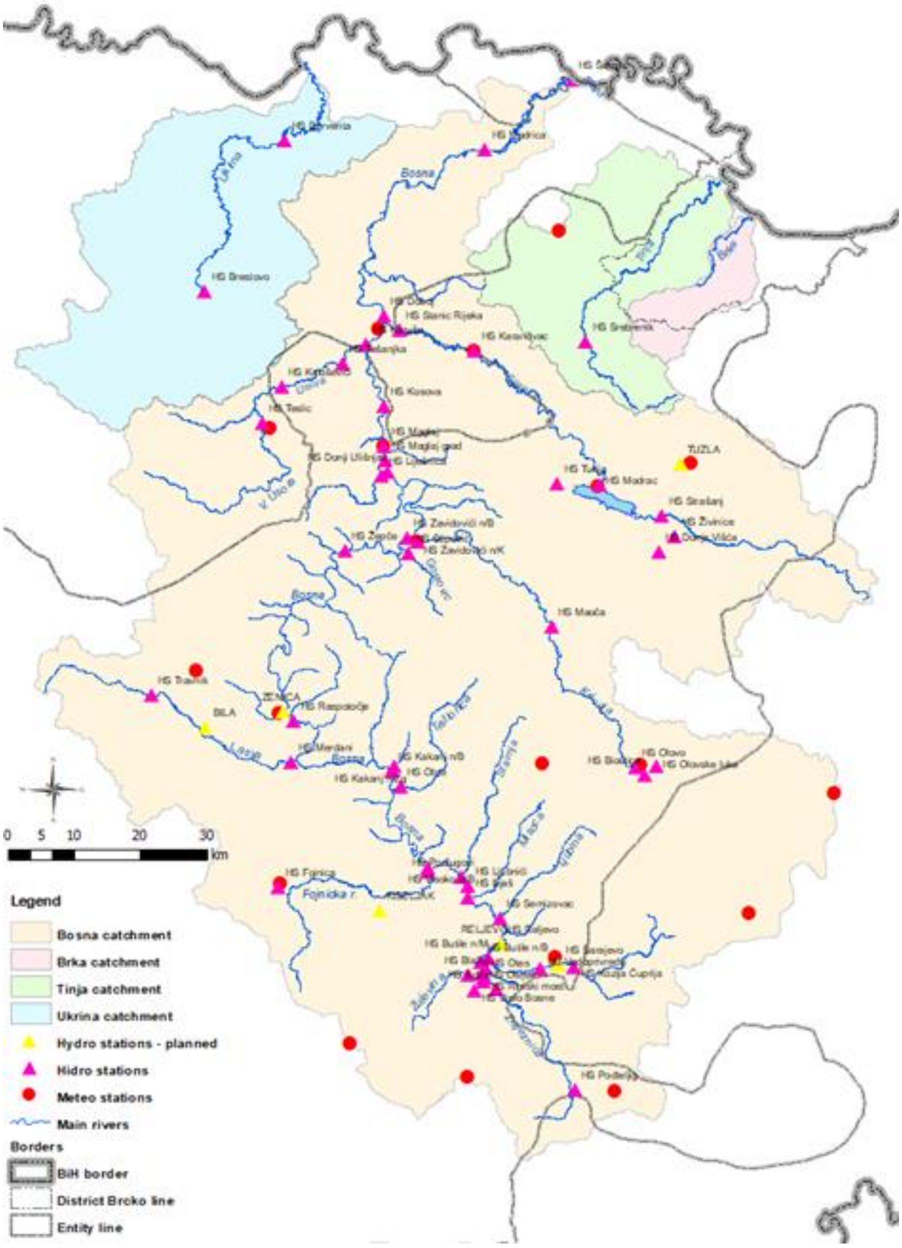


Figure 3. *Basins included in FF system [14]*

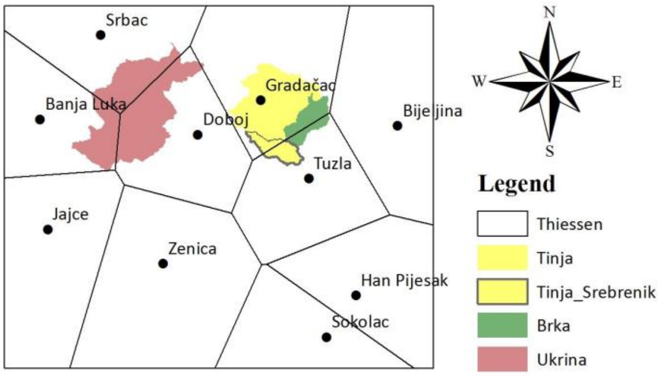


Figure 4. *UTB basins and Thiessen polygons developed for 9 meteorological stations that could possibly be used for the areal distribution of precipitation and temperatures*

Table 2. Review of available precipitation (P) and temperature (T) data

Meteorological station	Daily P	Daily T	Hourly P	Hourly T
Banja Luka	2008-2018	-	2008-2018*	2008-2017
Doboj	2008-2018	2008-2018	2008-2018*	2015-2018
Gradačac	2008-2015	2008-2014	-	-
Tuzla	2008-2018	2008-2018	2008-2018*	2008-2018
Srbac	2008-2018	2008-2018	2016-2018*	-

*no data from November through March

For Tinja basin there is only one hydrological station (HS Srebrenik) in the upper and mountainous part of the basin. For this HS, hourly water levels for the period 2008-2018 were available as well as rating curves obtained during measurements in period 2010-2016. Upon this data, hourly flows are determined. The only missing period of water level data was the period during and after flood in May 2014, specifically between 15.05.2014-23.06.2014.

4. GENERAL METHODOLOGY FOR SETTING THE HYDROLOGICAL AND HYDRAULIC MODEL

4.1. HYDROLOGICAL MODELLING – MODEL SETUP, CALIBRATION AND SENSITIVITY ANALYSIS

At the initial stage of modeling, Tinja catchment is divided in two sub-catchments at HS Srebrenik. Since there was observed runoff at the Srebrenik station, that part of the catchment is calibrated automatically using autocalibration tool given in NAM [15]. Rest of the basin, as well as whole Ukrina and Brka basins, are calibrated using proposed methodology. For the purpose of combined hydrological and hydraulic modeling, these basins needed to be divided in several sub-catchments – where the inflow is needed in hydraulic reaches. The division of the basins is shown on Figure 5. Ukrina is divided on 14, Tinja on 5 and Brka on 8 sub-catchments. Simulation time step for all models is one hour. Where available, hourly data are used. Otherwise, daily data are interpolated assuming uniform distribution of precipitation within the day. Basic NAM model setup is used, without interflow (CK_2 coefficient) and lower groundwater reservoir, with total of 9 parameters.

Table 3. List of NAM parameters and respective value ranges used in parameter sensitivity analysis

Parameter	Units	Description	Range
$\mathbf{U_{max}}$	mm	Maximum water content in surface storage	5-20
$\mathbf{L_{max}}$	mm	Maximum water content in lower zone/root storage	20-300
CQOF	-	Overland flow coefficient	0.1-1
CKIF	hrs	Interflow drainage constant	200-1000
CK1	hrs	Timing constant for overland flow	0-50
CK2	hrs	Timing constant for interflow	0-50
TOF	-	Overland flow threshold	0-0.99
TIF	-	Interflow threshold	0-0.99
TG	-	Groundwater recharge threshold	0-0.99
CKBF	hrs	Timing constant for baseflow	1000-4000
CQlow	mm	Recharge to groundwater	0-100
CKlow	hrs	Time constant for routing lower baseflow	1000-30000

Prior to ungauged basins calibration procedure, model parameter sensitivity analysis is conducted with full version (all parameters) of NAM model. Sensitivity is analyzed on the gauged Tinja basin part, up to HS Srebrenik by keeping 11 parameters constant while the one for which sensitivity is analyzed is changed by 20% from their respective range (Table 3). For each parameter change, simulation is run and efficiency calculated. When this efficiency is plotted against each parameter value from the predefined range, impact of parameter value change on model performance is well observable. If efficiency is changing little or nothing no matter which value parameter takes, those parameters are insensitive. This means that they do not influence model results i.e., no need to be calibrated. Conversely, when small parameter change induces quite model efficiency change –

impacts heavily on model simulation results, parameter is sensitive. This means that they are important for modelling process and must be calibrated.

Gauged part of the Tinja basin is calibrated upon the available hourly runoff observed at the HS Srebrenik using an automatic optimization algorithm Shuffled Complex Evolution Metropolis – University of Arizona (SCEM-UA, [16]) embedded within the model. This optimization algorithm has a goal to find a single best parameter set in the feasible parameter space (instead of many different sets that give similar model performance). Objective functions used for model calibration are chosen to cover all aspects of hydrograph, i.e., dynamic (root mean square error RMSE), volume (overall volume balance) and matching of the peak flow above certain threshold (RMSE for high flow). The model warm-up period (period that is excluded in objective functions calculation) is set to one year (365 days). After automatic calibration, manual fine-tuning of parameters is performed in order to refine model results to match specific needs of simulation of high flows.

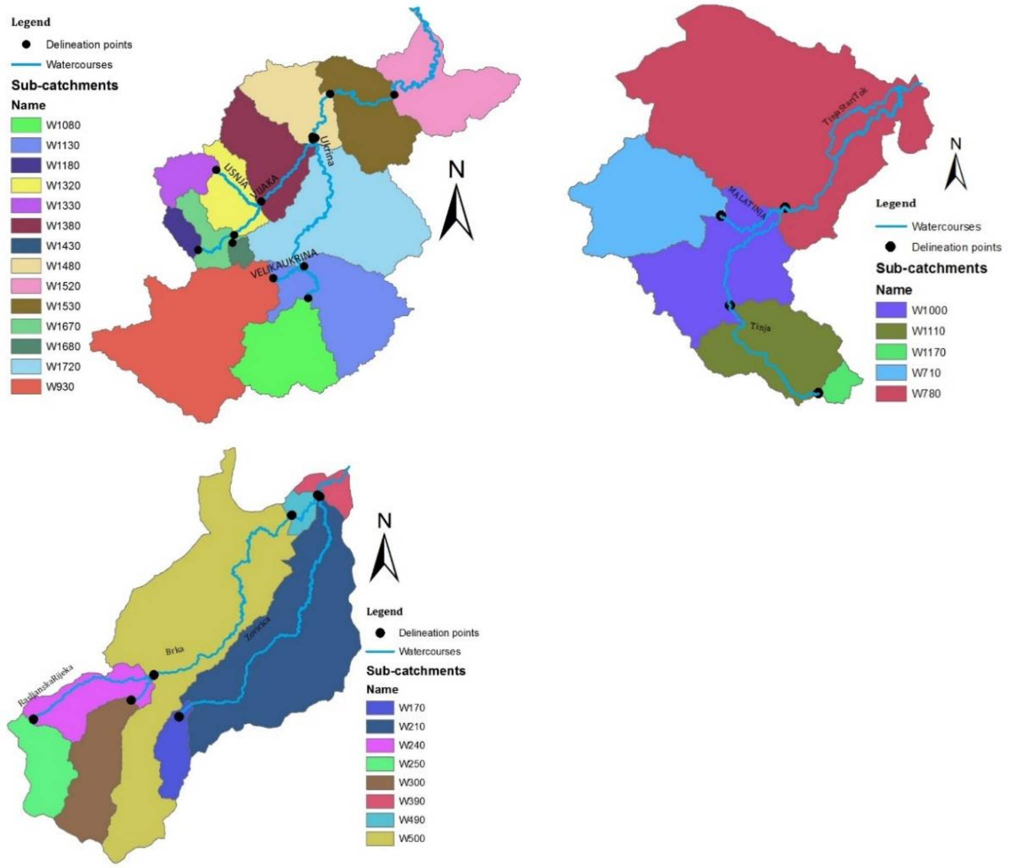


Figure 5. *Division of Ukrina (upper left), Tinja (upper right) and Brka (down left) into sub-catchments in NAM* [14]

According to data available, period for calibration and validation is only 2008-2014, where 2008 is a warm-up year. General recommendation for calibration length is at least 5 years, so calibration period is 2008-2013, while year 2014 is used for model validation (validation of results in the independent year outside the calibration period).

To calibrate ungauged basins, their behavior in terms of runoff generation mechanism is transferred from gauged catchments by means of regionalization process. In this process, catchment similarity plays great role assuming that nearby catchments behave in hydrologically similar way. The basic approach in catchment similarity is spatial proximity that emerges from the assumption that rainfall-runoff relationship varies smoothly in place or are uniform in the specific (predefined) region. Some studies [17] showed that spatial proximity yields much better prediction results in ungauged basins than with any other catchment characteristic, while best results are obtained by combining spatial proximity approach and catchment attributes, which is applied here.

In this study, several catchment's attributes are chosen for regionalization of optimized parameters in the Bosna River basin sub-catchments: (a) catchment area, (b) average catchment slope, (c) drainage length (sum of all watercourses on the basin), (d) density of drainage length (drainage length divided with basin area), (e) forest coverage, (f) mean index of drainage density (GIS tool line density, density of linear feature in the neighborhood of each output raster cell [18]), (g) catchment shape length, (h) catchment shape (difference between min and max basin elevation divided with area) and (i) percent of basin under hypsometric curve between two elevations (for example 450-500 m.a.s.l.).

Regression is based on these catchment attributes and optimized parameter sets for the Bosna River sub-catchments. Prior to that, pool of sub-catchments is grouped by their similarity according to each attribute.

After hydrological model parameter determination, general simulation results are checked upon regional relative flow duration curves (presented as ratio to mean flow) constructed of available data from the hydrological stations on Bosna River Basin. At the end, modeling results are verified using available proxy site data. For this purpose, additional spatial data that were available are areas under potential significant flood risk (APSFR) and maximum inundation zones along the Ukrina river based on 2010 flood. The latter one is used for models' re-calibration.

With all of above, general framework for setting up the RR model for ungauged basins consists of following steps:

- Collect data from the nearby catchments,
- Extract catchment similarity indices, both for donor catchments (from which parameters will be transferred) and ungauged catchments,
- Calibration of the similar gauged catchments,
- Regression analysis, i.e., correlation between each optimized model parameter and catchment characteristic,
- Estimation of ungauged model parameters from the regression model (choosing only the one with strong correlations),
- Assessment of simulation results with respect to regionalized runoff characteristics (flow duration curves) and proxy data,
- Fine-tuning of parameter estimates to produce simulations consistent with the regionalized runoff characteristics,
- Validation of coupled hydrological and hydraulic model with additional parameter fine-tuning.

It is clear that results of sensitivity analysis are dependent of the analyzed basin. Since no data are available for the Ukrina and Brka basins, sensitivity analysis could not be performed. To overcome the potential issue of having different sensitive parameters for different basins, correlation between all NAM parameters and all basins are analyzed before final conclusion. If some of the insensitive NAM parameters (according to performed sensitivity analysis) show significant correlation with some of the catchment characteristics, it will be employed in the calibration procedure.

4.2. HYDRAULIC MODELLING

The quasi 2D approach is applied to simulate unsteady flow along Ukrina, Tinja and Brka rivers. Numerous river branches and consequently link channels along with several type of boundary and interior conditions, are used to simulate a complex flow pattern during the flood events. In this paper, only few key aspects of hydrodynamic modelling using quasi 2D approach implemented in MIKE 11 models for Ukrina, Tinja and Brka are presented.

In Figure 6, small portion of computational domain of Ukrina river that covers the town of Derventa is shown. Several branches are connected with link channels (blue lines with arrows at the one end) to simulate flows in urban environment. The link channels connect the branches separated mainly by road embankments (also, it can be said that cross sections are separated). In that case, the link channels simulate flow over the embankments. The boundary with link channels can also represent high terrain or even bank lines in the absence of levees. Branches can be also "latteraly" separated by fictional boundaries in the case of wide inundations to better predict inception of flooding.

As can be seen in Figure 6, branches are not only separated laterally. At the location of bridge embankments, floodplain centerlines are disconnected and longitudinal conveyance is omitted. It is clear that this method can be applied only if overtopping conditions are out of considerations. If overtopping occurs, interior boundary condition should be defined on the single branch to represent inline structures.

Figure 6. *Elements of 1D model for Ukrina River in the city of Derventa (Flow-path centerlines, Cross-sections and Link channels)*

One of the most challenging tasks in modelling process was to include the effects of Drenova reservoir (Drenova river – tributary of Ukrina river) on flood wave attenuation. Due to the fact that geometry of the reservoir was not available, fictitious cross section was created to resemble the Volume-Elevation curve of Drenova reservoir (Figure 7). The cross sections are defined on the standard (1D) river branch. It means that “full” 1D unsteady flow equations are applied for this portion of domain to simulate flood wave propagation along the reservoir.

The dam of Drenova reservoir is represented in the model with predefined Q-H relationship for its spillway and outlet structures. Therefore, structures are included in the model through one interior boundary condition meaning that two Q-H relationships for each structure are combined into one - single family of curves.

The NAM and hydrodynamic models are linked by defining input hydrographs computed in NAM model as inflows used in hydrodynamic models. The hydrographs are converted to uniformly distributed inflows along the river reaches. The input hydrographs used in Tinja model are shown in Figure 8.

At the downstream ends of Ukrina, Tinja and Brka rivers, stage hydrographs are defined. The water surface elevations at those locations are obtained by interpolating stages measured at corresponding gauging stations along the Sava River.

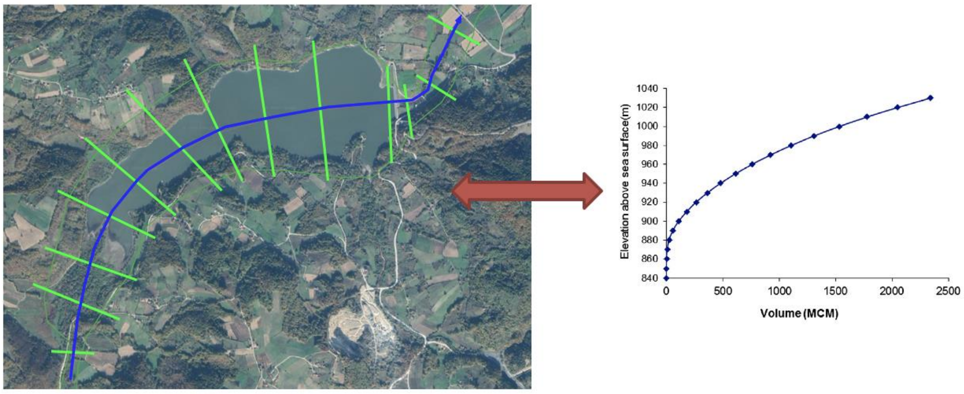


Figure 7. *Cross-sections along the Drenova reservoir (left) and corresponding Volume-Elevation curve*

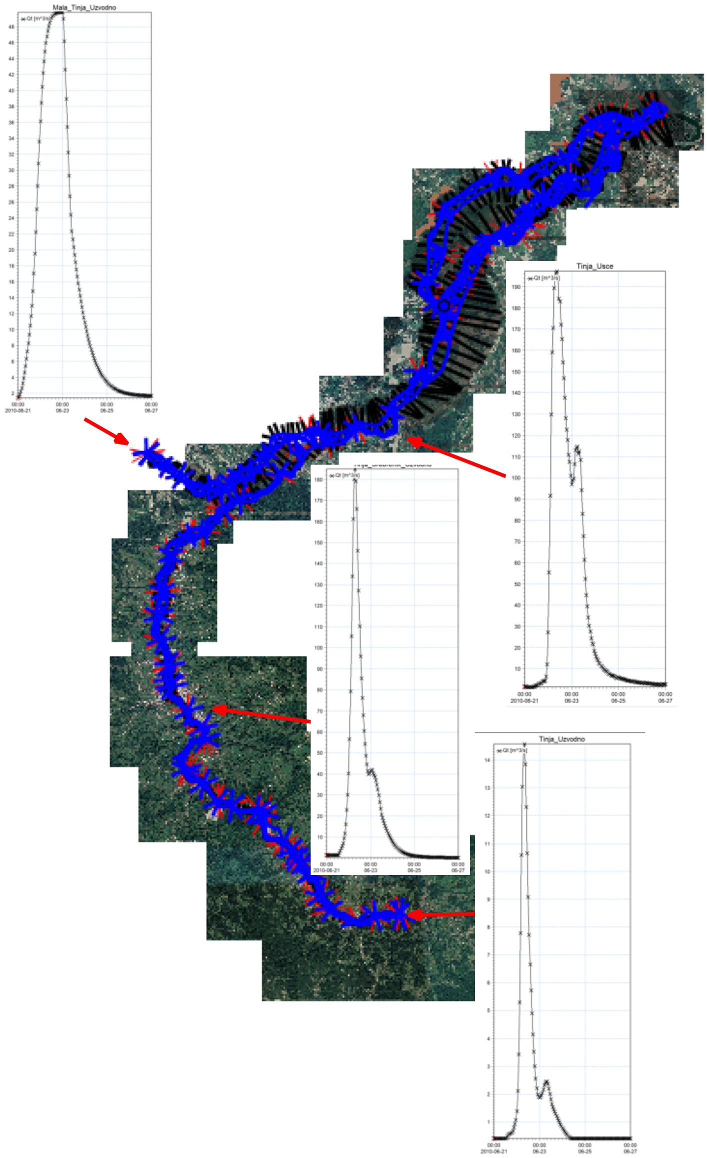


Figure 8. *Hydrological inputs along the river network for Tinja River*

5. APPLICATION IN UNGAGED BASINS – RESULTS AND DISCUSSION

5.1. HYDROLOGICAL MODEL SENSITIVITY ANALYSIS

Results of sensitivity analysis show that model output (assessed through model Kling-Gupta efficiency-KGE [19]) is highly dependent on CQOF, CK1 and CK2. Less sensitive are U_{max} and L_{max} while for TOF rapid change in model performance is observed when TOF value are higher than 0.5. This indicate that dominant processes in this particular catchment is related to overland flow (parameters CQOF, CK1 and TOF), partly interflow (parameter CK2) and upper soil storage water capacities (surface and root storage, parameters U_{max} and L_{max}).

The insensitive model parameters do not influence model performance and in the plot (not shown here) are characterized with the straight horizontal line which means that no efficiency change is made no matter which value parameter takes from the parameter space. Small sensitivity is observable to TG parameter, but only when its value is below 0.5. It seems that interflow, baseflow and groundwater component of water balance are not dominant processes for Tinja up to Srebrenik catchment.

5.2. REGIONALIZATION OF THE MIKE NAM PARAMETERS – MODEL CALIBRATION

Between optimized model parameters for all Bosna sub-catchments and all analyzed catchment characteristics, no correlations above 0.2 (which is very low and insignificant) was found. This was subject to further refinement of the catchment choice based on catchment similarity and particular catchment characteristic. This means that donor catchments that have quite different characteristic from the ungauged catchments were removed from the pool of catchments and correlations are analyzed again. This step is repeated for each characteristic individually.

Regarding catchment area, no significant correlations were found. For the average catchment slope, significant correlation is found only with CK1,2 parameter (timing constant for overland flow) including only 10 relatively low-land catchments with slopes between 6-15%. From this pool of catchment, ones with very small areas are removed and significantly better results are achieved. Correlation coefficient is 0.76 while regression model is two-degree polynomial, as shown on Figure 10, left. Somewhat weaker correlation is found between catchment drainage length and CQOF (overland flow coefficient) parameter, R^2=0.66. However, this parameter is highly correlated with the drainage density, as shown on Figure 9, right.

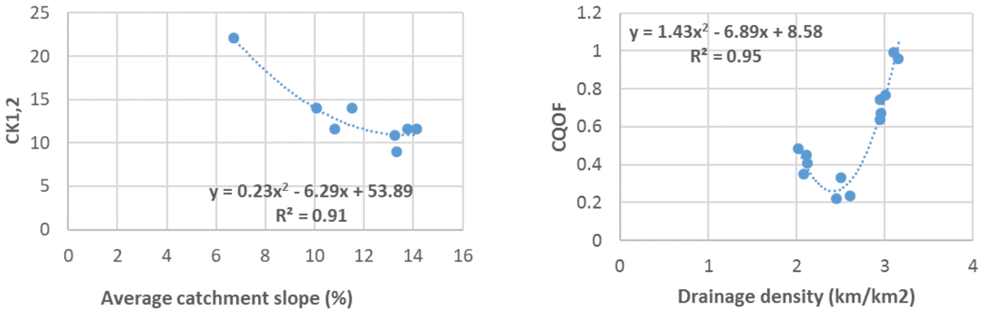


Figure 9. *Regression models average catchment slope and $CK_{1,2}$ parameter*

According to the percentage of forest coverage on catchments, 12 catchments was found similar to the ungauged catchments. As was expected, parameters related to the surface storage and root zone was correlated with this characteristic. Correlations are shown on Figure 10.

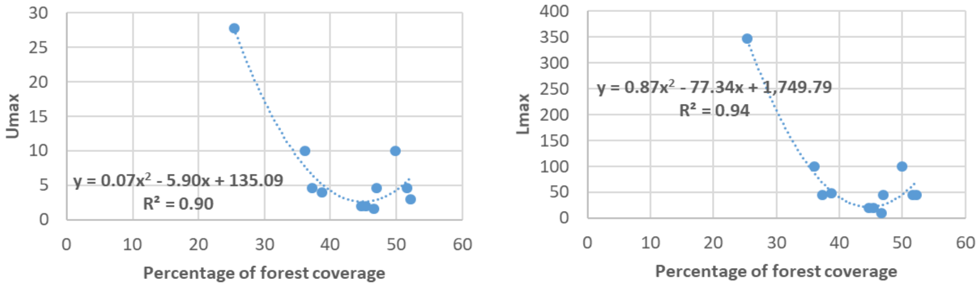


Figure 10. *Regression models for forest coverage percentage and root zone model parameters*

Parameter of threshold for overland flow TOF is correlated with the drainage density index, as shown on Figure 11.

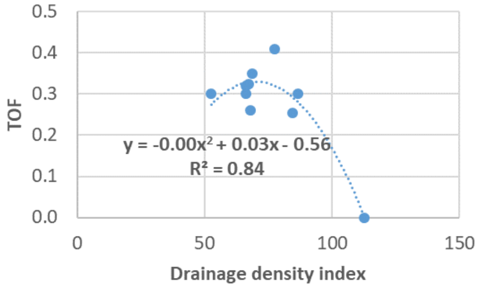


Figure 11. *Regression model for drainage density index and TOF model parameter*

In summary, all sensitive model parameters are explained (with their correlations) with some of the catchment characteristic. Insensitive parameters are not, which was expected, since their role in modelling process is of little important because they do not interfere with the model efficiency. This obviously is true for all Bosna sub-catchments, not only for gauged part of the Tinja catchment for which sensitivity analysis is performed.

From the analysis above, parameter values for ungauged basins and their sub-catchments can now be easily determined, knowing their characteristics employed in above regression models. However, in the situations where regional model gives irrational parameter values (for example, CQOF larger than 1, or L_{max} larger than recommended 300), values are kept at the maximum/minimum of the recommended parameter range.

5.2.1. Similar catchments and flow duration curves

After previous analysis, it became clear which catchments are similar by one or more characteristics with the ungauged catchments under this study. From the complete list of similar catchments, the ones with very small observation period (i.e., few years only, because of the bias of the optimized parameters values) and the ones with very small area (correlation analysis with catchment area showed that the results from the catchments smaller than 100km^2 deviate from the scatter the most) are removed. That left 18 sub-catchments from the Bosna River Basin to be used for validation of the models.

Figure 12 shows standardized (divided with mean flow) flow duration curves for the 18 catchments that are similar by its attributes with catchments Tinja ungauged part, Ukrina and Brka. On the plot, two curves are highlighted: the one for Tinja-Srebrenik sub-catchment obtained from observed flows (black dashed line) and one for Ukrina catchment up to Derventa station formed with historical observational data in period 1964-1983 (thick red line). From these FDCs, range is formed (showed as grey range on Figure 13) and used to validate results for sub-catchments of Ukrina, Tinja and Brka.

Results showed that modelled FDC are within the defined range of the regional FDC so there is no need for further refinement of model parameters (plots not shown here due to space limitation of the paper).

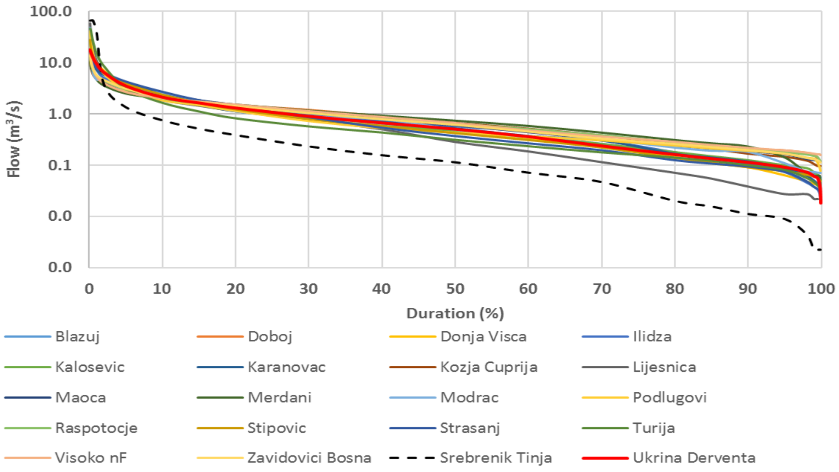


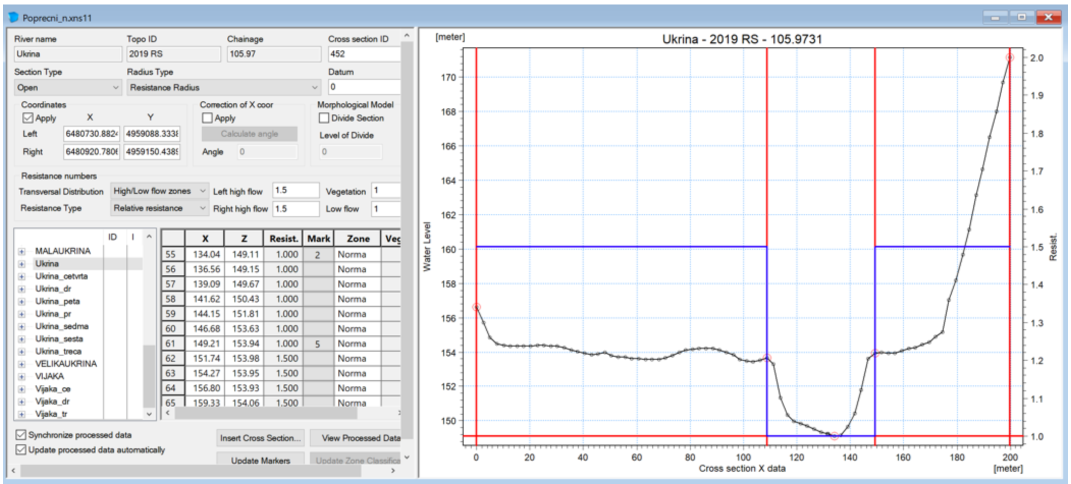
Figure 12. *Relative flow duration curves (to mean flow) for the sub-catchments of Bosna River Basin that are similar to ungauged basins of Ukrina, Tinja and Brka*

5.3. HYDRAULIC MODEL CALIBRATION

It was concluded that the most significant parameters of HD models for Tinja, Ukrina and Brka, beside the hydrological inputs, are Manning's coefficients and the parameters related to the link channels. Due to lack of available data that can be used to predict inception of flooding or lateral momentum and mass transfer between main river and floodplains, parameters of the link channels are estimated by expert judgment and only Manning's coefficients for regular branches (floodplains and main rivers) are subject to calibration.

The initial guess for Manning's coefficients is based on land cover data. Afterwards, the Manning's coefficients and inflows are varied until the historical APSFR boundaries and observed peaks of stage hydrographs were reproduced in numerical simulations of historical flood events.

Variation of adopted Resistance value (ratio between local and base value of Manning's coefficient) across the one cross section of Ukrina river is depicted in Figure 13.



Poprecni_n.xns11

River name: Ukrina
Topo ID: 2019 RS
Chainage: 105.97
Cross section ID: 452
Section Type: Open
Radius Type: Resistance Radius
Datum: 0
Coordinates: ☑ Apply
Left: X 6480730.882 Y 4959088.333
Right: X 6480920.780 Y 4959150.438
Correction of X coor: ☐ Apply
Angle: 0
Morphological Model: ☐ Divide Section
Level of Divide: 0
Resistance numbers
Transversal Distribution: High/Low flow zones
Resistance Type: Relative resistance
Left high flow: 1.5
Right high flow: 1.5
Vegetation: 1
Low flow: 1

	X	Z	Resist.	Mark	Zone	Veg
55	134.04	149.11	1.000	2	Norma	
56	136.56	149.15	1.000		Norma	
57	139.09	149.67	1.000		Norma	
58	141.62	150.43	1.000		Norma	
59	144.15	151.81	1.000		Norma	
60	146.68	153.63	1.000		Norma	
61	149.21	153.94	1.000	5	Norma	
62	151.74	153.98	1.500		Norma	
63	154.27	153.95	1.500		Norma	
64	156.80	153.93	1.500		Norma	
65	159.33	154.06	1.500		Norma	

☑ Synchronize processed data
☑ Update processed data automatically

Figure 13. *Variation of Resistance value across one cross section of Ukrina River*

5.4. COUPLED HYDROLOGIC-HYDRAULIC MODEL RESULTS AND MODEL RE-CALIBRATION

The calibration (re-calibration) of coupled models is made through iterative process depicted in Figure 14. Parameters of previously calibrated NAM model are tuned in order to get satisfactory water levels according to historical flood zones from 2010 and known APSFR limits. The process is repeated in several iterations.

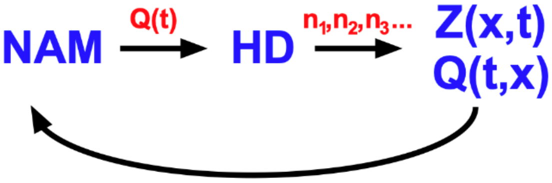


Figure 14. *Scheme of re-calibration process of NAM and HD models*

Validity of the runoff simulation is cross-referenced with the proxy data (recorded water level during 2010 flood that occur in the area of UTB basins). Hydraulic model run showed need for some of the sub-catchments parameters refinement in order to increase runoffs. As previously stated, parameters that are the most influential to runoff increase are CQOF and $CK_{1,2}$ and L_{max} to some extent. Therefore, these parameters are fine-tuned for all sub-catchments located downstream of the HS Srebrenik of Tinja basin until simulated water levels are closer to the extent of the APFSR.

Upon results of the hydraulic models and known data from Drenova reservoir during the 2010 flood as well as APFSR extent, water levels should be higher in the areas of Ukrina River tributaries Vijaka and Lišnja. Therefore, CQOF, $CK_{1,2}$ and L_{max} parameters of these sub-catchments are also tuned so to meet the recorded 2010 flood extent. For Brka basin, small increase of high flows was also needed.

With these new parameters, resulting FDC are compared with regional range. Modelled FDC again show good matching with regional ones, especially in the range of high flows, which is extremely important due to purpose of the hydrological model results. Figure 15 shows those results for Ukrina sub-catchments.

In Figure 16 the comparison between calculated and observed hydrographs at location of Srebrenik gauging station is shown for different phases (iterations from a) to d)) of calibration process. As explained earlier, both NAM and HD models are tuned to obtain satisfactory results. Compliance with second criteria for calibration is being checked by visual comparison of APSFR limits and calculated flood zones. In Figure 17 calculated flood zones for final step of calibration process are shown.

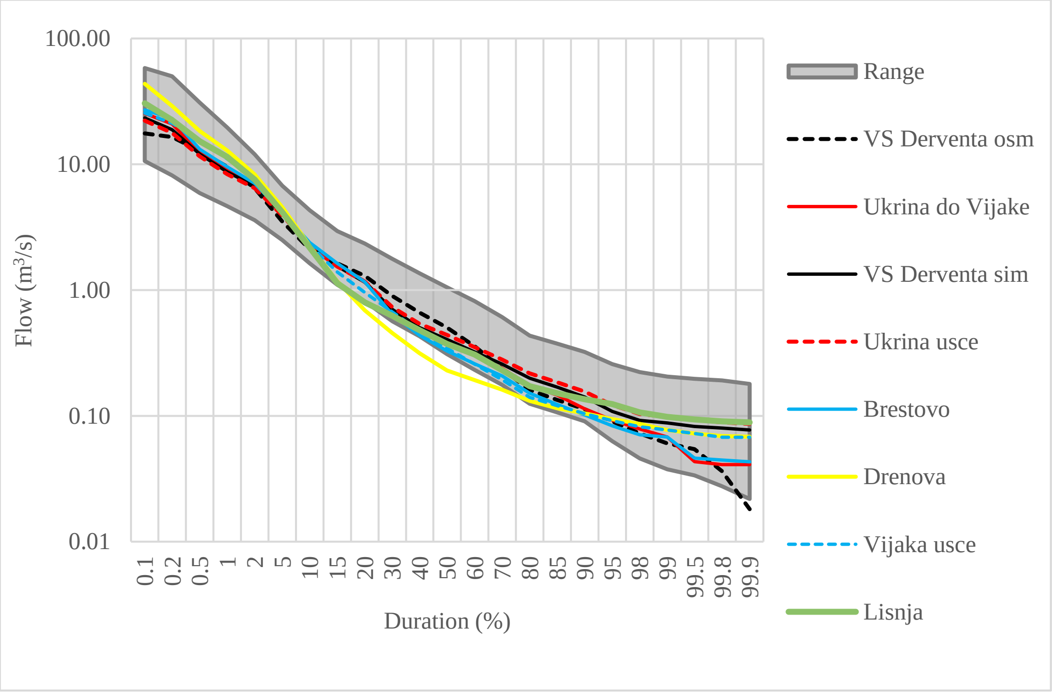


Figure 15. *Comparison of flow duration curves from gauged catchments (grey range) and simulated for Ukrina model sub-catchments*

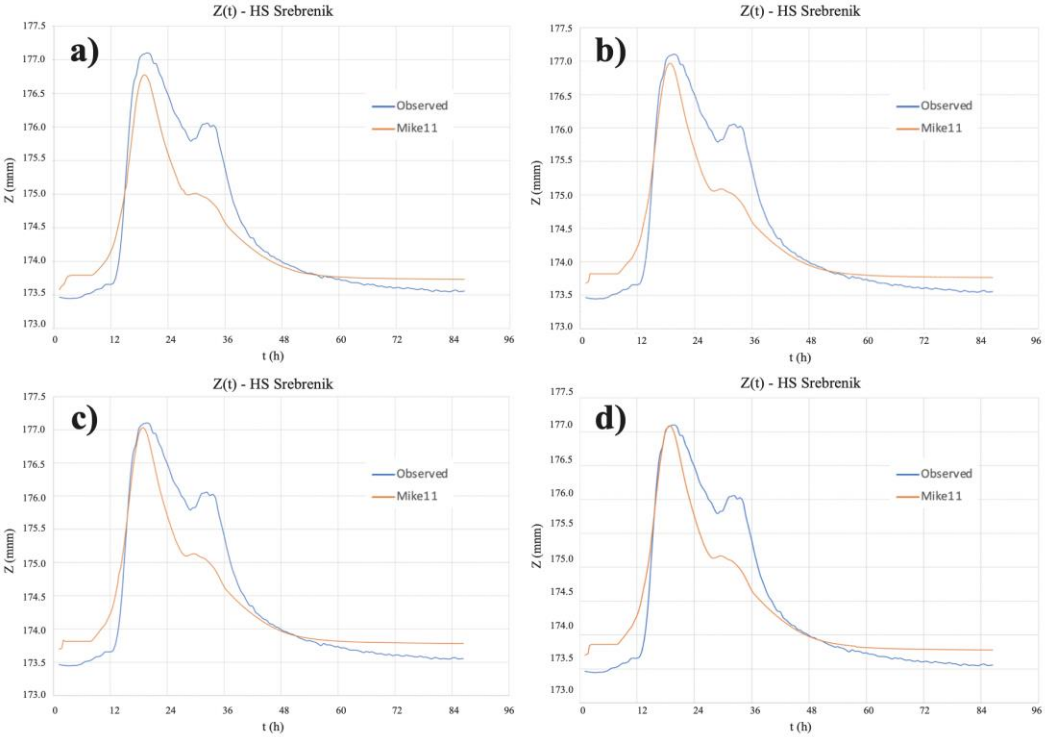


Figure 16. *Comparison of calculated (orange line) and observed (blue line) stage hydrographs for different phases of re-calibration process*

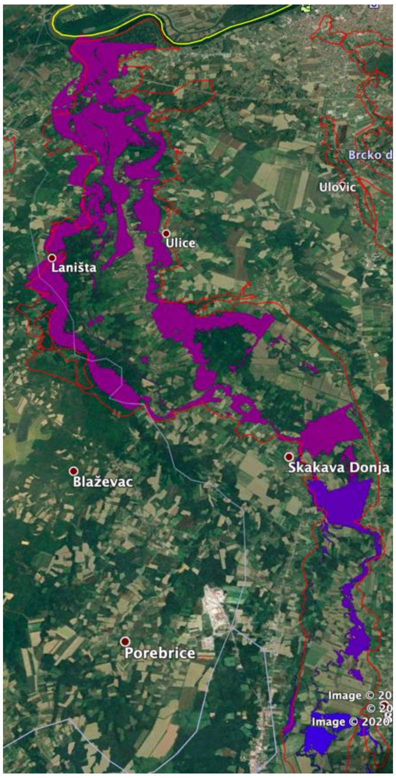


Figure 17. *Calculated flood zones (areas filled with various colors) and APSFR limits (red lines) for Tinja River*

6. CONCLUSIONS

In this study, methodology for hydrological and hydraulic modeling of ungauged basins that can be used in flood forecasting and early warning systems is presented. Due to lack of observed data on the basins, hydrological model is calibrated using regionalized regression models established between calibrated model parameters on nearby Bosna River sub-catchments and distinctive catchment characteristics, while parameters of the hydrodynamic model are assumed by expert judgement. Validation of the methodology was possible with historical areas under potential significant flood risk observed during the flood in 2010.

With applied methodology, it is observed that simulations of coupled hydrological and hydraulic models somewhat underestimated flood peaks on Ukrina, Tinja and Brka Rivers. The discrepancy in simulations could not be considered as error per se, since the simulations are compared to only one historical flood event. However, flood underestimation is consistent for all subbasins. The validation would be better if several floods were available, since flood mechanism varies from event to event due to storm characteristics and antecedent soil wetness, above other factors.

In general, proposed methodology proved to be worth of future development and upgrading. One of the upgrades to the proposed methods are further and in more detail exploration of catchments similarity in regression analysis in order to improve model's parameter estimation. Also, models validation should be extended to more flood events and with the results of flood forecasting system that operates in real-time in order to detailly validate the proposed methodology.

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