River network modelling to improve understanding of complex interactions between river environment and highway design

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Abstract: Highway planning is a complex task with many challenges since the interaction of this very long structure with rivers, streams and other structures on riverbanks is inevitable. Highway crossings design poses a special challenge to experts and requires detailed hydrological and hydraulic analyses to define the best solution. A generally accepted approach is to use state-of-the-art hydrological, 1D and 2D hydraulic models to better understand the interaction of the highway and rivers, and define the scope of works and measures that will minimize the effects of highway construction on the water regime. A very important first step in this modeling process is the hydrological analysis, which is needed to define different flood scenarios. This paper presents the hydrograph computation methodology, which includes the application of the coupled hydrological model HEC-HMS and the hydraulic model 1D HEC-RAS. The methodology can be used to create many scenarios where a large number of parameters (precipitation, soil moisture, etc.) are varied on the large basin area, delineated into many sub-basins. The paper also presents the results of the methodology applied for the Morava Corridor design.

INTRODUCTION

In highway engineering, the diversity of problems is broad and includes the design of highway embankment and its river crossings, ranging from small streams to large rivers. It is often necessary to evaluate the impacts that future land use, proposed flood control and other planned measures will have on the highway and the river crossings. The designer also has a responsibility to adequately assess flood potentials and environmental impacts that planned highway and river crossings may have on the watershed.

Considering the size of the investment and the importance of new infrastructure facilities, it is necessary to consider and define the required river engineering works and measures at an early design stage. These river engineering works may be needed to minimize the effects of the highway construction on the water regime, ensure the protection of the highway from floods and fluvial erosion or protect the existing state of the environment in the river valley [1].

In highway design, the primary concern is with the surface runoff portion of the hydrologic cycle. Generally, either flood hydrographs or peak flows for a range of flood frequencies should be determined at many sites along the highway. Flood hydrographs are needed where a detailed description of the time variation of runoff rates and volumes is required. The flood peak discharge is crucial for the highway stream crossings which are traditionally designed to allow the free flow of a given quantity of water with an acceptable level of risk [2].

Relevant values to be used for design purposes should be related to unfavorable hydrological situations at a certain probability of occurrence. Therefore, the primary purpose of the hydrological modelling is to generate flood events of a certain probability at all the input locations of the 2D hydraulic models, prepared both for the current and future state of the river valley. These flood events may reflect the existing climatic conditions or conditions of climate change.

The goal of this paper is to present the methodology for river network hydrological modelling that includes the application of the coupled hydrological model HEC-HMS and the hydraulic model 1D HEC-RAS. It can be used to create many scenarios where a large number of parameters (precipitation, soil moisture etc.) are varied on the large basin area, delineated into many sub-basins.

This paper presents the application of the methodology to the Morava Corridor Project, where the results of hydrological modeling were used to generate input data for hydraulic models, as required for the development of safe and rational technical solutions.

MODELLING CONCEPT

Flooding is caused by flood waves that are stochastic, which is why they are described by the exceedance probability. In this sense, the degree of area's flood protection depends on the discharge exceedance probability at which that area will be flooded. Designing hydrotechnical facilities that may be exposed to the effect of floods includes the assessment of the risk of high waters in advance. The risk of high waters is the probability that the maximum instantaneous discharge in the year will exceed a pre-set value, i.e., the discharge at which the area will be flooded $P\left\{Q_{max} \geq q_{max,P}\right\} > P$.

In addition to the danger of high discharges, a high volume of flood wave is also a danger for some facilities. In such cases, a two-dimensional function of the distribution of basic parameters of flood hydrograph is applied to determine the exceedance probability. Thus, there's a very wide range of possible combinations of maximum annual discharges and maximum flood wave volumes for the same exceedance $P\left\{\left(Q_{max} \geq q_{max,P}\right) \cap \left(W_{max} \geq w_{max,P}\right)\right\} > P$ probability.

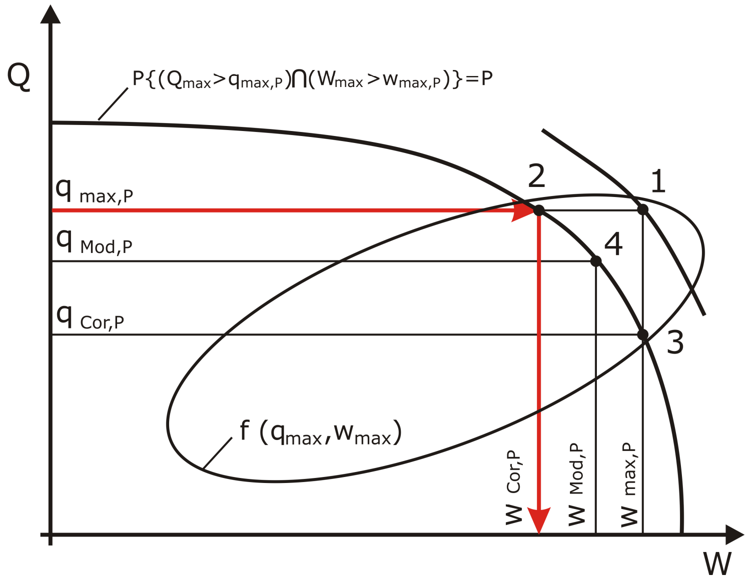


***Figure 1.** Possible combinations of maximum annual discharges and maximum flood wave volumes*

Defining the discharge required for regulation facilities design in the highway zone includes the analysis of the maximum annual discharge of the same marginal probability and the corresponding flood wave volume for the adopted exceedance probability $-P\left(q_{max,P}\ ,\ w_{cor,P}\right)$, point 2 in the previous figure. The return period $T(q_{max,P})$ is the average number of years between two exceedances. It is expressed $q_{max,P}$ as the reciprocal of the exceedance probability $(q_{max,P}) = \frac{1}{P(q_{max,P})}$. It should be noted that the risk, in the narrow sense, represents the probability that the value $q_{max,P}$ will be exceeded at least once during the design life of the facility of L years:

$$R\left(q_{max,P}\right) = 1 - P\left\{Q_{max} \geq q_{max,P}\right\}^{L} = 1 - \left(\frac{1}{T(q_{max,P})}\right)^{L} \tag{1}$$

For the determination of the exceedance probability of flood waves in small basins, the assumption is introduced that rainfall event whose precipitation sum has a probability p produces a wave of the same probability of occurrence. However, this assumption cannot be applied in a complex river network.

In a complex river network, it is not possible to know in advance which rain will result in a flood wave of some probability, since the hydrograph of the required probability may result from a combination of different rainfall events on the upstream parts of the basin.

As rainfall events are described with three elements - the precipitation sum, the duration of the event and the distribution of precipitation within the event, the problem of determining the combination of the probabilities of rainfall elements that result in a hydrograph of a certain probability becomes increasingly complex. Also, the beginning of rainfall events in all parts of the basin does not have to start at the same time. The output hydrograph is also affected by runoff conditions, which are not the same across the basin.

Determining the relevant values for design of different facilities that may be exposed to the effect of floods involves modelling complex processes: converting rainfall in the basin upstream of the facility into runoff, propagation and transformation of runoff along the river course and computing hydraulic parameters (levels, velocities, tangential stresses, etc.).

The modelled river basin most often includes several watercourses, and therefore represents a complex river network with spatially inhomogeneous delineation, i.e., it consists of sub-basins of large and small areas. In order to perform the computation to all sub-basins, a time step corresponding to the minimum time of concentration of flood waves in small sub-basins should be selected in hydrological computations.

The process of determining the relevant values for protection facilities designs in the river course and highway interaction zone consists of five steps: (1) defining design values of hydrographs; (2) defining the design values of the rainfall elements (precipitation sum, event duration, and distribution of precipitation within the rainfall event) and design hyetographs for all combinations of probabilities; (3) formation of synthetic hydrographs; (4) selection of representative synthetic hydrographs of selected exceedance probability; (5) hydraulic flow modelling and selection of relevant values for design.

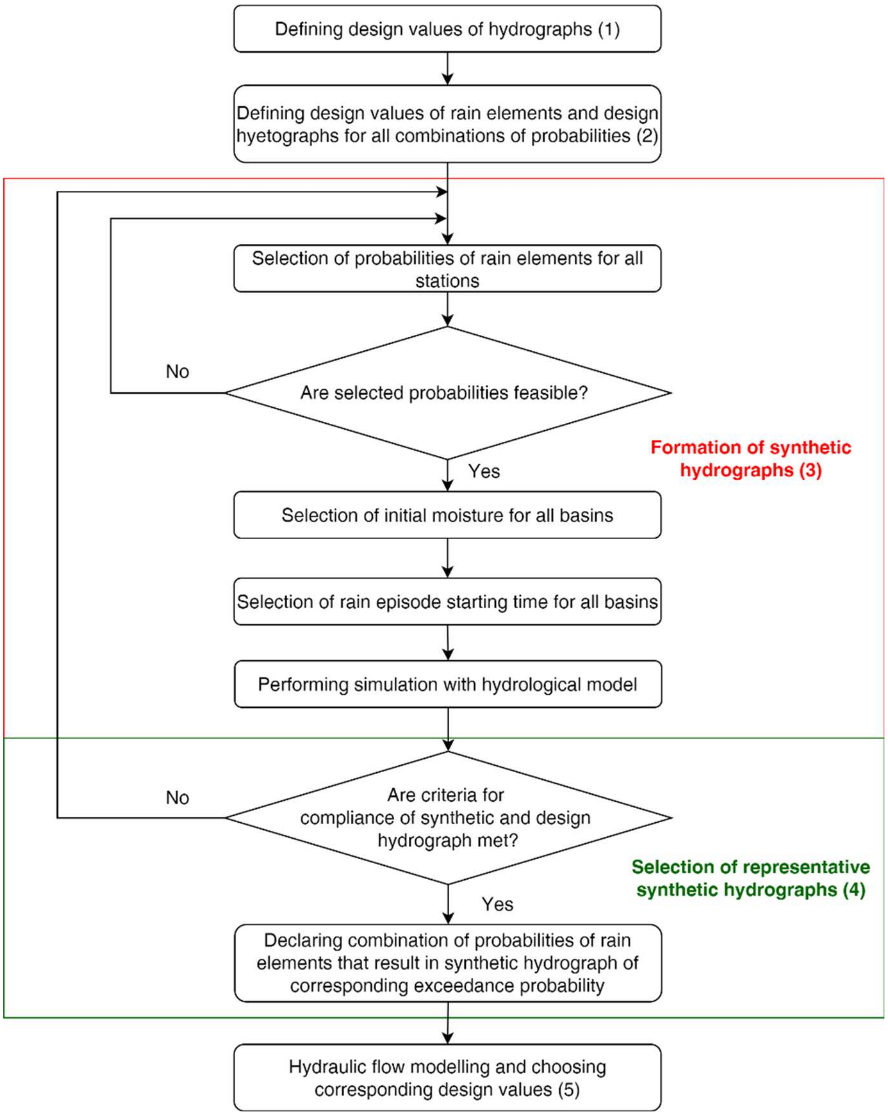


Figure 2. *Scheme of the process of determining the relevant values for designing protection facilities*

Design hydrographs

Design hydrographs should be formed based on the series of maximum annual instantaneous discharges and the series of wave volume of hydrographs where the maximum annual instantaneous discharge - corresponding wave volume was realized. Design values of the runoff hydrograph elements are calculated and the design runoff hydrographs of the characteristic exceedance probabilities P are formed. Design values of the hydrograph elements are determined by adjusting the theoretical distributions to the empirical probabilities of the series. The quality of the adjustment is determined by the χ^2 test. The shape of the hydrograph for each considered probability P is determined by the Goodrich method:

$$Q_p(t)=q_{p,\max}\cdot 10^{-\alpha\left(\frac{(1-X_t)}{X_t}\right)} \tag{2}$$

where:

$Q_P(t)$ - design hydrograph ordinate of flood waves with probability P at time t,

$q_{max,P}$ - the maximum ordinate of the design hydrograph flood waves with probability P,

X_t - relative abscissa of the hydrograph $X_t=\frac{t}{T_P}$,

$T_{por,P}$ - hydrograph rise time.

Parameter α_P is a parameter that depends on the form of the hydrograph $\alpha_P=f(\lambda_P)$. The hydrograph rise time is estimated based on historical hydrographs, and the parameter α_P from the condition that the volume determined by the Goodrich method is equal to the design volume $W_{cor,P}$.

Design values of rainfall elements

The design value of the precipitation sum during rainfall event is determined based on the daily precipitation sum design value and the design rainfall duration. The precipitation distribution within the rainfall event is also important for the runoff formation. Design values of described rainfall elements are set for the purpose of determining the hydrograph of the selected exceedance probability.

Defining design daily precipitation sums is based on data from: precipitation stations (PS) where the daily precipitation sums are measured, and main meteorological stations (MMS) where the rainfall is measured continuously, and the daily precipitation sum is obtained for the period from 6:00 h UTC of the previous day to 6:00 h UTC of the day of observation, where i =1, 2, …n, is the total number of PS and MMS.

Based on the series of daily precipitation sums ($Hdn_{j,k}$, where j is the number of days in a year, k is the year), the series of maximum annual daily precipitation sums for all stations are formed $Hgod.max.dn_{k,i}$. They serve as the basis for defining the design values of maximum annual daily precipitation sums $Hmax.dn_{p1,i}$, where p1 is the probability that the maximum annual daily precipitation sum, greater than or equal to Hmax.dn, will occur at the station. The design values are determined by adjusting the theoretical distributions to the empirical probabilities of the series. Five theoretical distributions are used: Pearson 3, Log-Pearson 3, Log Normal, Gumbel and General Distribution - GEV (Generalized Extreme Value). The quality of the fitting was determined by a χ^2 test, so the distribution that best fits the empirical values was chosen.

Only daily precipitation sums are measured at precipitation stations. As the unfavorable hydrological situation can be caused by precipitation of shorter or longer duration than one day, it is necessary to determine the design precipitation sum for different rainfall durations. The design precipitation sums for event durations different than one day is determined via reduction curves. The reduction curve is the ratio of the design precipitation sum ($H_{uk}(T_k)$) of rainfall duration T_k and the design maximum annual precipitation sum:

$$(H_{max.dn.})\psi(T_k)=\frac{Huk(T_k)}{Hmax.dn.} \tag{3}$$

The value of $\psi(T_k=1440 \text{ minutes})\geq 1$ is because the maximum annual precipitation sum for the duration of 1440 minutes is usually higher than the maximum annual (daily) precipitation sum, measured at 6 h UTC. By interpolating the reduction curves on the MMS, the reduction curves for all precipitation stations are determined $\psi\left(Tk_{p2,i}\right)$.

The duration of the rainfall event at the meteorological station is determined based on the duration of the rainfall events where the maximum annual precipitation sums have been realized. The design values of the rainfall events duration can be determined only at MMS, because the exact duration of the rainfall event is known only at MMS, while at other precipitation stations it is generated by interpolation. Duration of the rainfall events $Tk_{p2,i}$ for the characteristic probabilities of occurrence p2 are determined based on the design durations at the MMS.

Precipitation distribution is set on the MMS within a rainfall event based on measurement data during rainfall events with maximum annual precipitation sums. At precipitation stations it is obtained by interpolation. The result is a dimensionless precipitation sum line for different probabilities of occurrence p3. Precipitation sum lines are formed for each event with a maximum annual precipitation sum, and then a series $\frac{H}{Huk}$ for the chosen $\frac{T}{T_k}$ where: H is the sum of precipitation up to the moment T, T_k is the duration of the rainfall event, and the Huk is the total amount of precipitation during the rainfall event.

The formation of design hyetograph is done by combining the probabilities of individual precipitation elements, so that the design hyetograph is not associated with one exceedance probability, but a combination of probabilities p1, p2 and p3.

Synthetic hydrographs

The process for creating synthetic hydrographs consists of the following steps: generation of possible combinations of probabilities for precipitation elements for sub-basins according to predefined criteria; formation of design precipitation hyetographs for possible combinations of rainfall element probabilities for all sub-basins; setting the range of the initial soil moisture parameters, i.e., parameter CN for all sub-basins; determining the start of the rainfall event for all sub-basins; carrying out simulations using a hydrological model for design hyetographs, CN parameter and rainfall event start time.

Selecting synthetic hydrographs of a specific exceedance probability

The selection of a synthetic hydrograph of a specified exceedance probability is made based on comparison of a synthetic hydrograph and a design hydrograph of a specified exceedance probability. The comparison should be made as follows. Firstly, maximum discharges for design and synthetic hydrographs are set, and its difference is computed. Then, if the difference between maximum discharges is less than dQ, the volumes are checked: peaks of design and synthetic hydrographs are set at the same moment in time; the hydrographs are shortened so that design and synthetic hydrograph have the same duration (τ_n), because the recession limb of the hydrograph after that time does not significantly affect the volume; the volumes of shortened hydrographs are computed; checking that the deviation of the volumes of synthetic and design is less than dV. If the volume deviation is less than dV, the probability of the design hydrograph will be assigned to the synthetic hydrograph. Parameters dQ, dV and τ_n are determined according to the system that is being modelled.

Selecting a hydrological scenario of a specific exceedance probability

In cases where the highway and the river interact there is usually more than one hydrologic station along the river course. Because of that, the chosen hydrological scenario with a certain exceedance probability is a scenario in which the synthetic hydrograph with the same probability is realized at all stations.

Considering that modelling is done on basin areas consisting of a large number of sub-basins and that the formation of synthetic hydrographs is done by combining 5 elements that can have different probabilities, the number of scenarios becomes infinite. It is clear that such computations are impossible to implement, so it is required to shorten the list of scenarios, but so that the maximum variety of scenarios is obtained and as much search range as possible is covered.

The first step in reducing the number of scenarios is the selection of possible rainfall elements and CN parameter probabilities. The next step in reducing the number of scenarios is to group the sub-basins, so that all sub-basins belonging to one group have the same probabilities of the selected rainfall element. The third step is to introduce assumptions about a possible combination of probabilities between sub-basin groups.

When this is done for larger basins, the number of combinations, despite the introduction of the assumptions, may be such that the computations are impossible to carry out, so it is necessary to implement additional simplifications.

There is a large number of scenarios that correspond to the same exceedance probability. The one that gives the most unfavorable hydrotechnical values is selected as the relevant scenario.

Hydraulic flow modelling

Hydraulic model included Zapadna Morava river along the Morava Corridor and tributaries that intersect with highway route (as the Južna Morava, Rasina and Ibar). The 2D hydraulic model is created using the RiverFlow2D software for modelling the river floods in current climate conditions and the conditions expected due to climate change.

Details about the hydraulic modelling are presented in the paper Collaborative Hydraulics - Next Generation Tools for Highway Design in Complex Interactions with River.

CASE STUDY OF THE MORAVA CORRIDOR PROJECT

The future corridor of the E-761 highway from Pojate to Preljina mostly passes through the valley of the Zapadna Morava and shortly through the valley of the Velika Morava. The length of the highway from Pojate to Preljina is about 110 km, while the length of the Zapadna and Velika Morava on this stretch is about 138 km. The route of the planned highway is almost entirely in the zone that is exposed to flooding by the Zapadna and Velika Morava, and mostly is in the direct contact with the river course (at the intersection points and in the zones where the route of the highway is near the riverbed).

The aim of the modelling is to define the water level and other hydrotechnical values at all intersections of the highway route and the watercourse, as well as at the locations where the highway route approaches the watercourse. Due to the long length of interaction between the highway and watercourse, the basin area (Figure 3), for which is required to model runoff and flow along the rivers, is large and heterogeneous in terms of rainfall regime, runoff, and discharge conditions.

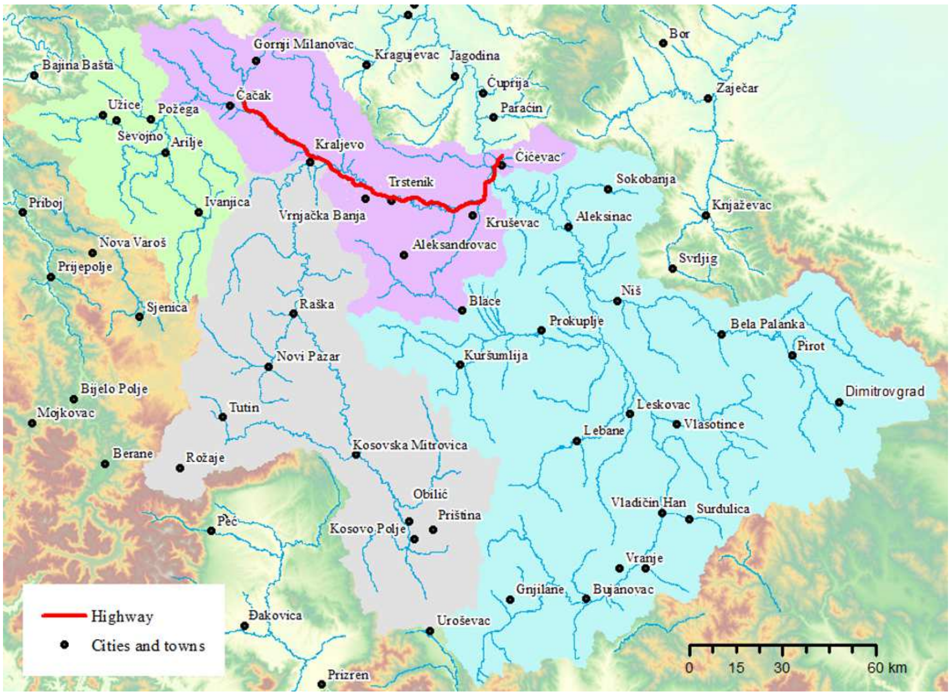


Figure 3. Modelled basin area

HEC-HMS software package was used for modelling the process of converting rainfall into runoff. HEC-HMS is an established, worldwide recognized, and innumerably successfully applied software package for hydrological modelling of flood events. HEC-HMS is designed to simulate the complete hydrological process in the basin of a branched river network using an empirical concept of hydrological modelling. The result of the application of the hydrological model are hydrographs at the downstream boundaries of the basins.

Propagation of flood waves along river courses is implemented using the 1D HEC-RAS model.

The coupled HEC-HMS and 1D HEC-RAS model provides input hydrographs for the 2D hydraulic model, which more precisely determines the hydraulic values relevant for the structure design in the highway and watercourse route intersection zones. Places where hydrographs are provided are shown graphically in the following figure (Figure 4). Hydraulic modelling was performed with the RiverFlow2D hydraulic model.

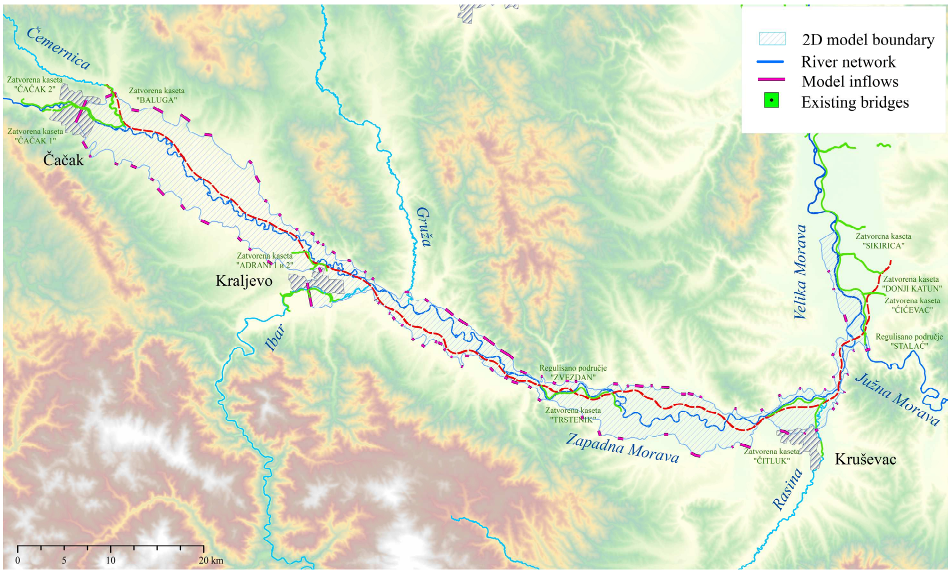


Figure 4. *Hydraulic 2D Model Input Locations*

Discharge data at hydrological stations and precipitation data at precipitation and main meteorological stations are available for modelling. There are 24 hydrological stations (Figure 5) along the entire basin, 4 of them are in the zone of interaction of watercourses and highway route on the section from Pojate to Preljina. Three hydrological stations are located on the Zapadna Morava (Miločaj, Trstenik and Jasika) and one on the Velika Morava (Varvarin). The hydrological data on multi-year series of mean daily discharges at hydrological stations and series of maximum annual instantaneous discharges were used to form design hydrographs, as well as hourly hydrographs for the events selected for model calibration.

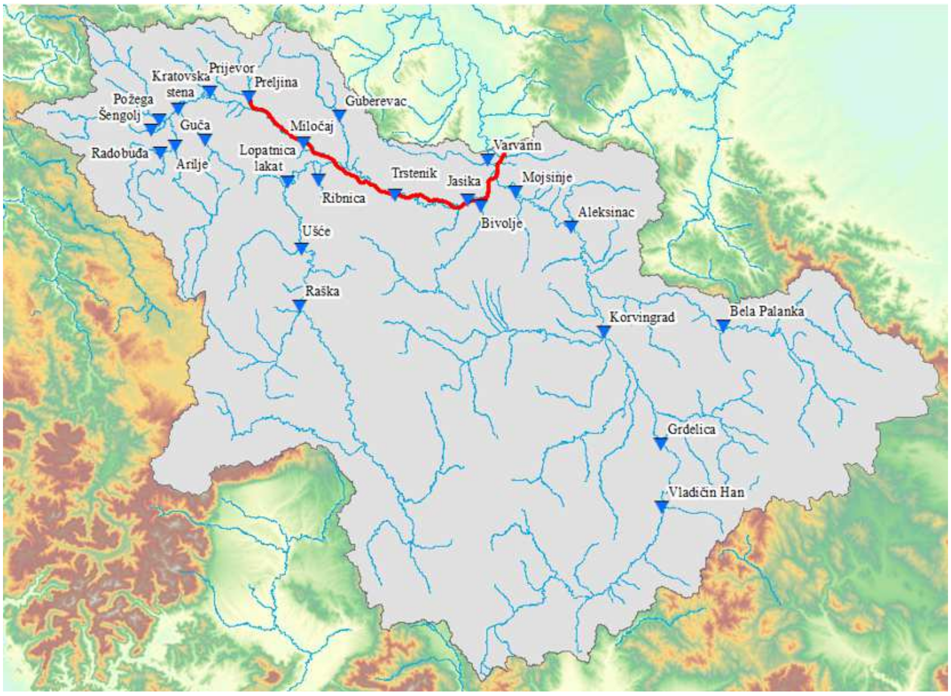


Figure 5*. Layout of hydrological stations*

Data on daily precipitation sums from 34 precipitation stations and 11 main meteorological stations (Figure 6) were used to define the design maximum annual daily precipitation sums, and data on hourly precipitation sums during selected events were used for calibration.

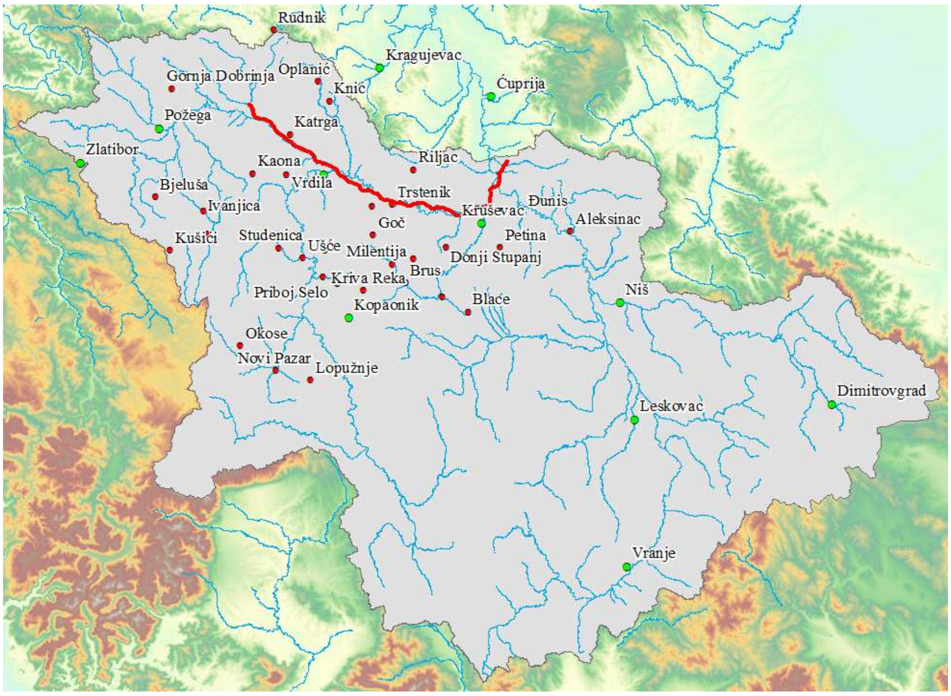


Figure 6. *Layout of rainfall and main meteorological stations*

Design values of daily precipitation sums were set for all precipitation and main meteorological stations. Design values of the rainfall duration and the reduction curve used in the formation of design hyetographs are taken from the documentation [3].

Design hydrographs were formed for 4 hydrological stations in the highway interaction zone and the Zapadna and Velika Morava for maximum annual discharges and corresponding flood wave volumes.

Modelled basin is delineated into 153 sub-basins in the HEC-HMS model, out of which 13 are frontal sub-basins, 5 are sub-basins between two hydrological stations and 135 are considered as smaller basins.

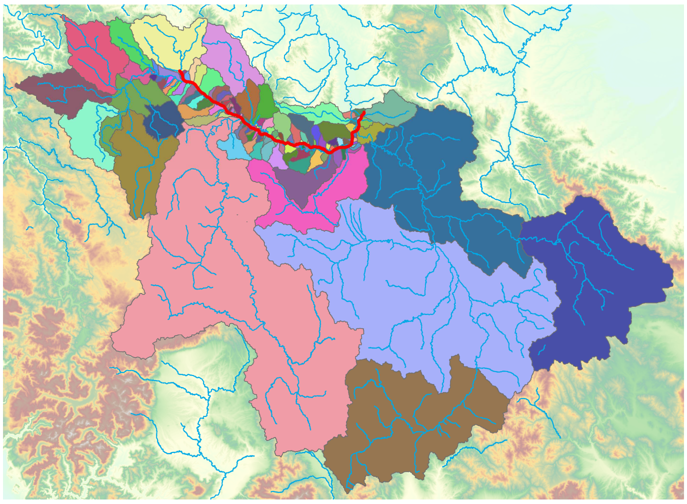


***Figure** 7. Basin delineation in the HEC-HMS model*

Synthetic hydrographs at hydrological stations were formed for design hyetographs determined at the precipitation and main meteorological stations. Design hyetographs were created for the assumed probabilities of occurrence of the design elements of rainfall: daily precipitation sum, precipitation duration and precipitation distribution within the rainfall event. Terrain and the state of the previous soil moisture are also described by the probability of occurrence, through the probability of occurrence p4 of the parameter CN. The CN parameter is determined for different soil moisture conditions. The probability of the CN parameter is simulated by a uniform distribution for each sub-basin.

In order to perform the computation of synthetic hydrographs, due to the infinite number of combinations of input elements, simplification was performed by considering: the characteristic probability of daily precipitation sums and rain duration 0.1%, 1%, 2%, 5% and 10%; the probability of precipitation distribution within the rainfall event 20%, 50% and 80%; probability of occurrence of the CN parameter: 1%, 25%, 50%, 75% and 99%.

In addition to the input hyetographs and the state of previous soil moisture, the synthetic hydrograph is also affected by the time of occurrence of the design rainfall event τ. Rain does not start to fall on the entire basin at the same time, so τ is the time difference from the moment that the rain starts to fall on the first sub-basin until the moment that it starts on the specific sub-basin. The start of the rainfall event at precipitation stations has been varied in the interval of 0-48 hours.

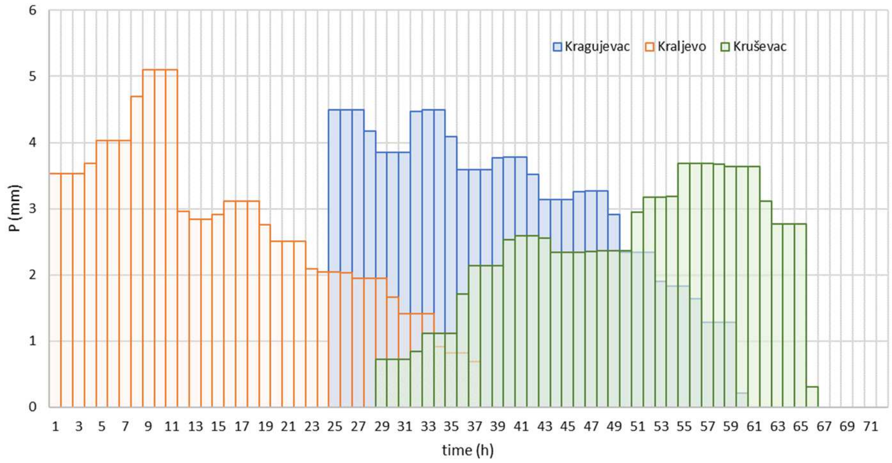


Figure 8. *Example of design hyetographs at three precipitation stations*

The probability of occurrence of a synthetic hydrograph was determined based on the comparison of synthetic and design hydrographs of predefined exceedance probabilities. It is done based on the chosen criteria of peak and wave volume matching. Due to the size of the subject area, it was taken that the flood wave duration is $\tau_n = 15$ days. Synthetic hydrographs where differences from the design hydrograph of the characteristic exceedance probability are less than the predefined difference – dQ =10% for the peak, and dV = 15% for the volume, were assigned the same exceedance probability as the design hydrograph.

Given the previously mentioned large number of sub-basins, spatial grouping of stations with the same probability of precipitation elements and spatial grouping of sub-basins with the same probability of CN (Figure 9) were performed.

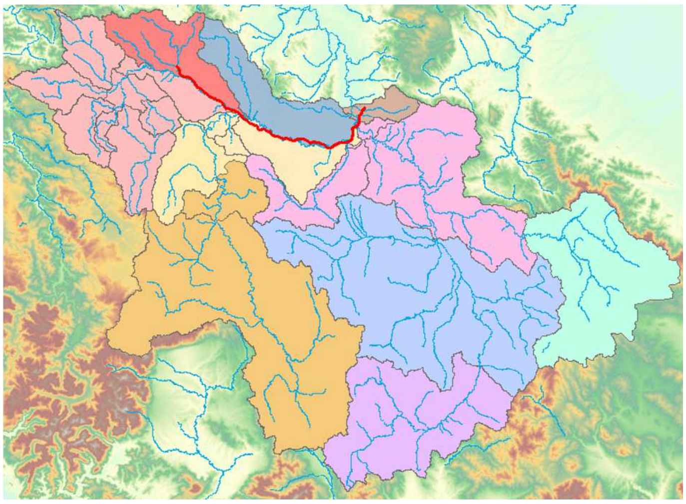


Figure 9. *Grouping of sub-basins with the same probability of occurrence of the design precipitation sum, precipitation duration and CN parameter*

In total, 10 groups of stations and 10 sub-basins were defined. Considering the choice of scenarios, assuming that the probabilities p1, p2 and p3 are independent, is made between 5 discrete values for p1, p2 and p4 and 3 values for p3, it is clear that the number of scenarios would be such that computations for all scenarios could not be performed in due time. Rainfall event time of occurrence for each of the 10 groups of stations from the set of discrete values 0-48 should be considered as well, since it is much more likely that rainfall will not occur in the entire area at the same time.

Given such a large number of combinations, it is obvious that it is not possible to perform a computation for each combination. Therefore, it was assumed that the combination of the probabilities of daily precipitation sums, as well as the probabilities of precipitation duration, depends on the distance from each other, as follows:

- For the groups of stations i, j with the distance of the centers $L \leq 50$ km, the probabilities of the occurrence of maximum annual design daily sums of precipitation p1i and p1j cannot be "away" more than 1 step. For example, if for one group of stations p1i =1%, for another group of stations at a distance $L \leq 50$ km the probabilities may be p1j =0.1%; 1% or 2%. The same applies to the probabilities p2.
- For the groups of stations with the distance of the centers 50 km<L≤100 km, the probabilities of the occurrence of maximum annual design daily sums of precipitation p1i and p1j and the probabilities of occurrence of precipitation duration p2i and p2j cannot be "away" more than 2 steps,
- For the groups of stations with the distance of the centers 100 km<L≤150 km, the probabilities of the occurrence of maximum annual design daily sums of precipitation p1i and p1j and the probabilities of occurrence of precipitation duration p2i and p2j cannot be "away" more than 3 steps,
- For the groups of stations with the distance of the centers 150 km<L≤200 km, the probabilities of the occurrence of maximum annual design daily sums of precipitation p1i and p1j and the probabilities of occurrence of precipitation duration p2i and p2j cannot be "away" more than 4 steps,
- For groups of stations with the distance of the centers L>200 km, all combinations of the probability of occurrence of maximum annual design daily sums of precipitation p1i and p1j, as well as p2i and p2j are possible.

Despite all the aforementioned simplifications, the number of combinations is still such that computations are impossible to implement. That is why the constrained Monte Carlo method [4] has been applied, which should search more efficiently for logical combinations. Logical combination is one that is more likely to happen in the nature.

Since the conditions for selecting p1 and p2 are the most restrictive, first sets of probability variations are generated for all groups of precipitation stations V_{p_1} and V_{p_2}, such as to satisfy the assumption of the possible occurrence of probabilities of daily precipitation sums and precipitation duration based on the distance. The resulting sets V_{p_1} and V_{p_2} contain all permitted variations of p1 and p2 values at all precipitation stations, that is, one member of the set contains the value of one probability at all precipitation stations for one scenario. There are no rules that introduce dependencies between the different probabilities of precipitation elements and the CN parameter, so each of the probabilities p1, p2, p3 and p4 are independent.

The generation of hydrological scenarios was implemented in two phases. First phase is that, with the Monte Carlo restricted method, a limited number of hydrological scenarios were created where all parameters are defined except τ. 300,000 scenarios had been created. In the second phase, out of the hydrological scenarios generated in the first phase, ten times more hydrological scenarios are formed by randomly varying the parameter τ for each group of stations in the interval from 0 hours to 48 hours. In this way, rainfall for one hydrological scenario is varied in time to increase the chance of finding a case where significant rainfall coincides at critical points in the river course and causes the most unfavorable scenario.

In total, 3,000,000 hydrological scenarios were generated, which needed to be evaluated by executing the same number of calculations with a hydrological model. Since the computations are performed at an hourly step, and the wave transformation is performed with a 1D hydraulic model, the time required to perform one computation is approximately 1 minute, depending on the hardware used to perform computations. It is obvious that it is not efficient to perform such a large number of computations on a single computer, so for the purpose of performing parallel computations, the WoBinGO platform was used [5]. The following figure (Figure 10) illustrates the procedure for creating a hydrological scenario of a certain exceedance probability.

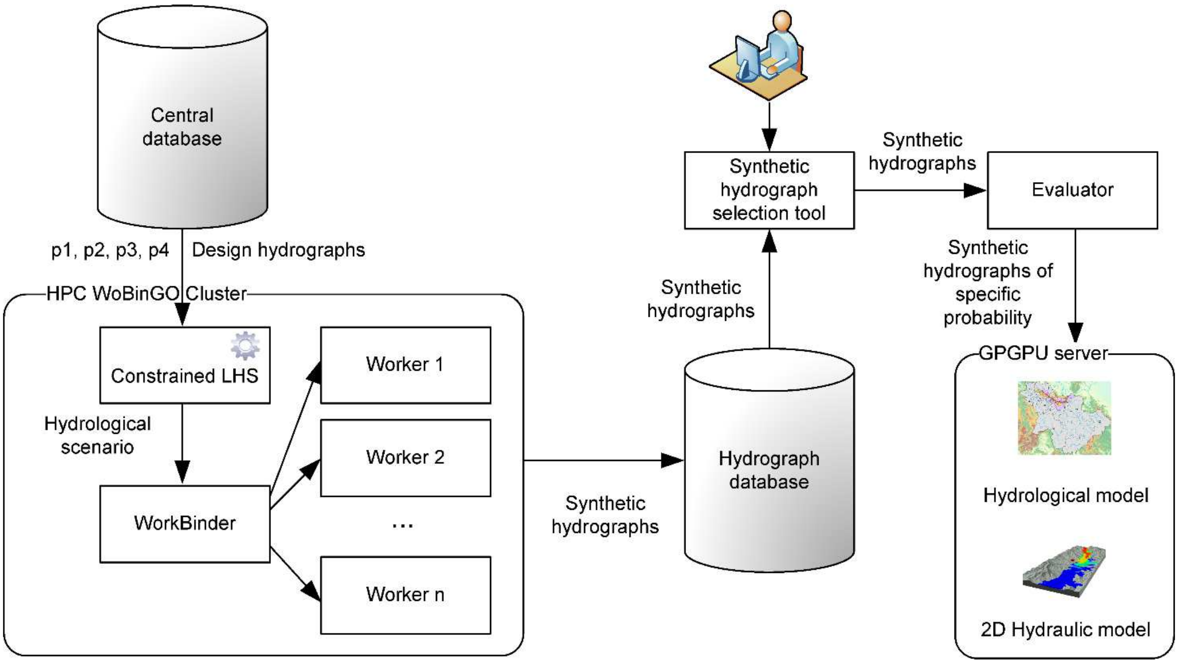
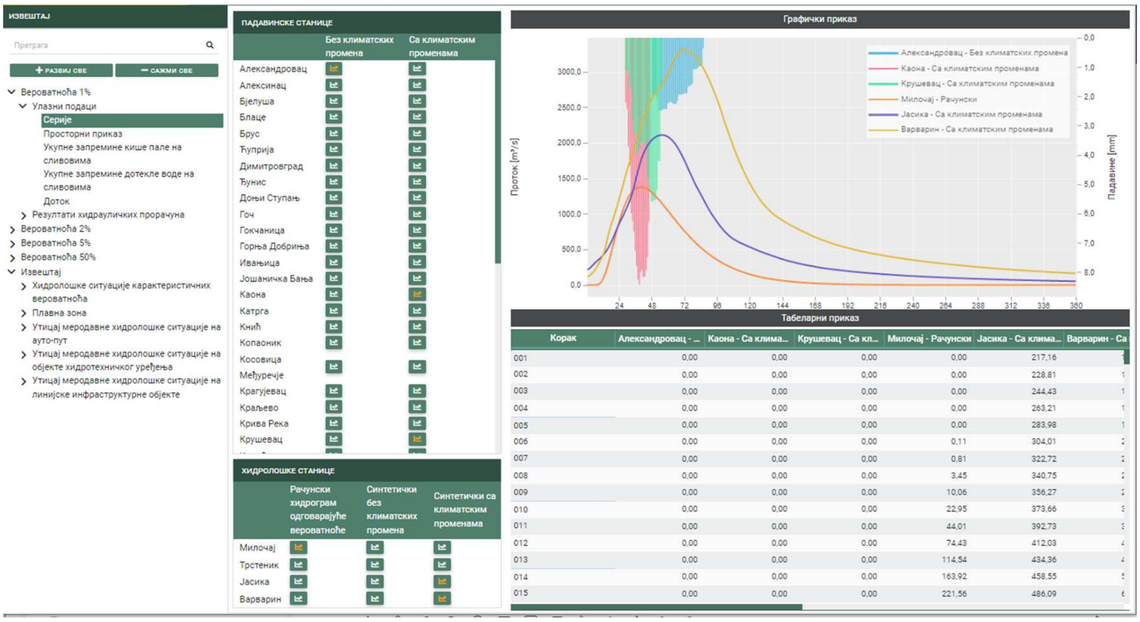


***Figure 10.** HPC platform for creation of hydrological scenario of specific probability*

A set of automated software components has been formed since the process of generating hydrological scenarios of a specific exceedance probability is planned to be repeatable. Hydrological scenarios are formed based on input data from the central database and are then computed on workers. A 300 nodes grid cluster was used to compute the initial 3,000,000 scenarios in a few days. The result of the computation is 3,000,000 synthetic hydrographs at hydrological stations, with hourly discharge values for a flood wave of 15 days. Because of this, there was a need to store a large amount of data, so a special unit called a hydrograph base was formed, which also enables the search of scenarios.

A special user tool for the selection of synthetic hydrographs was also created, and it provides the expert with the mechanisms for searching scenarios in the hydrograph database, as well as the possibility of setting parameters for the selection of hydrographs that are similar to design hydrographs. When the expert selects synthetic hydrographs corresponding to the hydrological scenario of a specific exceedance probability, the corresponding scenario is then sent to the evaluator which forms the inputs for the hydrological model, the results of which are forwarded to the 2D hydraulic model. In this way, 2D hydraulic model computations provide data for design decisions. An example of the special user tool window is presented in the Figure 11.



- Вероватноћа 1%
  - Улазни подаци
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    - Укупне запремине дотекле воде на сливовима
    - Доток
  - Резултати хидрауличких прорачуна
- Вероватноћа 2%
- Вероватноћа 5%
- Вероватноћа 50%
- Извештај
  - Хидролошке ситуације карактеристичних вероватноћа
  - Плавна зона
  - Утицај меродавне хидролошке ситуације на ауто-пут
  - Утицај меродавне хидролошке ситуације на објекте хидротехничког уређења
  - Утицај меродавне хидролошке ситуације на линијске инфраструктурне објекте

ПАДАВИНСКЕ СТАНИЦЕ

	Без климатских промена	Са климатским променама
Александровац	📈	📈
Алексинац	📈	📈
Бјелуша	📈	📈
Блаце	📈	📈
Брус	📈	📈
Ћуприја	📈	📈
Димитровград	📈	📈
Ђунис	📈	📈
Доњи Ступањ	📈	📈
Гоч	📈	📈
Гокчаница	📈	📈
Горња Добриња	📈	📈
Ивањица	📈	📈
Јошаничка Бања	📈	📈
Каона	📈	📈
Катрга	📈	📈
Кнић	📈	📈
Копаоник	📈	📈
Косовица	📈	📈
Међуречје		
Крагујевац	📈	📈
Краљево	📈	📈
Крива Река	📈	📈
Крушевац	📈	📈

ХИДРОЛОШКЕ СТАНИЦЕ

	Рачунски хидрограм одговарајуће вероватноће	Синтетички без климатских промена	Синтетички са климатским променама
Милочај	📈	📈	📈
Трстеник	📈	📈	📈
Јасика	📈	📈	📈
Варварин	📈	📈	📈

Табеларни приказ

Корак	Александровац - ...	Каона - Са клима...	Крушевац - Са кл...	Милочај - Рачунски	Јасика - Са клима...	Варварин - Са
001	0,00	0,00	0,00	0,00	217,16	
002	0,00	0,00	0,00	0,00	228,81	
003	0,00	0,00	0,00	0,00	244,43	
004	0,00	0,00	0,00	0,00	263,21	
005	0,00	0,00	0,00	0,00	283,98	
006	0,00	0,00	0,00	0,11	304,01	
007	0,00	0,00	0,00	0,81	322,72	
008	0,00	0,00	0,00	3,45	340,75	
009	0,00	0,00	0,00	10,06	356,27	
010	0,00	0,00	0,00	22,95	373,66	
011	0,00	0,00	0,00	44,01	392,73	
012	0,00	0,00	0,00	74,43	412,03	
013	0,00	0,00	0,00	114,54	434,36	
014	0,00	0,00	0,00	163,92	458,55	
015	0,00	0,00	0,00	221,56	486,09	

***Figure 11.** Example of the special user tool window*

The initial process of determining hydrological scenarios was carried out for hydrological stations Miločaj, Trstenik, Jasika and Varvarin. The selection of the hydrological scenario with the corresponding probability of exceedance is made so that synthetic hydrographs of the same probability are created at all four hydrological stations.

The following is an example of modelling the hydrological situation 1%, which implies the simultaneous occurrence of synthetic hydrographs with an exceedance probability of 1% at all 4 hydrological stations in the Zapadna and Velika Morava in the highway zone, taken from the documentation [6].

From the available set of hydrological scenarios with an acceptable divergence tolerance from the design hydrographs on all four control cross sections, 173 combinations that make up a hydrological scenario with a probability of occurrence 1% were extracted. Since these scenarios differ from one another in both the spatial and time distribution of precipitation, and therefore in the way of flood wave creation, the representativeness of a given scenario is determined in the context of the purpose, i.e., the objectives of hydraulic computations, for which a given hydrological scenario provides input hydrographs. For the purpose of designing flood protection facilities, it is desirable that the representative hydrological scenario gives minimum uniform divergence of synthetic and design hydrographs simultaneously on all four control hydrological profiles with a hydrological situation of 1% probability of occurrence. With this criterion in mind, additional analyses of all 173 scenarios were implemented, and based on the analyses results, a representative hydrological scenario was selected.

The combinations of precipitation elements probabilities and CN parameter for the selected combination are shown in the Figure 12 and Figure 13. Precipitation start time versus the first moment of rainfall event on the entire basin is shown in the Figure 14 and spatial distribution of total precipitation sums by sub-basins is shown in the Figure 15.

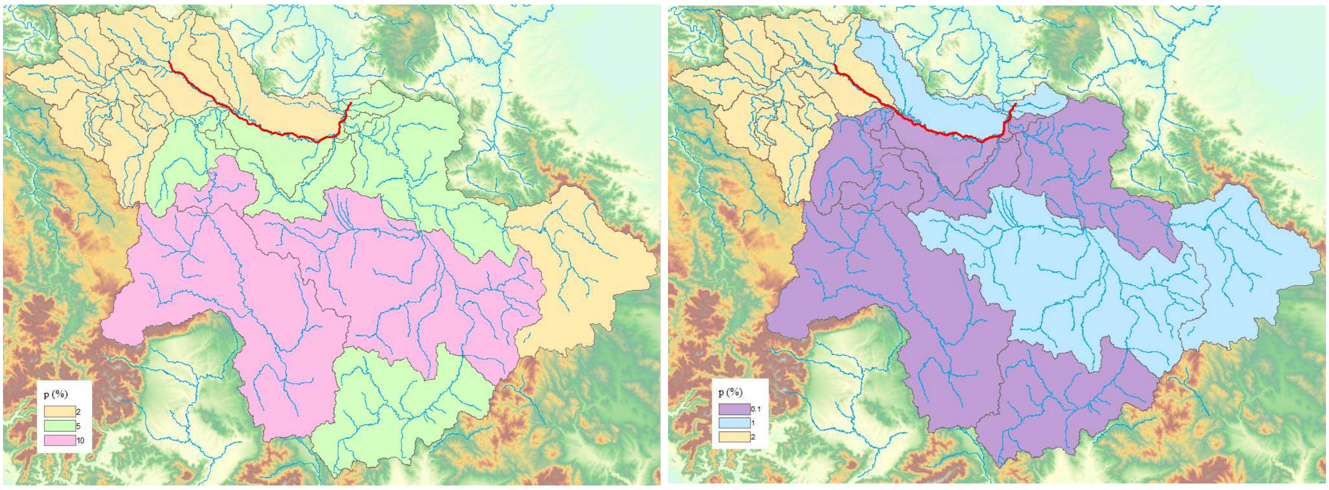

Figure 12. *Combination of the precipitation sum design probabilities (left) and the precipitation duration (right)*

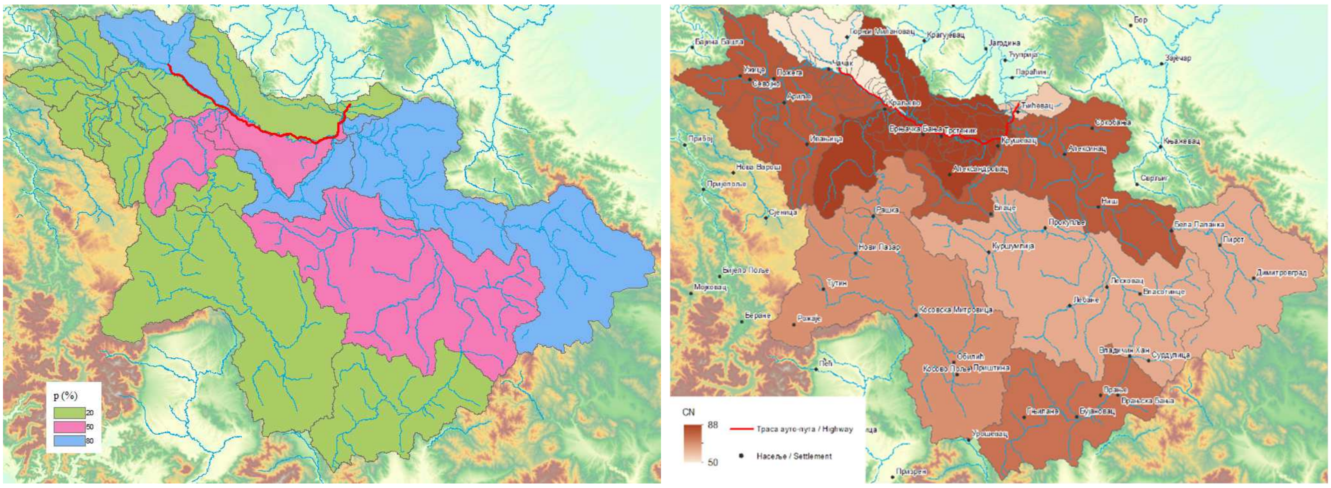

Figure 13. *Combination of rain distribution probabilities within rainfall event (left) and CN parameter (right)*

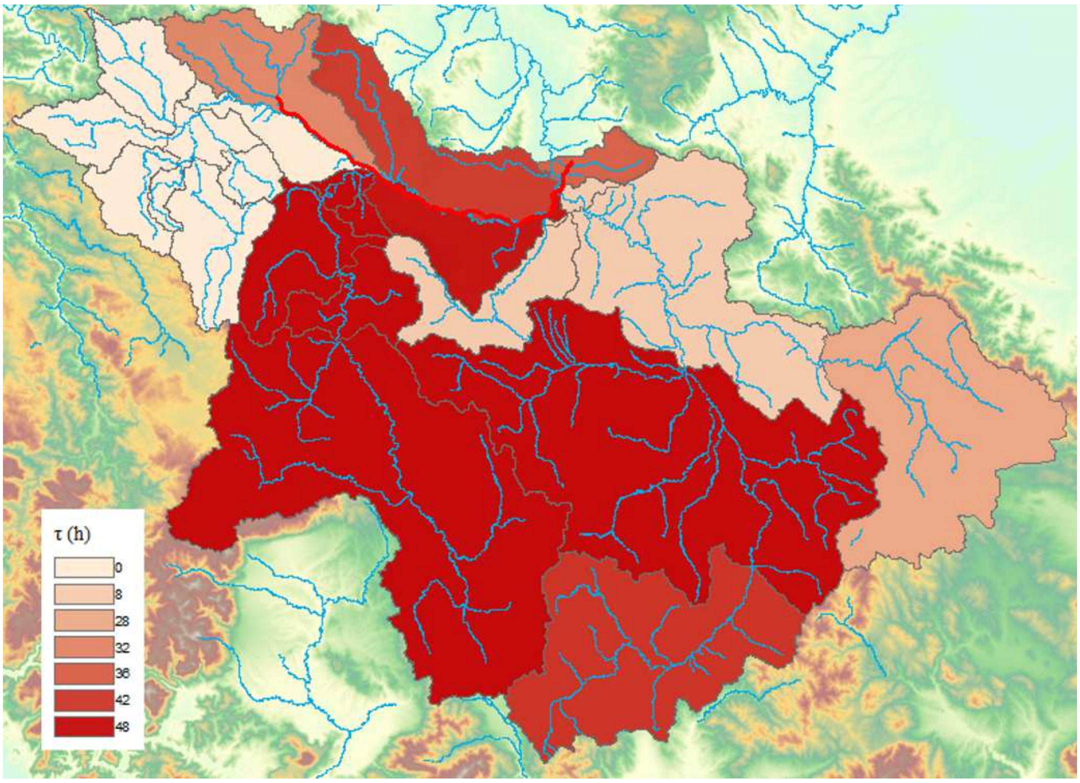

Figure 14. *Combination of rain delay against the first moment it started to rain on the basin*

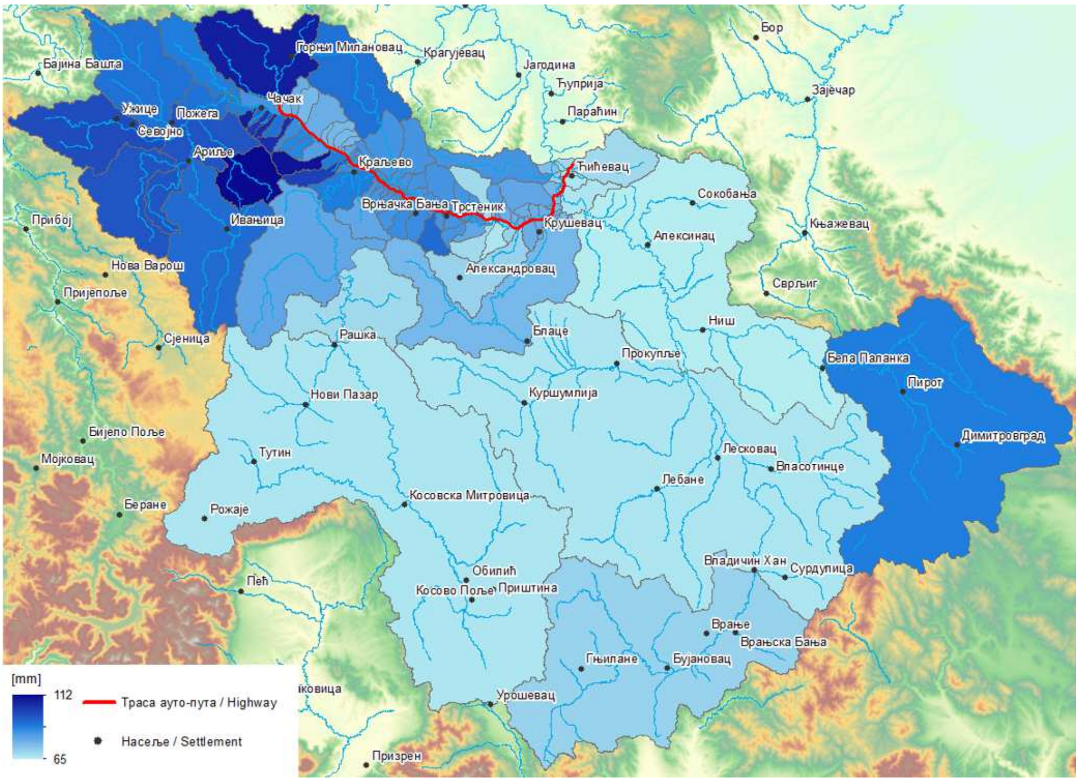

Figure 15. *Spatial distribution of total precipitation sums by sub-basins*

Synthetic and design hydrographs on all 4 hydrologic stations are shown in Figure 16 and Figure 17. Results of spatial distributions of runoff are given in the Figure 18, and hydrographs of inflow on the main input profiles into the 2D hydraulic model are shown in the Figure 19. Results of hydraulic calculations of the 2D model for two states of construction are presented – without the highway and when the highway is built. In order to see the impact of the highway construction, the differences between the level of future and existing state (Figure 20) are presented.

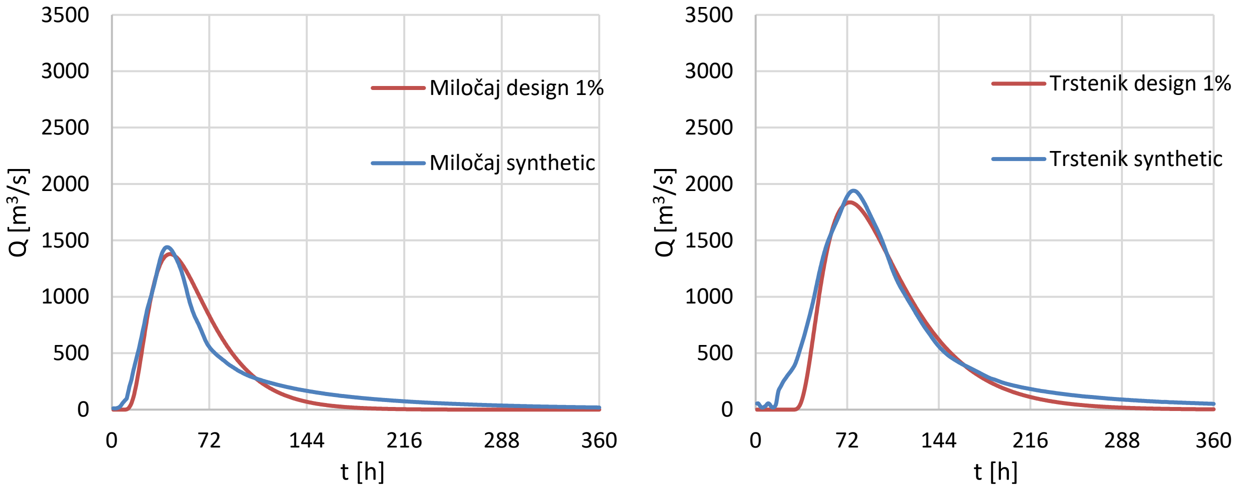

Figure 16. *Design and synthetic hydrographs of the Zapadna Morava at HS Miločaj and HS Trstenik*

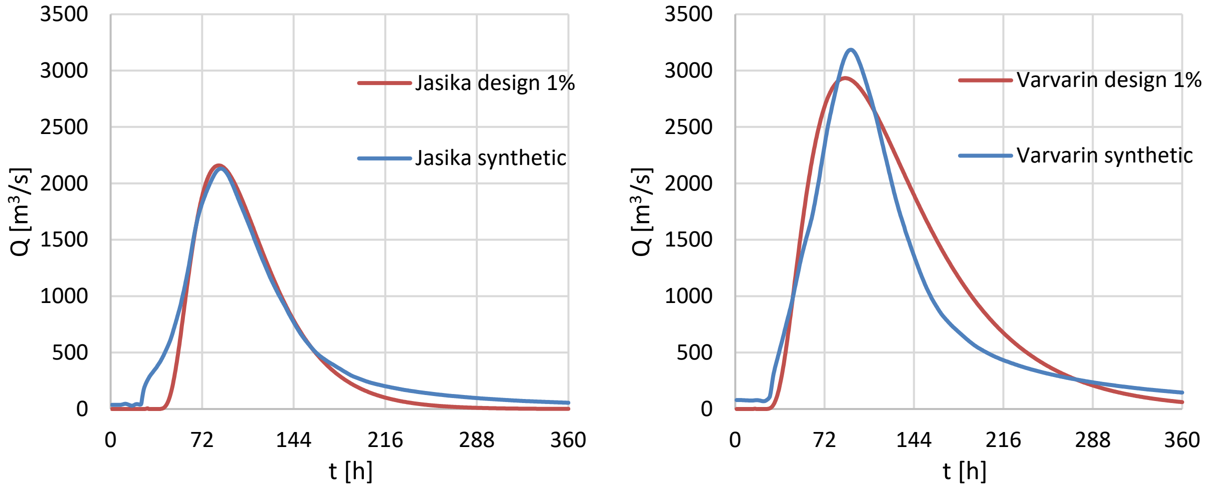

Figure 17. *Design and synthetic hydrographs of the Zapadna Morava at HS Jasika and Velika Morava at HS Varvarin*

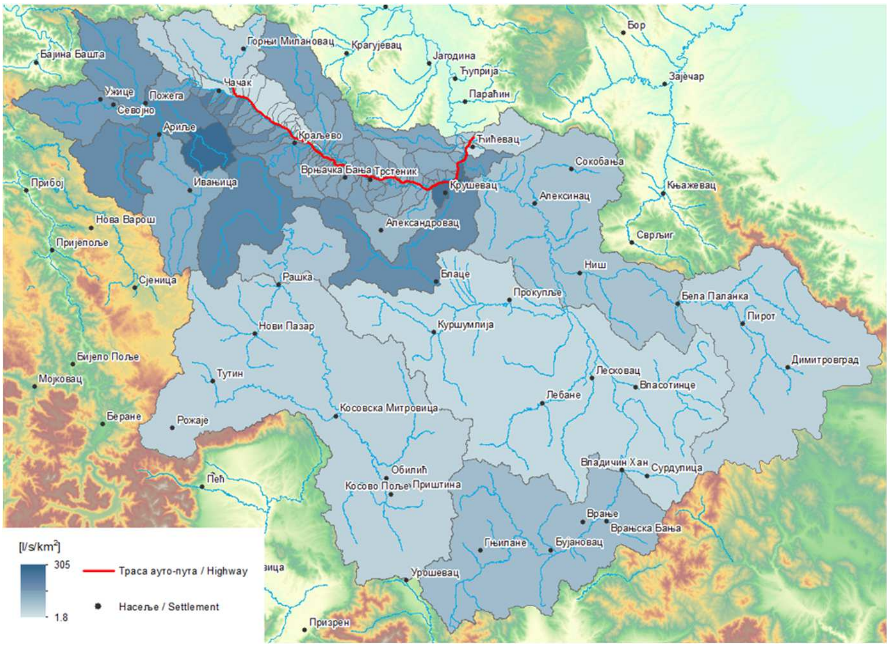

Figure 18. *Spatial distribution of runoffs by sub-basins*

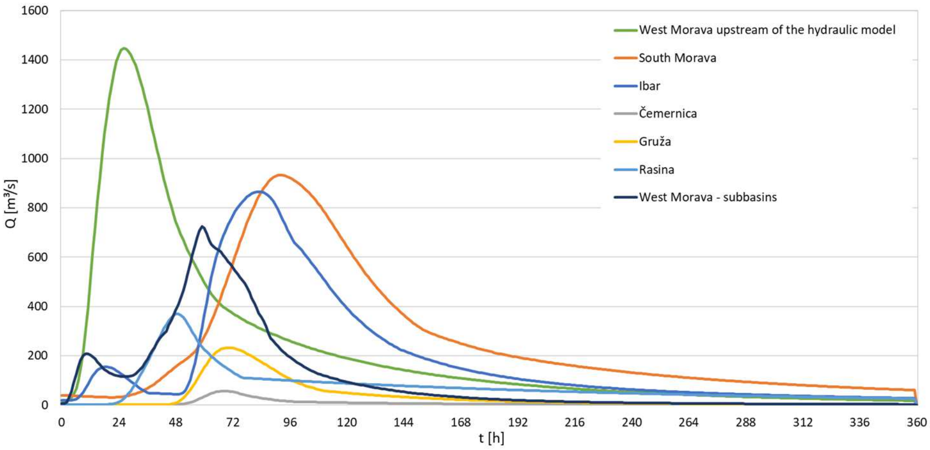

***Figure 19**. Hydrographs of inflow on the main input profiles of the hydraulic model*

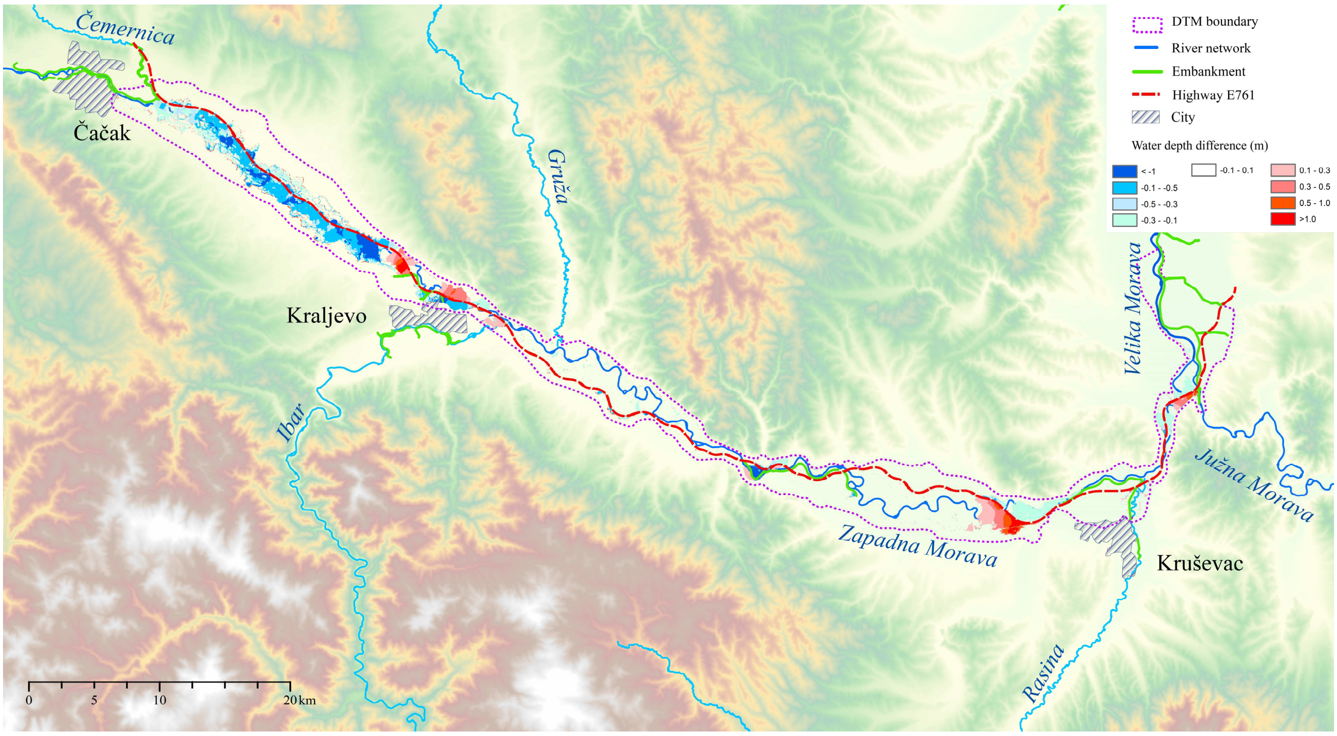

***Figure 20.** Difference between the levels of future and existing state of highway construction*

CONCLUSION

The relevant values for facilities design such as discharges, water levels, velocities, and tangential stresses, depend on climatic conditions, runoff conditions, riverbed geometry and are associated with the particular flood frequencies.

Understanding of the interaction between water regime and highway facilities is only possible using hydrological and hydraulic modelling. Hydrological and hydraulic modelling allows analysis and comparison between different scenarios (climate and present/future conditions), assessment of the protection level and selection of relevant values for flood protection design of the future highway and hydrotechnical facilities.

The presented input hydrograph computation methodology for the 2D model application, which results in hydrotechnical values relevant for the designing of hydrotechnical facilities, includes the application of the coupled hydrological model HEC-HMS and the hydraulic model 1D HEC-RAS.

The methodology consists of creating many scenarios where a large number of parameters (precipitation elements, soil moisture condition, rainfall event start time, riverbed conditions, and others) are varied on the large basin area, delineated into many sub-basins.

Determining synthetic hydrographs for all possible scenarios requires mass computations that, at this point, could not be performed with the available hardware within a reasonable timeframe. It was therefore necessary to implement certain assumptions and introduce certain simplifications to reduce the number of considered scenarios that could be implemented. A methodology was designed to achieve this and to obtain the maximum variety of scenarios, and to cover as much study area as possible. Software and user tools have been developed for the application of the above-described methodology.

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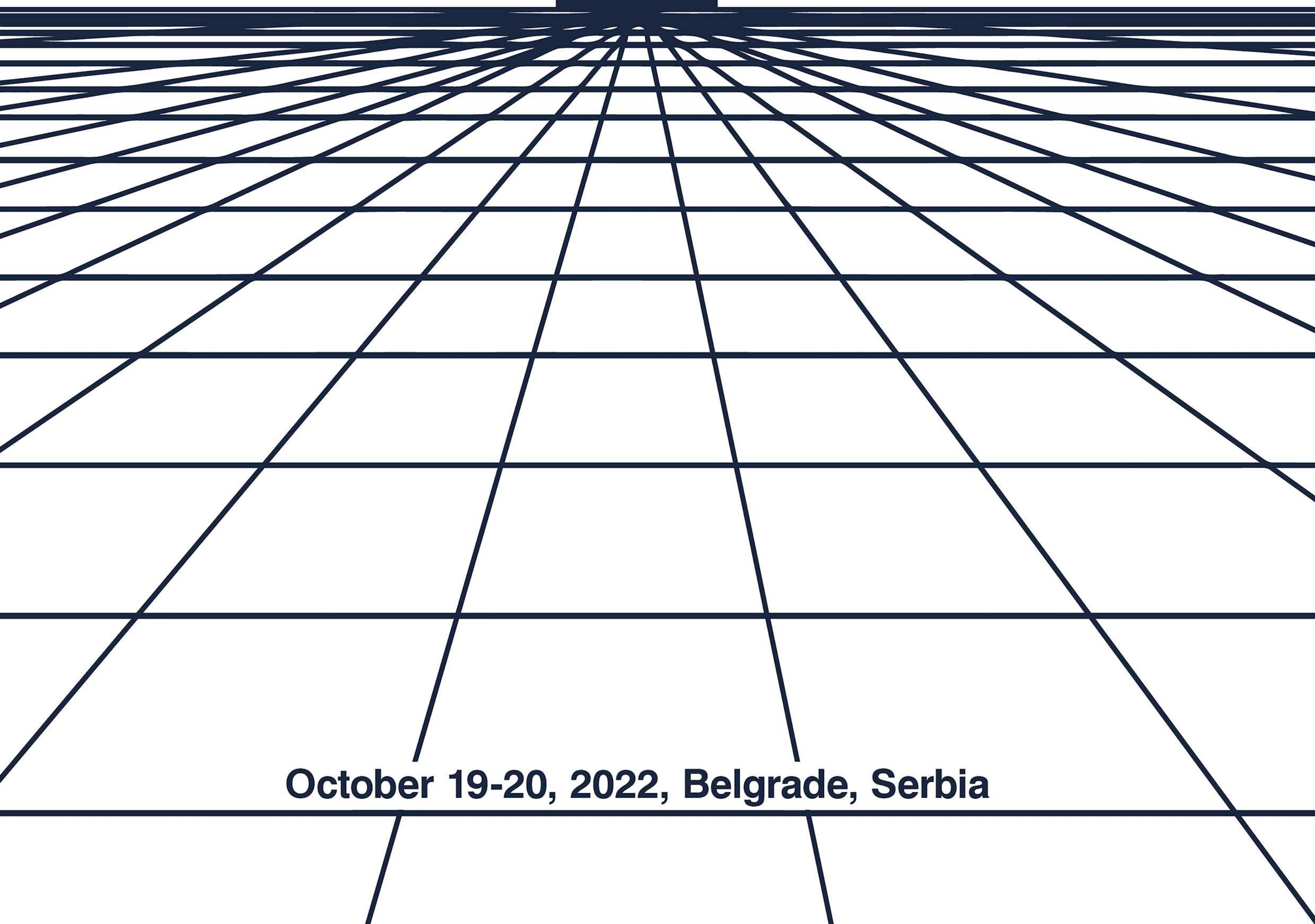
Editors

Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
in the Honour of 75 Years of the

Jaroslav Černi Water Institute



October 19-20, 2022, Belgrade, Serbia

EDITORS
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PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

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