REPORT FROM PILOT ACTION – Report from testing the dynamic model to assess cumulative effect of N(S)WRM

Croatia /Croatian Waters	Final version
Pilot catchment Bednja	December 2019

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1. APPLICATION OF THE HYDROLOGICAL MODEL

1.1 Description of the catchment

The Bednja River basin occupies 616 km² and can be divided into two topographically different parts: upland and lowland. The lowland part accounts for app. 30 % of the basin area and spreads along the Bednja course from its confluence with the Drava River up to its 55th km. The upland part spreads upstream of the village of Presečno in the length of app. 51 km of the river course and accounts for app. 70 % of the overall basin area (app. 477 km^2). In the upland part there are app. 48 torrential basins with approximately 250 km of watercourses. The hydrographic network is much more developed in the upland than in the lowland part of the basin. Based on the hydrological data recorded at the Bednja River stations, high waters occur in March and April caused by snowmelt and spring rain.

The basin area is largely un-built, with the vegetation cover made of forests (49 %), orchards and vineyards (app. 21 %), and agricultural land (30 %).

The population mostly lives in villages and deals with traditional farming on small, fragmented plots lying on hill slopes, which is highly unfavourable from the aspect of exposure of the surface soil layer to erosion.

The most important road in the basin is a section of the Zagreb-Goričan motorway which cuts the Bednja basin into two parts at a place slightly further downstream of the natural borderline between the upland and lowland parts of the basin. The major share of the motorway across was built on an embankment with several culverts which represent "obstacles" to the flow of high waters of the Bednja and its tributaries. A similar problem occurs near the Varaždin – Golubovec railway.

The most significant hydraulic structures in the basin are multi-purpose reservoirs and barriers (dams). There are flood protection dikes along both Bednja riverbanks, upstream of its discharge into the Drava. Floods sometimes occur several times a year, as the result of which the flooded area along the Bednja gradually attains swamp-like characteristics and cannot be used for agriculture. In such areas valuable wetlands have developed with endangered species on the county and even national level.

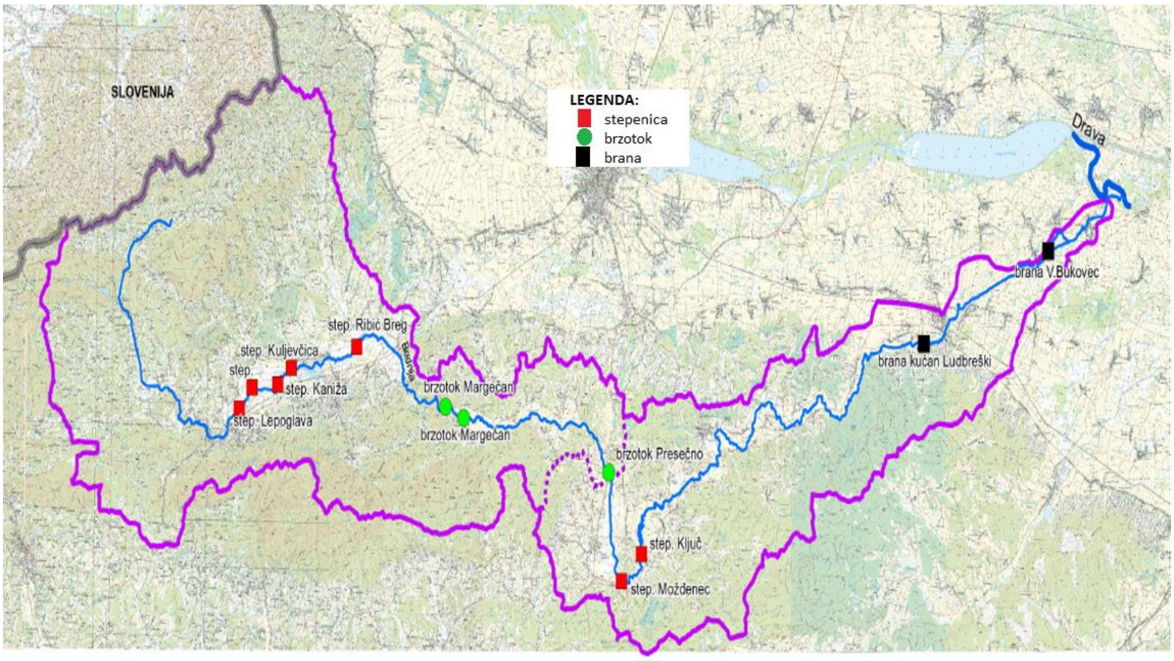


Figure 1. Bednja River basin – Bednja River with existing hydraulic structures.

According to Natura 2000, in the Bednja basin there are 14 sites important for the conservation of endangered species and a total of 12 sites with different levels of protection: 1 regional park, 3 nature monuments, 1 significant landscape, 1 park forest and 6 monuments of park architecture.

There is a serious problem of flash floods that form after intensive rainfall in a significant number of the Bednja tributaries. A sudden increase in discharges causes the movement and transport of significant sediment quantities into the lowland parts of the watercourses and the Bednja recipient. It is not rare that flash floods are accompanied by landslides that put houses and commercial buildings at risk.

In accordance with the Decision on the designation of vulnerable zones in Croatia (OG 130/12), areas sensitive to pollution with nitrates from agriculture have been established. Based on that Decision, in the Bednja River basin only its minor part belongs to nitrate-vulnerable zones.

Characteristic	**Unit**	**Value**
Character of catchment		lowland 30%/low hills 70%
Catchment size:	km^2	616
Average flow low/avg/high*	m^3/s	0.8/7/77
Extreme flow low/high*	m^3/s	0.003/179
Annual precipitation low/avg/high**	mm	481/931/1312
Annual air temperature min/avg/max**	°C	10.4 (avg)
Agriculture area	%	30
Urban area	%	2
Forest area	%	49
Open Water area	%	0.1
Flooded area (1/100 years)	km^2	37.7
Artificial drainage area	km^2	
Ecological status no good/bad	water body	6 water bodies / 2(bad), 3 (moderate), 1 (good)
Major problems to achieve good ecological status		Phytobenthos, Macrophytes, Macrozoobenthos, Total N and Total P

Table 1. Characteristics of th Bednja pilot catchment. Note: * From multiannual statistic 1949-2016; ** From multiannual statistic 2007-2016.

1.2 Watershed delineation

The watershed delineation was done based on digital elevation model (DEM) with a resolution of 25 meter resolution inside settlements and 100 meter resolution outside of settlements, on topographic maps scale 1:25000 scale and a hydrographic network using GIS analysis (fig. 2).

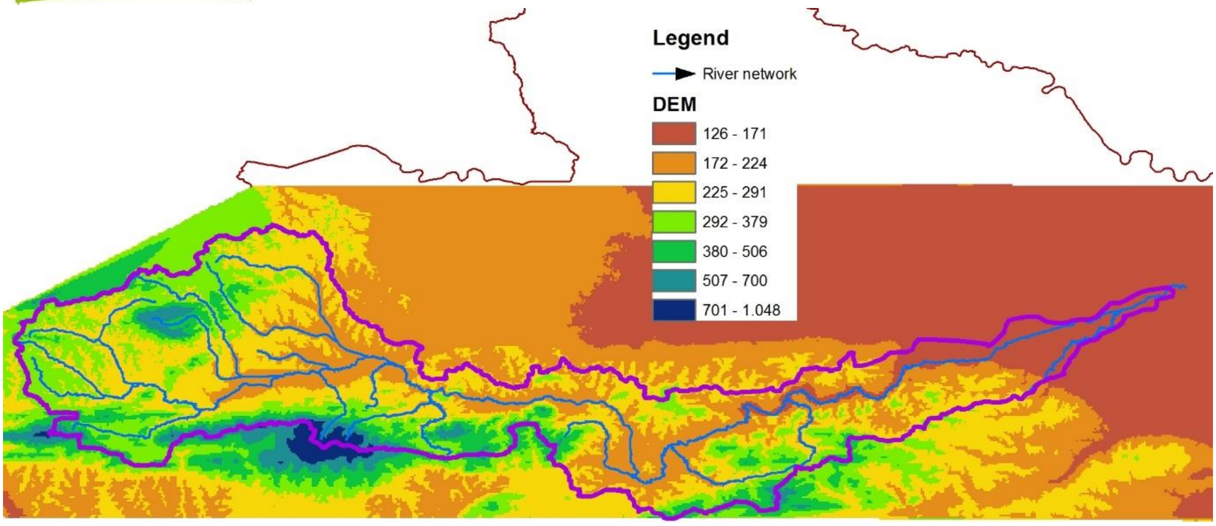


Figure 2. DEM and river network.

Based on watershed delineation a conceptual hydrological model using the HEC-HMS software. Hydrological model was made in 2 parts, upper (part I, II and III) and lower part (IV and V) (fig. 3).

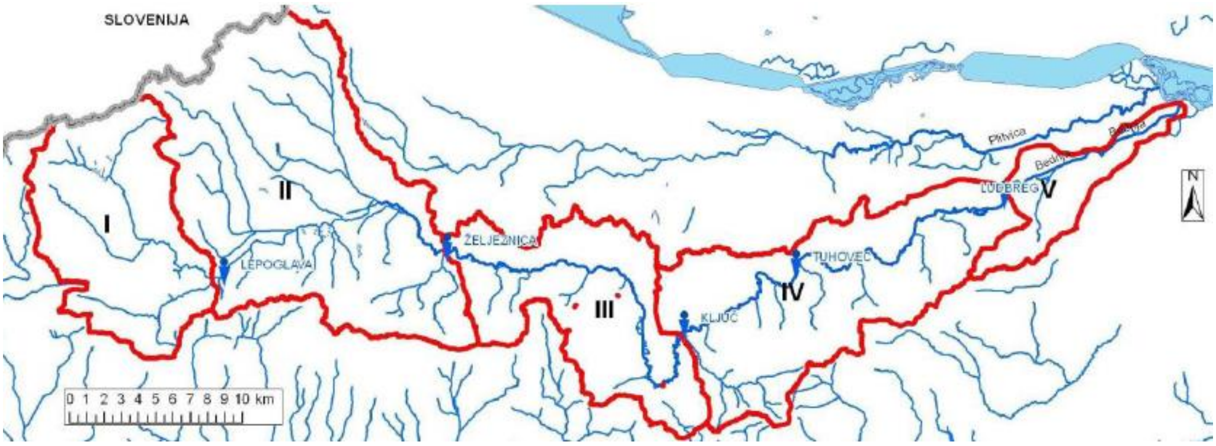


Figure 3. Bednja basin with delineated borders of sub-basins up to individual hydrological stations.

1.3 Land cover, soils and HRUs delineation

The Corine Land Cover (CLC) 2012 layer was used as the primary data source for the land cover map.

The CLC Croatia represents a digital database with data about the status and changes in land cover and land use in Croatia. The CLC Croatia is consistent and homogenized with with the land cover data of the entire European Union.

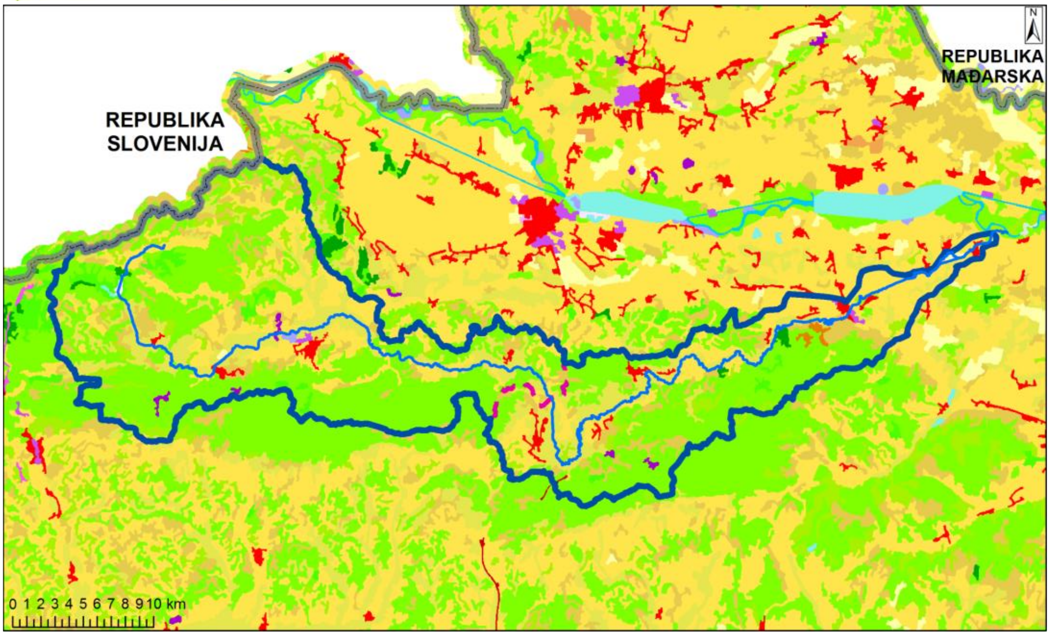


Figure 4. Extract from the CORINE Land Cover Croatia map with delineated Bednja basin.

The characteristics of soil in the upland part of the Bednja basin are defined by the Croatian Soil Map in a scale of 1:300,000. The soil map presents soil units. In the Bednja basin, several soil units with different characteristics are mapped. Based on the characteristics of soil units, hydrological types of soil have been obtained which are used further on in hydrological analyses. One hydrological soil type includes several soil units with similar hydrological characteristics. Hydrological soil types are the result of analysis of soil maps and available data.

There are four basic hydrological types of soil: A, B, C, and D. Type A soils are characterized by a high infiltration rate and a low run-off potential. Soils of hydrological type B are characterized by a medium infiltration rate, while type C soils have a low infiltration rate. Type D soils have a very low infiltration rate and a high run-off potential.

In the Bednja basin, soil units are reduced to the basic hydrological types of soil:

B - Humic ranker silicate on sandstone, conglomerate and shale
- Ranker on eruptive rocks (quartzite)
- Eutric grey soil on deposits
- Acid (distric) brown soil on loess
C - Eutric brown soil on sand
- Gitja
- Alluvial meadow, gley
D - Rendzina on flysch
- Resin on marl
- Loessivized soil typical on clays

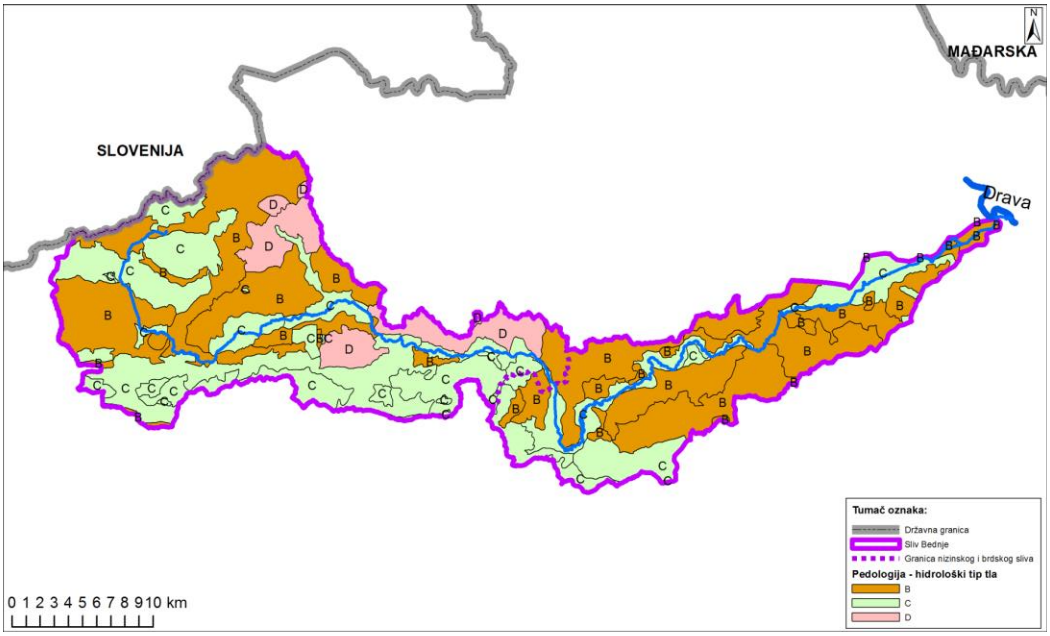


Figure 5. Soil map according to hydrological type in the Bednja basin.

Land use and cover - the main categories and land use information were taken over from the County Plans.

The CLC database was created according to the CORINE Program (Co-ordination of Information on the Environment) approved by the EU and was rated on the EU level as the basic referent set of data for spatial and territorial analyses.

The Bednja basin is divided into 101 sub-basins in total (HRU), with the required characteristics defined for each sub-basin.

1.4 Weather data

Weather (meteorological) data was obtained from the Croatian Meteorological and Hydrological Service (DHMZ).

The Bednja basin was divided according to the reference meteorological (weather) stations (MS) using the Thiessen method.

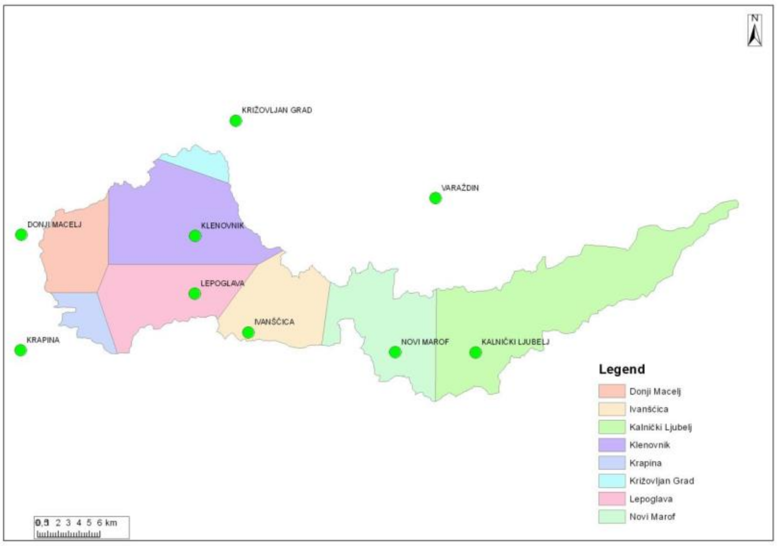


Figure 6: Division of the basin using the Thiessen method.

Even though the nearest meteorological stations Varaždin and Krapina are equipped with automatic rain gauges and have at their disposal data about short-lasting rainfall, they both lie beyond the Bednja orographic basin. For that reason, the Klenovnik meteorological station was selected as reference station for the upland part of the Bednja basin, whereas the Novi Marof meteorological station was selected as reference station for the lowland part of the Bednja basin.

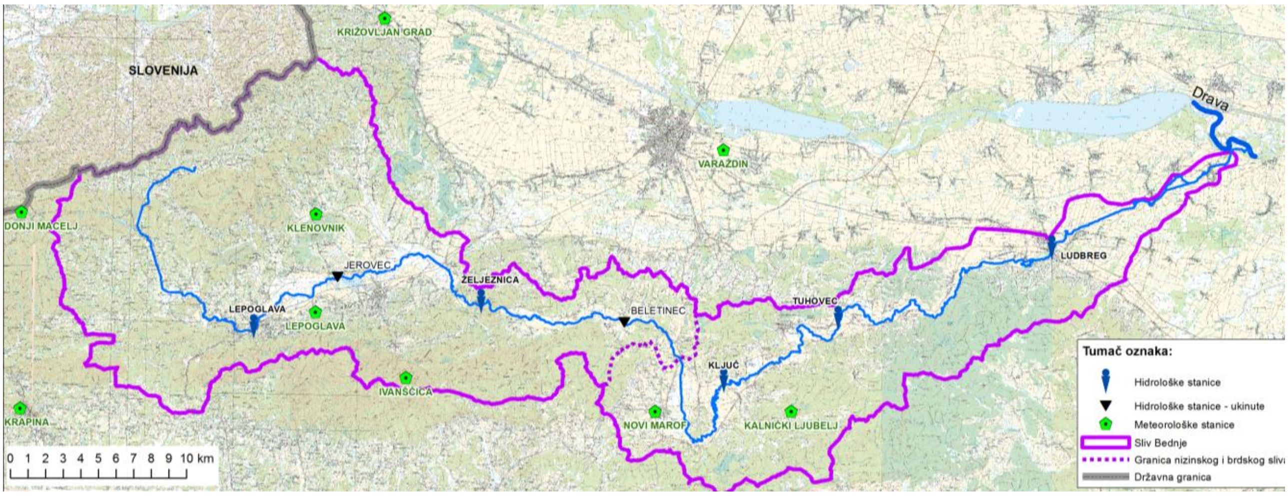


Figure 7. Meteorological stations used for modelling and flow gauges used for calibration/validation.

In the analyses, annual maximum daily rainfall quantities were estimated using the general distribution of extreme values according to Jenkinson for return periods of 5, 10, 20, 50, 100 and 1000 years for MS Klenovnik and MS Novi Marof.

Based on the daily rainfall data for MS Klenovnik for the 1983-2013 period, rainfall events of different duration were analysed. The selected rainfall analysis period includes the last 30 years, which is a sufficiently long series for statistical analyses. Moreover, that period includes both dry and wet decades. Based on the earlier analyses of the duration of water waves at HS

Lepoglava, rainy episodes with intensive rainfall with continuous 4-day duration were extracted from days-long rainy events corresponding with the recorded water waves, forming series that were statistically analysed, obtaining as the result depth-duration-frequency curves.

1.5 Model calibration and validation

1.5.1 Description of the hydrological model

The selection of data for the hydrological model calibration is based on the historical data about floods. Major floods in the Bednja basin used to happen mostly in early spring and in the autumn months. According to the data about recorded floods, in the majority of cases the Bednja would leave its channel and spread onto the surrounding ground, mostly in the low-lying ground in the vicinity of the mouths of larger tributaries. The cause of the recorded floods was the rainfall lasting several days, with average rainfall of between 70 and 140 mm (recorded at MS Klenovnik).

1.5.2 Hydrological analyses of discharges recorded at hydrological stations in the Bednja basin

There are five active hydrological stations (HS) in the Bednja river basin, i.e. on the Bednja River itself. Analysed hydrological stations: Lepoglava, Željeznica, Ključ, Tuhovec and Ludbreg.

The discharge series were defined for a particular hydrological station based on stages which are a directly measured hydrological value and on discharge curves which are defined based on discharge measurement. The discharges calculated in this way, as well as the measured stages, and the defined stage-discharge curves are found in the Hydrological Database (HIS-2000) of the Croatian Meteorological and Hydrological Service (DHMZ).

The maximum annual discharges of different Bednja river return periods were analysed applying standard theory distribution functions for the five HSs: Lepoglava, Željeznica, Ključ, Tuhovec, and Ludbreg.

Analysing the hydrographs (average daily discharge data) of the recorded water waves, it was identified that the water waves on the Bednja River last on the average 4 days (HS Lepoglava) and 5 days (HS Željeznica, HS Ključ, HS Tuhovec, HS Ludbreg). Therefore, the maximum annual water wave volumes (constant duration of 4 and 5 days) were analysed. Based on the duration of water waves, the time during which a water wave rises at HS Lepoglava is 24 hours, whereas at the other hydrological stations it takes it around 30 hours.

A complete synthetic hydrograph of direct discharge is constructed using the Goodrich formula, for which the basic elements are the maximum (peak) discharge Qmax, rising time tp, and hydrograph time base tB.

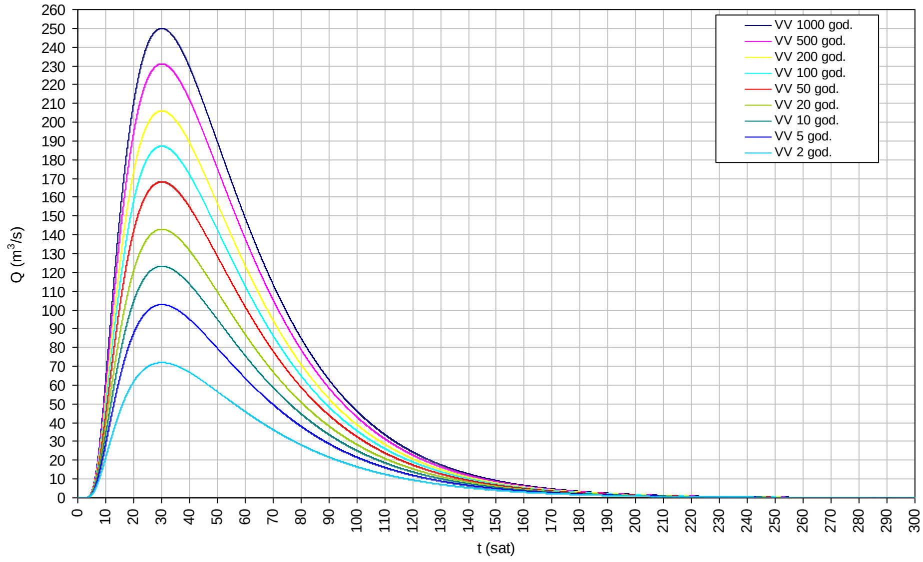


Figure 8. High water waves of different return periods of Bednja river at Ludbreg profile.

On the section of the Bednja course upstream of HS Lepoglava, as well as on the Bednja tributaries, there is no systematic gauging and observations of hydrological values. For that reason, for the purpose of determining the shares of individual sub-basins in the hydrograph of the Bednja high waters, a detailed hydrological model had to be developed that uses rainfall as an input value and the hydrograph defined at the hydrological station as an output value.

1.5.3. Hydrological model rainfall-runoff for all ungauged sub-basins in the Bednja using the HEC – HMS model

The selection of the reference meteorological station at which rainfall is gauged is important for the hydrological model.

Even though the meteorological stations Varaždin and Krapina are equipped with automatic rain gauges and have at their disposal data about short-lasting rainfall, they both lie beyond the Bednja orographic basin. For the upland part of the Bednja basin, the Klenovnik meteorological station was selected as reference station due to its position, elevation and availability of data. The Novi Marof meteorological station was selected for the lowland part of the Bednja basin. The selected stations dispose of daily rainfall data.

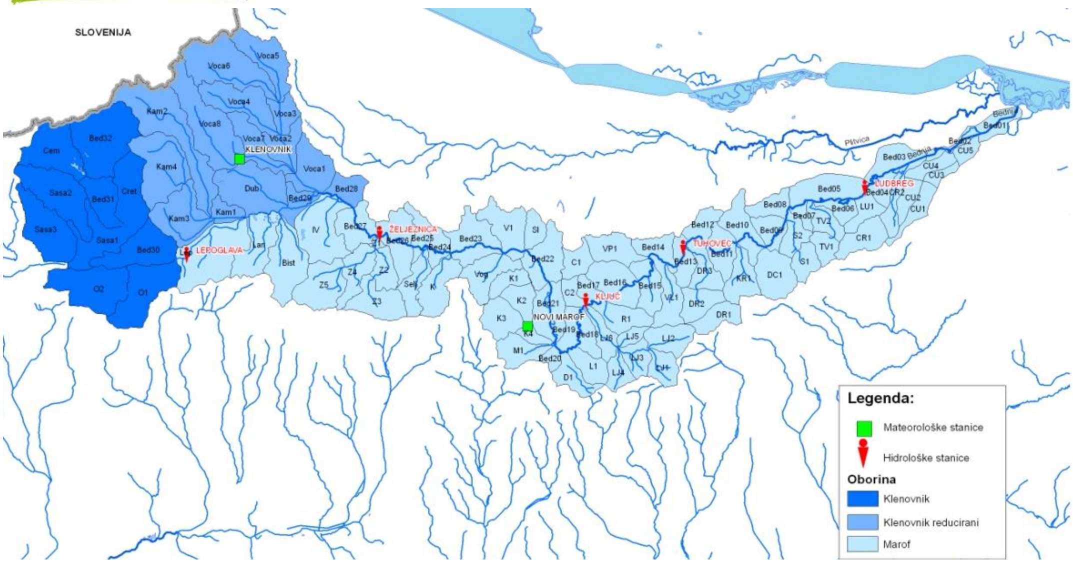


Figure 9. Selected reference rainfall in the basin.

For the purpose of assessing the hydrological contribution of the ungauged basins of the Bednja tributaries under high water conditions, a conceptual hydrological runoff model was developed using the HEC-HMS 4.0 software (Hydrologic Engineering Center - Hydrologic Modeling System).

The hydrological model of the Bednja basin was developed in two parts: the model of the upstream part of the basin covers the basin to the control profile of HS Ključ, while the model of the downstream part of the basin covers the basin downstream of the control profile of HS Ključ to the river's confluence with the Drava.

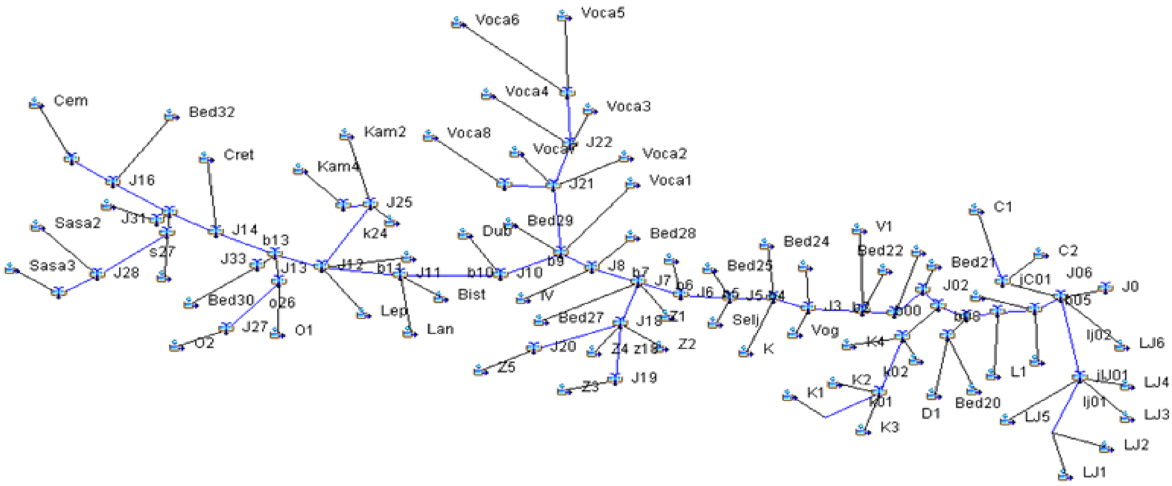


Figure 10. Scheme of the upstream hydrological model up to HS Ključ.

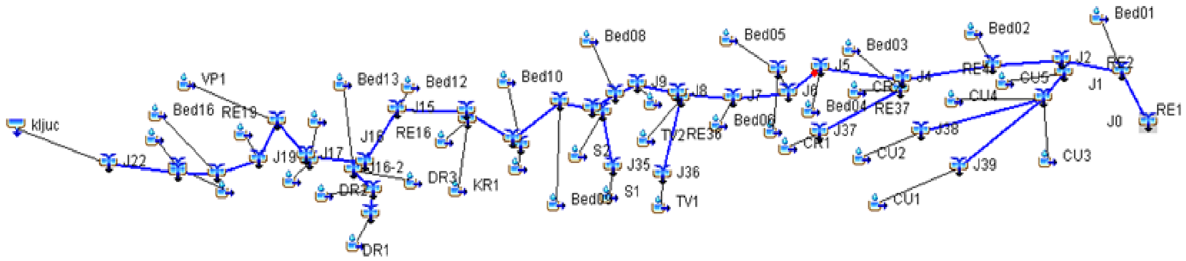


Figure 11. Scheme of the downstream hydrological model from HS Ključ to confluence with the Drava.

The Bednja basin is divided into 101 sub-basins in total, with the required characteristics defined for each sub-basin.

The following characteristics of the sub-basins are entered into the hydrological model:

- Surface area (km^2),
- Basin length (m),
- Average basin slope (m/m),
- The adopted curve number (CN) for the soil type in the basin,
- Time of concentration (min),
- Basin lag time (min).

The water wave used for calibration was recorded in the period 5 – 9 December 2005 and was caused by the rain fallen on 5 – 6 December 2005 (in total 29.8 mm). Earlier wet condition had been caused by the rain fallen in the period between 26 November and 1 December 2005 (in total 70.4 mm). The water wave belongs to a return period of 2 – 5 years in terms of peak discharge, and to a 2-year return period in terms of volume.

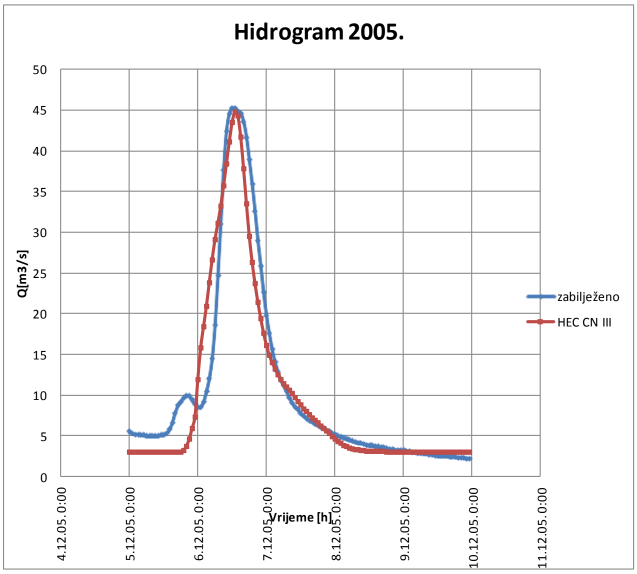


Figure 12. Calibration – Comparison of recorded and simulated water wave from the year 2005 at HS Lepoglava.

Model validation was done for the water wave recorded in the period 10 – 13 March 2006. It had been caused by the rain fallen in the period 10 – 13 March 2006 (in total 37.7 mm). Earlier wet condition had been caused by the rain fallen on 5 March 2006 (in total 25.4 mm).

The water wave belongs to a 5-year return period in terms of peak discharge, and to a return period of 2 – 5 years in terms of volume.

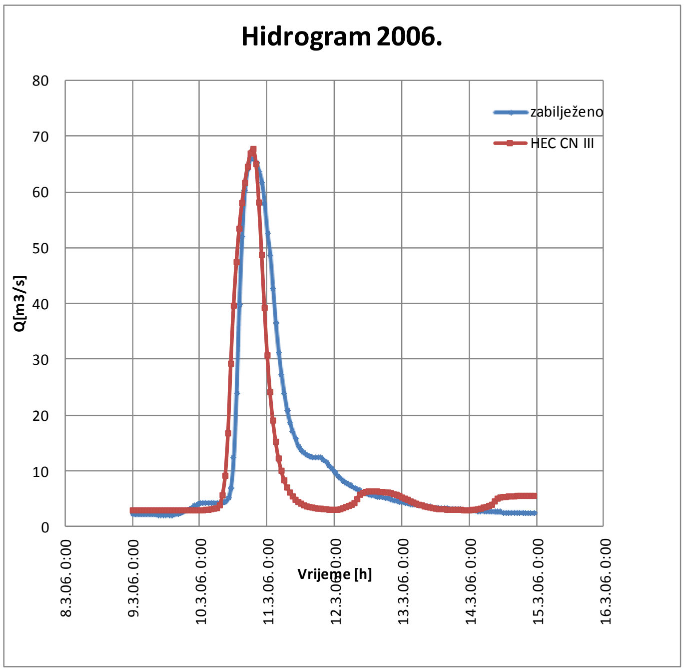


Figure 13. Validation – Comparison of recorded and simulated water wave from the year 2006 at HS Lepoglava.

Simulations were made on the hydrological model for the topological scheme of the Bednja basin developed earlier using as input data a hyetograph of a rain event, and as control data (for comparison) the hydrographs recorded at the locations of HS Lepoglava, HS Željeznica, HS Ključ and HS Ludbreg. HS Tuhovec was excluded from the model due to certain inconsistencies in its data compared to the data from the other hydrological stations.

Model calibration and validation was done on the recorded water waves which in terms of their characteristics (peak discharge and volume) belong to 2- and 5-year return periods.

Based on the reference rainfall or hyetographs of different return periods, the model was used to calculate hydrographs at the locations of hydrological stations. These were compared to the synthetic hydrographs of the same return periods obtained from statistical analyses of the meausured data. The comparisons indicate a good match.

The hydrological model was calibrated and validated based on the water waves measured at the hydrological stations. The synthetic water waves obtained from the statistical analysis of the gauged data from the hydrological stations were compared with the theoretical waves obtained from the hydrological model for the correponding return periods.

1.5.4 Simulated hydrographs of water waves of different return periods at HS

Based on the earlier defined reference rainfall or hyetographs of different return periods, the model was used to calculate hydrographs at the locations of hydrological stations. These were compared to the synthetic hydrographs of the corresponding return periods calculated and construed based on the performed statistical analyses of the meausured data. Synthetic hydrographs obtained based on the statistical analyses of the measured data (from HS Lepoglava, Zeljeznica, Kljuc) are compared to the hydrographs obtained from rainfall-based hydrological modelling.

	Q_{STAT}[m^3/s]	Q_{HEC} [m^3/s]
PP 2	34.40	41.10
PP 5	56.50	67.70
PP 10	71.20	76.70
PP 20	85.20	86.90
PP 25	89.70	93.80
PP 50	103.40	103.80
PP 100	117.00	115.70

	V_{STAT} [m^3]*10	V_{HEC} [m^3]*10^6
PP 2	4.57	6.65
PP 5	7.86	8.34
PP 10	10.05	9.68
PP 20	12.12	10.98
PP 25	12.74	11.40
PP 50	14.65	12.70
PP 100	16.48	14.01

Table 2. Comparison of hydrograph elements according to statistical analyses and according to the HEC HMS model for the simulated return periods at HS Lepoglava.

	Q_{STAT}[m^3/s]	Q_{HEC} [m^3/s]
PP 2	51.50	45.70
PP 5	72.60	73.40
PP 10	86.60	84.20
PP 20	100.10	96.70
PP 25	104.30	104.90
PP 50	117.40	118.60
PP 100	130.40	133.50

	V_{STAT} [m^3]*10^6	V_{HEC} [m^3]*10^6
PP 2	10.22	12.26
PP 5	14.56	14.96
PP 10	17.53	17.77
PP 20	20.46	20.56
PP 25	21.37	21.81
PP 50	24.26	24.50
PP 100	27.09	27.60

Table 3. Comparison of hydrograph elements according to statistical analyses and according to the HEC HMS model for the simulated return periods at HS Zeljeznica.

	Q_{STAT}[m^3/s]	Q_{HEC} [m^3/s]
PP 2	60.30	53.10
PP 5	82.40	81.00
PP 10	97.10	93.50
PP 20	111.20	108.70
PP 25	115.60	117.90
PP 50	129.40	137.30
PP 100	143.00	153.70

	V_{STAT} [m^3]*10	V_{HEC} [m^3]*10^6
PP 2	14.13	14.99
PP 5	19.24	18.65
PP 10	22.60	22.20
PP 20	25.80	25.82
PP 25	26.84	27.54
PP 50	30.02	31.21
PP 100	33.12	35.05

Table 4. Comparison of hydrograph elements according to statistical analyses and according to the HEC HMS model for the simulated return periods at HS Kljuc.

2. APPLICATION OF THE HYDRAULIC MODEL

A 2-d numerical model MIKE 21 (DHI) that uses available spatial data and synthetic water waves from each sub-basin which are the result of the hydrological model was selected for the hydraulic analysis and modelling of flows in the Bednja basin. The hydraulic model was also calibrated and validated based on the recorded water waves and recorded flood events.

2.1. Description of the river network

The hydraulic model covers nearly the entire Bednja riverbed, starting upstream of Trakošćan Lake all the way to the river's entry into the Drava. In the downstream section the model also includes part of the Drava riverbed and part of the Plitvica channel. As for the Bednja tributaries, several of them were identified that have considerable catchment areas and that contribute significant quantities of water into the Bednja at heavy rainfall events.

As for the Bednja tributaries, several have been identified that have significant catchment areas and that bring significant quantities of water into the Bednja during heavy rainfall. Such tributaries are for example the Kamenica, Voća and Željeznica streams. These tributaries, with several others that might be called significant, lie in the upper, upland part of the basin. In the lowland part of the basin, spreading from the Bednja-Drava confluence upstream to its km 55 near the settlement of Presečno, there aren't as many significant tributaries as there are in the upland part of the basin. The reason for that is a relatively narrow lowland part of the basin that spreads dominantly along the Bednja river channel, because of which there is no space for significant tributaries to form on such a short vertical distance from the basin boundaries to the Bednja channel. Nevertheless, within the lowland part of the basin, the streams Koruščak and Ljuba can be identified as relatively significant tributaries.

An analysis of sub-basin areas carried out in the development of the hydrological model can serve as a safe indicator of the relevance of a specific tributary, figure 14.

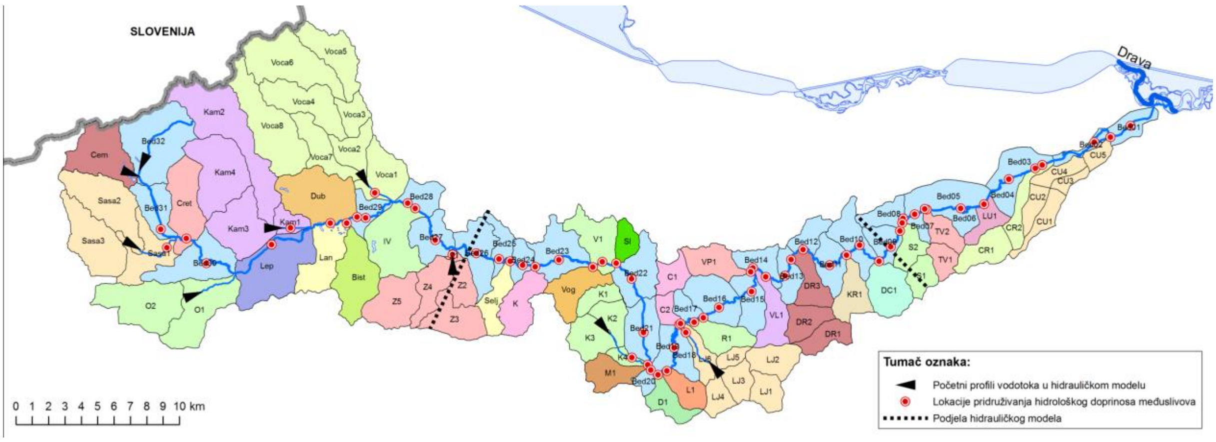


Figure 14. Hydrological and hydraulic scheme of the model.

In order to obtain a more realistic picture of flows at the places where the tributaries join the Bednja, the tributaries that have a considerable basin area composed of a number of bigger sub-basins and that contribute bigger water quantities are modelled together with their channels. The contributions of other sub-basins were introduced into the Bednja water balance in such a way that they were directly added to the Bednja channel as sources that appear in the continuity equation.

The most downstream part of the modelled area is mostly a lowland part of the basin. In that part, modelling is foreseen of the old Drava channel and of the Plitvica river which in that lowland section flows parallel with the Bednja River at a distance of 3-4 km; as such, the Bednja floodwaters flowing into the Plitvice basin and vice versa is definitely possible, particularly with waters of a higher return period. As for the first and second upstream part of the Bednja basin, the Bednja and the Plitvica waters are fully divided by terrain, with no possibility for the impacts of those two basins to mix.

2.2. Geometric data (DEM, cross-sections, boundary conditions)

In order to optimize the calculation time, the terrain of the wider catchment area was analysed to define the profiles suitable for dividing the area into a number of smaller model units. A digital terrain model (DTM) of the wider Bednja catchment area was developed defining the profiles suitable for dividing the modelled area into smaller units.

A DEM with a 30x30 m spatial resolution was used in densely populated areas and a 100x100 m spatial resolution in sparsely populated or unpopulated areas. Among the data on watercourses, 74 gauged cross-sections of the Bednja channel at a distance of app. 1 km, from the entry into the Drava to Ivanec, were available. The remaining section of the Bednja channel, from 74th km to the source (app. 106th km), is not covered by the surveyed cross-sections. The cross-sections of the Bednja channel were surveyed in the late 1990s and early 2000s.

Figure 15. Position of the Bednja cross-sections and of the mouths of significant Bednja tributaries.

The marked profiles were selected because they divide the entire modelled area into three approximately identically demanding parts, and have good positions in hydraulic terms. In the selected profiles the Bednja has a canyon-like course and all water from any calculated return period will flow through such profiles. The profiles selected in that way are suitable locations for model division, with a control profile at the downstream boundary of the upstream model becoming an upstream boundary condition of the downstream model.

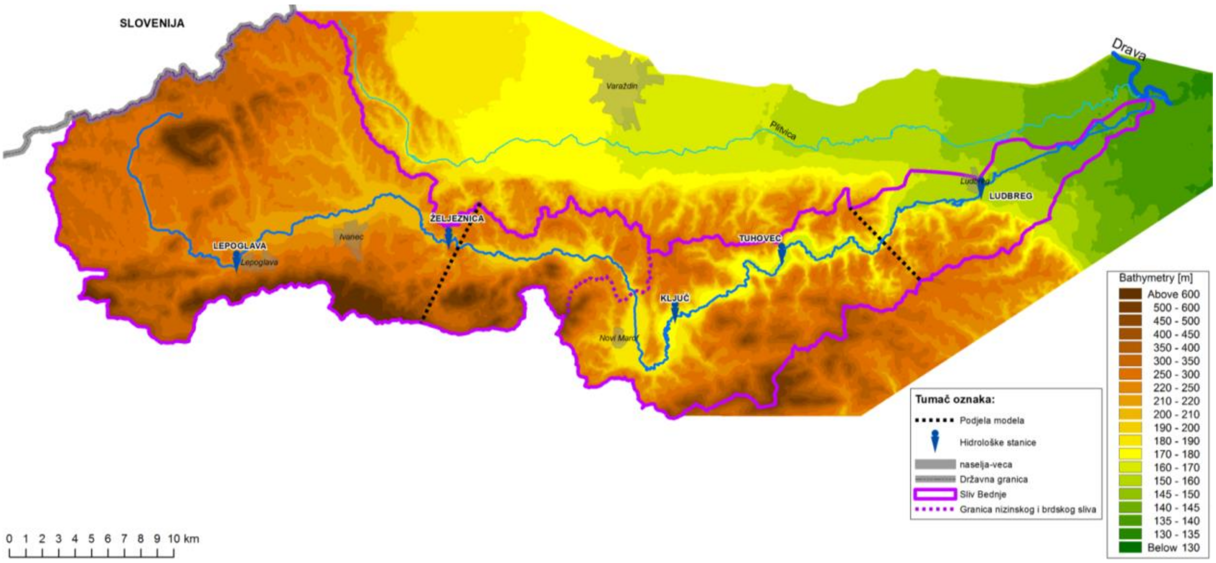


Figure 16. Hydrological stations, DEM and division of Bednja basin for hydraulic model.

Spatial discretization was done using a network of elements. In terms of discretization network detail or the size of discretization elements, the modelled area can be divided into two categories. The first category of denser spatial discretization mostly includes the channels of watercourses and other primarily linear elements such as flood protection dikes and road and railway embankments. Other areas can also, have denser spatial discretization. The second category with less dense spatial discretization, i.e. bigger spatial elements, covers all the other potentially flooded areas.

2.3. Description of the model structure

A simulation time step is defined based on the size of the spatial element and the duration of the modelled event. It needs to be noted that the given time step is the upper limit of the range of values and that it is used as long as the numerical stability criterion – Courant-Friedrichs-Lewy (CFL) condition – is fulfilled, i.e. as long as the CFL number is lower than that given or specified.

If for the given time step, depending on the relation between the size of the spatial discretization element and water velocity, the given CFL value is reached, the time step is reduced down to its defined lower limit, with a consequential increase in the duration of calculation time. When the hydro-dynamic conditions of flow return to a more favourable condition for a numerical model, i.e. when the water velocity is reduced, the originally defined simulation time step returns. Hence, the time step of model simulation is variable within the given limits and depends the most on the model's boundary conditions and spatial domain, i.e. its defined discretization network.

The watercourse channels are modelled as trapezoid channels (simplified channel geometry), where the bottom side of the trapezoid doesn't have to be horizontal. It is exactly the concept that the channels are modelled as trapezoid that to the largest extent defines the size of the channel discretization element. In order for the channel to be defined as trapezoid, three discretization elements – two for the riverbanks and one for the channel – are required in each cross-section. That means that a channel 30 m wide is in principle divided into three sections, each app. 10 m wide.

2.4. Hydrologic data

The water level at the most downstream profiles of the Bednja and the Plitvica is dictated by the Drava water level. A statistical analysis of Drava discharges at HS Donja Dubrava gives maximum discharges for different return periods. It was established that the feeder canal of the HPP Dubrava accounts for the maximum possible discharge, i.e. the capacity of the power house. The adopted values of discharge through the old Drava channel through the HPP Dubrava dam are the values from the statistical analysis of HS Donja Dubrava minus the capacity of the HPP Dubrava power house. The discharge through the old Drava channel is constant throughout the period covered by the model.

The old Drava channel downstream of the Dubrava reservoir dam was modelled with a discharge of the same return period as the Bednja and the Plitvica. Even though the linear correlation coefficient of maximum annual discharges of the Bednja (HS Ludbreg) and the Drava (HS Donja Dubrava) is very low, the adopted assumption of a simultaneous occurrence of statistical floodwaves is on the safe side and represents a kind of envelope of flood events for a given return period.

Since the flow direction is longitudinal down the channel, the criteria of numerical stability and good modelling practice permit that in that direction the elements are by app. 30% longer than they are wide.

2.5. Hydraulic data

A full 2D model was used to model the subject area. The 2D model has a considerable advantage over a 1D model in the modelling of high water events in lowland regions where the floodplain and the direction of water flow is difficult to foresee. It also has a major advantage in case of high waters flowing over flood protection dikes and other embankments (road or railway) where a flow component forms perpendicular to the dominant direction of flow and a direction that is difficult to foresee.

2.6. Model calibration and validation

The hydraulic model was calibrated by sections between the profiles of neighbouring hydrological stations with gauged hourly stage data. Based on the discharge-stage functions developed by the Croatian Meteorological and Hydrological Service (DHMZ), stage-discharge curves and hourly discharge values (hourly hydrographs) at the profiles of hydrological stations were obtained.

The model sections that don't have both boundary conditions defined by gauging at the hydrological stations are not covered by calibration, but have been assigned values of model roughness from the neighbouring calibrated domains. The area of the immediate Drava River basin, from the profile of the Dubrava HPP dam over the mouths of the Plitvica and Bednja rivers and further downstream of the Bednja mouth by app. 2 km, is also included in the model, i.e. its third, most downstream domain. The numeric model calibration has given the value of the Manning coefficient of hydraulic roughness in the channel and the assumed value in the flood zones.

Model verification has confirmed the assumed values of the modelled hydraulic roughness with satisfactory precision.

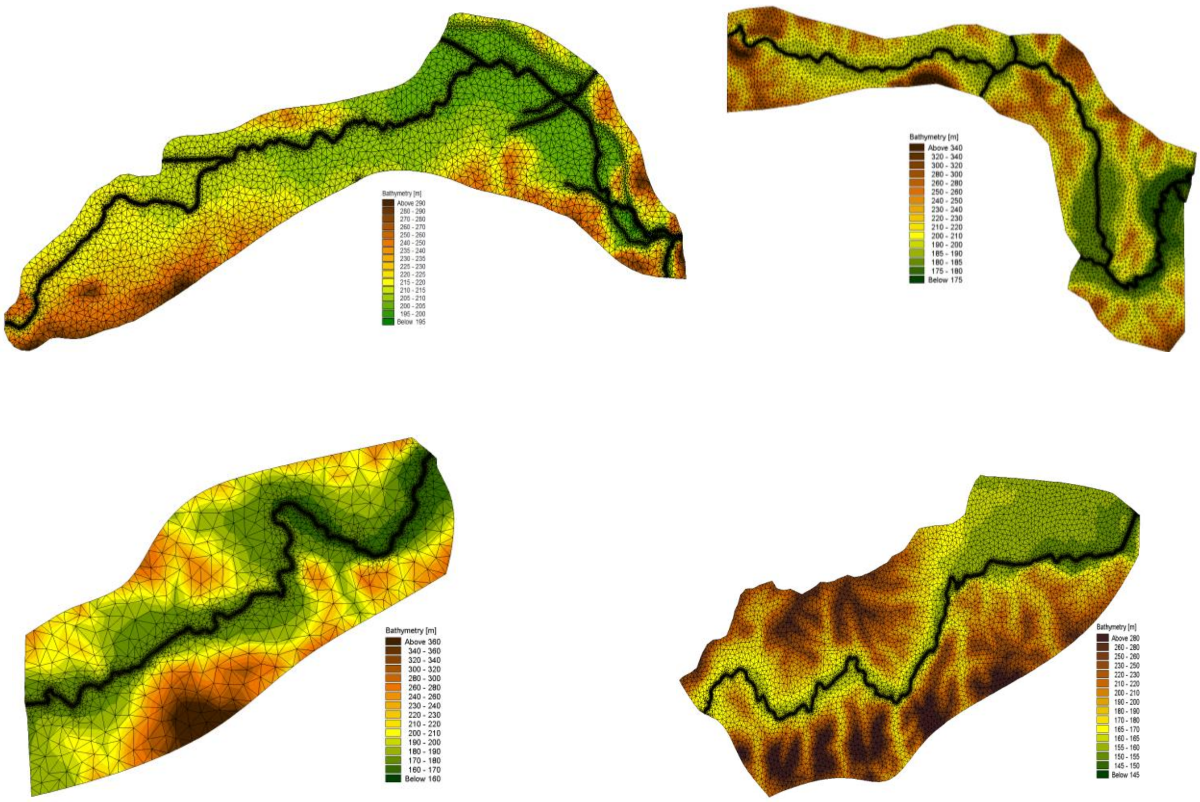


Figure 17. Domain of the modelled sections with spatial discretization network.

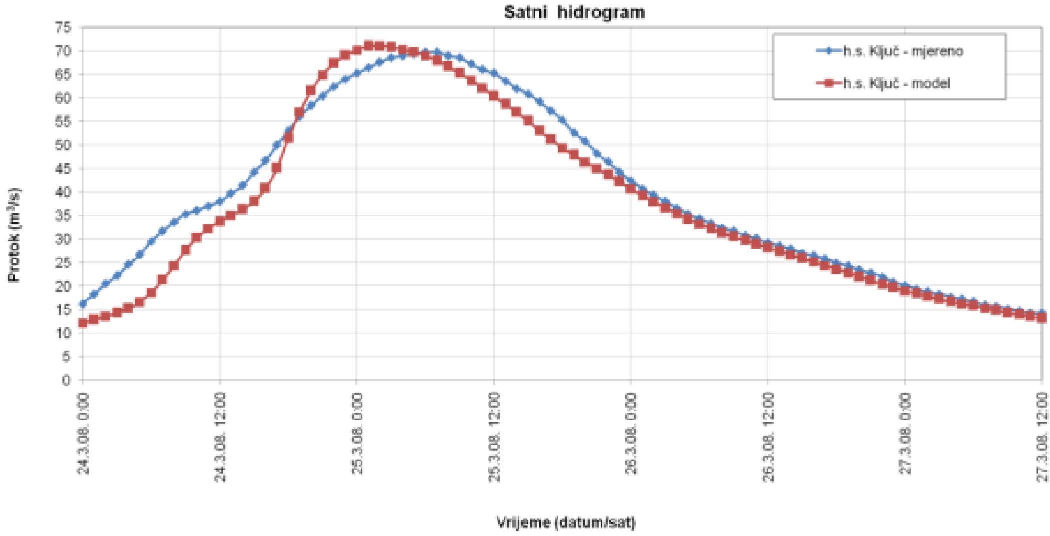


Figure 18. Results of hydraulic model calibration at Ključ hydrological station (comparison of gauged and modelled hourly hydrographs).

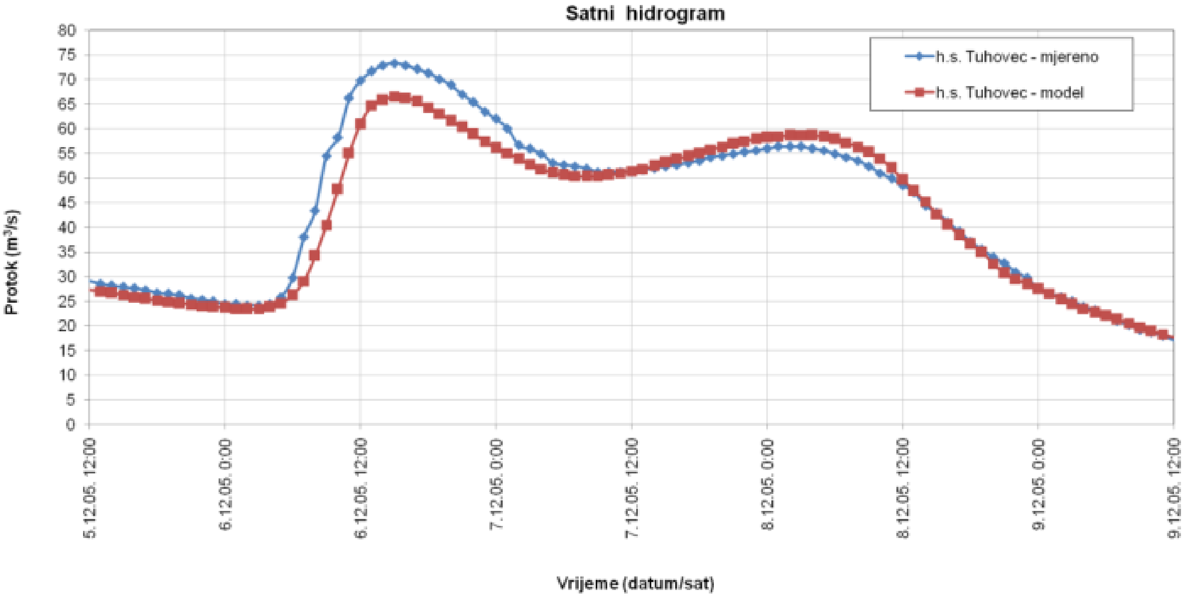


Figure 19. Results of hydraulic model calibration at Tuhovec hydrological station (comparison of gauged and modelled hourly hydrographs).

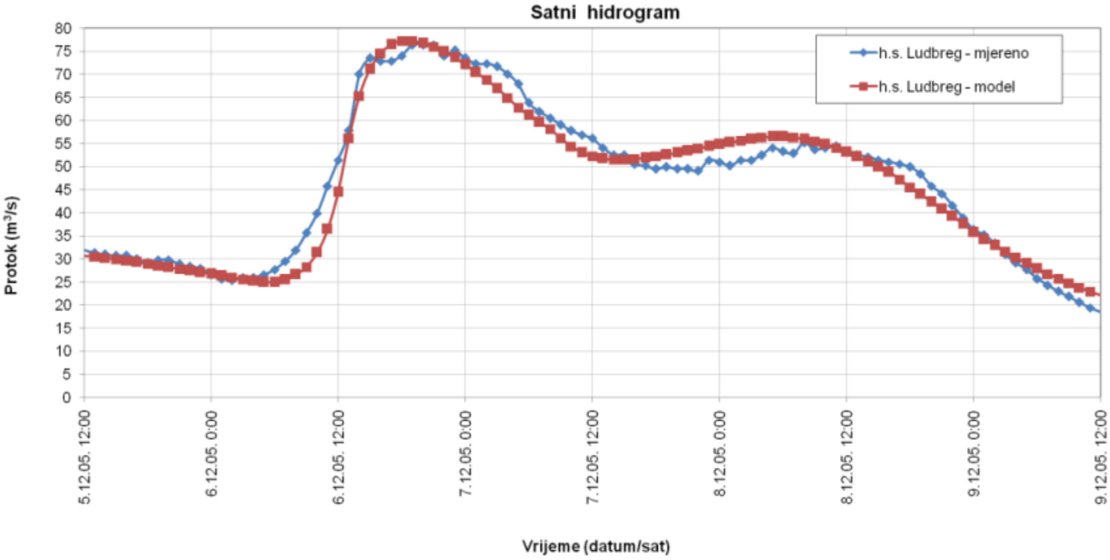
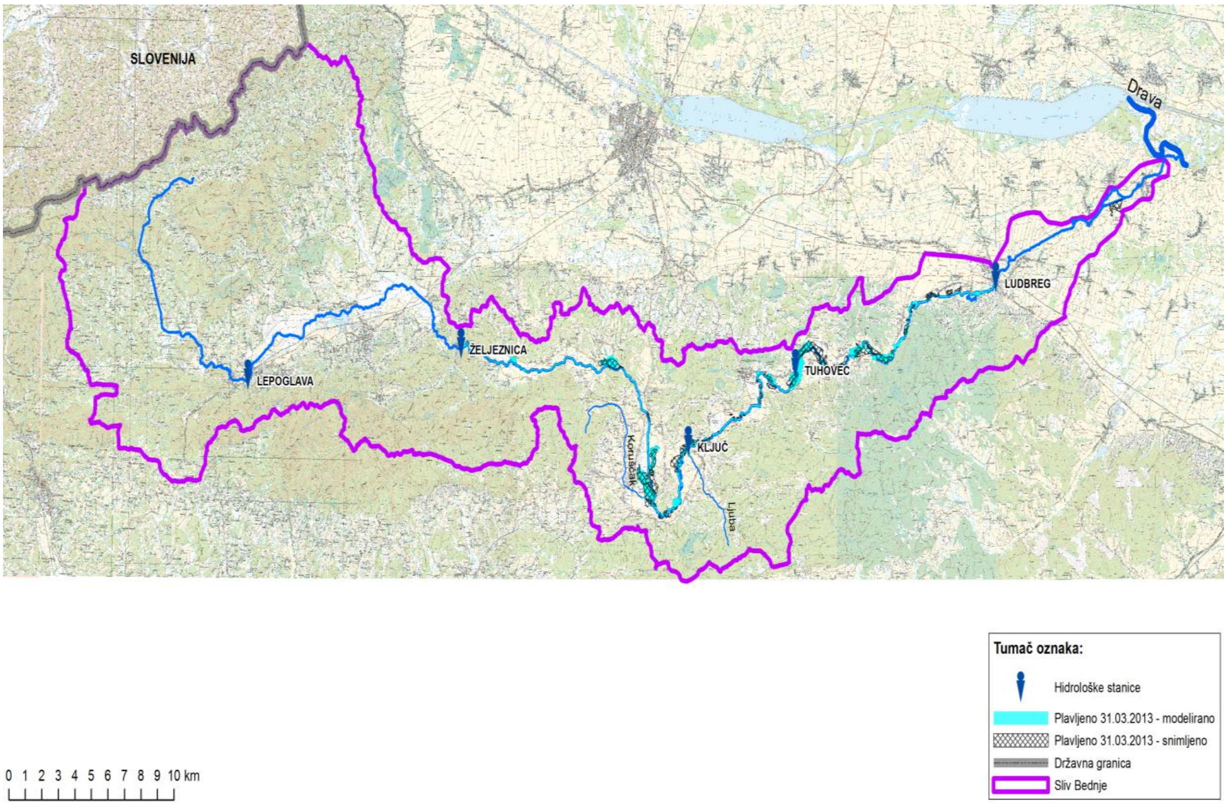


Figure 20. Results of hydraulic model calibration at Ludbreg hydrological station (comparison of gauged and modelled hourly hydrographs).

The model was validated against a March 2013 flood event during which the flood line was surveyed from the air and digitized through orthophotos.



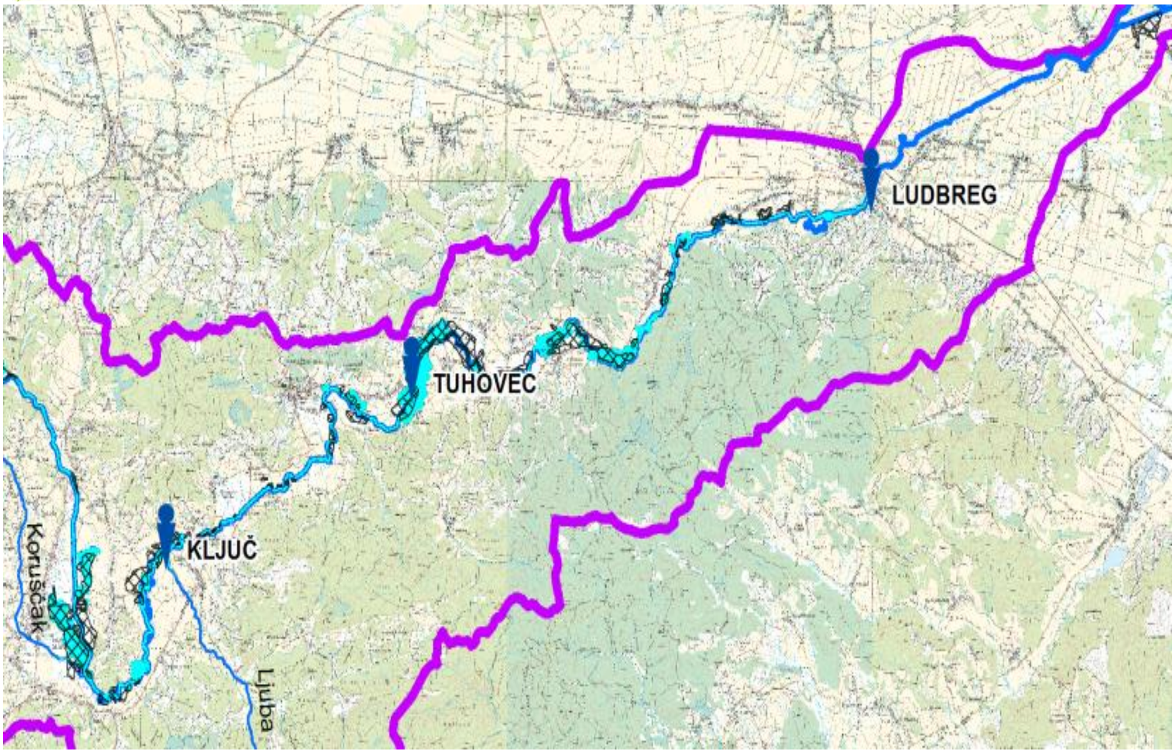


Figure 21. Results of hydraulic model validation.

3. MEASURES IN THE PILOT AREA

Expert measures are foreseen for flood defence in the Bednja basin, with proposed construction of three water retention basins (Koruščak, Kamenica 1 and Čret). In addition to the retention basins, the existing dikes in the lower part of the basin should be moved away from the river. These measures would reduce direct potential flood damage in the Bednja basin. Furthermore, by moving the dikes away from the river, riparian habitats are protected better, floods have a weaker impact, and maintenance requirements are lower.

According to the catalogue of measures and based on the basin analysis, the following basin-wide measures have been selected on the Bednja river:

- Polders, dry flood protection reservoirs, sediment trapping dams (T1);
- Widening or removing of flood protection dikes (T2).

3.1 T01- Polders, dry flood protection reservoirs, sediment trapping dams

Goal: Flood protection in the Bednja basin

Location/river topology: Lowland stream, easily accessible, agricultural land

General description: Construction of dams to reduce peak flow, controll discharge into the downstream basin and to reduce erosion on the downstream river.

Selected measures: Construction of three water retention basins for flood defense:

- Koruščak;
- Kamenica 1; and
- Čret

Below are illustrated potential locations of retention basins in the Bednja basin.

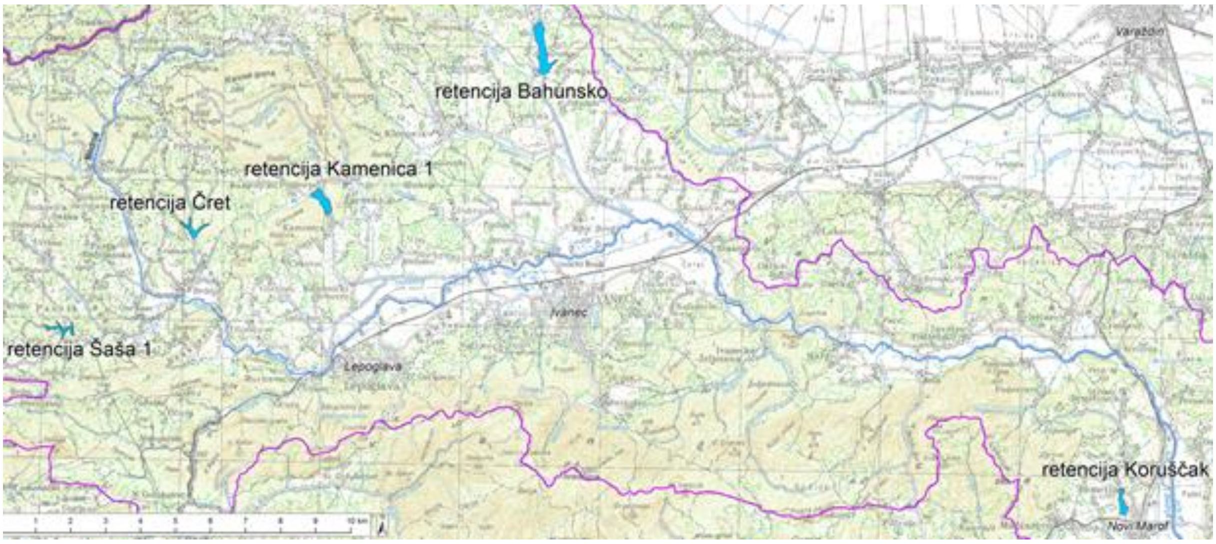


Figure 22: Potential locations of retention basins in the Bednja basin.

Table 5. The catchement and retention area

Retention basin	The catchment area upstream of the dam (km2)	Retention area (ha)
Čret	4.21	9.3
Kamenica	13.08	17.7
Koruščak	25.98	9.5

3.2 T02 – Widenning or removing of flood protection dikes

In addition to the retention basins, the existing dikes in the lower part of the basin should be moved away from the river. These measures would reduce direct potential of flood damage in the Bednja basin. Furthermore, by moving the dikes away from the river, riparian habitats are protected better, floods have a weaker impact, and maintenance requirements are lower.

Goal: flood risk reduction in the Bednja basin

Location/river topology: lowland stream (riparian area), easily accessible, agricultural land

General description: Dikes along Bednja will enable effective flood protection, limited pouring into the inundation that would be expanded by this measure; nutrient reduction is expected as a result of this measure. Moving the embankments away from the river bed brings significant benefits, such as flood risk reduction throughout the whole course, integration of sleeves and oxbow lakes, limited outpouring into the inundation (expanded by this measure) and nutrient reduction.

Selected measures: Reconstruction and construction of new dikes along Bednja river

As illustrated on the figure below, existing and planned dikes are stretching from Ludbreg to the mouth of the Drava.

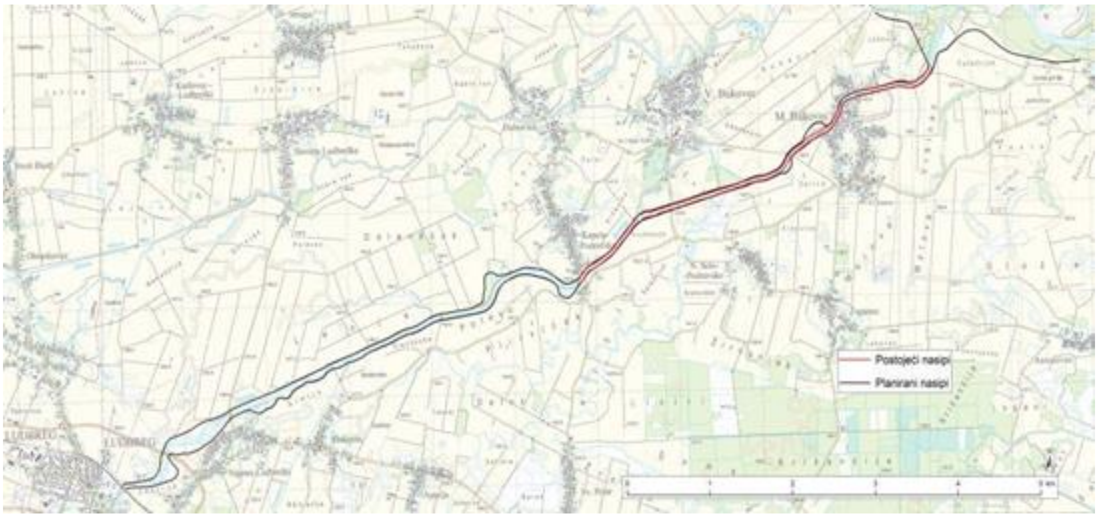


Figure 21: Existing and planned dikes along Bednja along the stretch from Ludbreg to the mouth of the Drava.

Basic dimensioning of dikes is presented in the table.

Table 6: Basic dimensioning of the dikes

Dike	Reconstruction of existing dike (river mouth – Kapela Podravska)	Construction of new dike (Kapela Podravska – Ludbreg)	Total length (reconstruction existing dike + construction of new dike)	Average height of the dike
Unit	km	km	km	
Left dike	5,28 km	6,25	11,8	1,4
Right dike	5,35 km	5,75	11,1	1,62

The maximum distance planned from the existing dike on the left bank is about 90 m, and on the right bank, about 50 m. The planned dikes have, for the most part, a trapezoidal profile with a crest width of 3 m and a slope of 1: 2. An access road of 4.0 m width is predicted at dike foot. In some sections it is not possible to construct an access road to the dike due to space limitations. The dike structure is made of a suitable mixed material that ensures stability of the dike and sufficient resistance to leakage.

4. **DYNAMIC MODELING OUTPUTS**

A hydrological-hydraulic analysis of the Bednja basin has been made for 3 upstream retention basins (Čret, Kamenica and Koruščak) and a dike on both sides downstream of Ludbreg for the hydrological state with 2, 5, 10, 25, 50, 100 and 1000 year return period floods.

Figures from 24 to 30 present the resulting floodlines for different return periods.

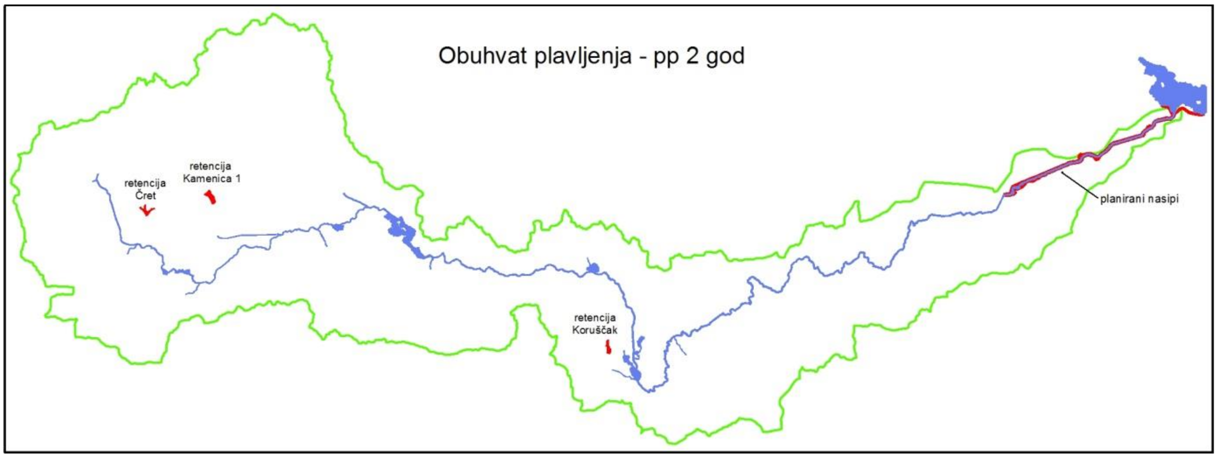


Figure 24. Hydrological state with 2 year return period flood.

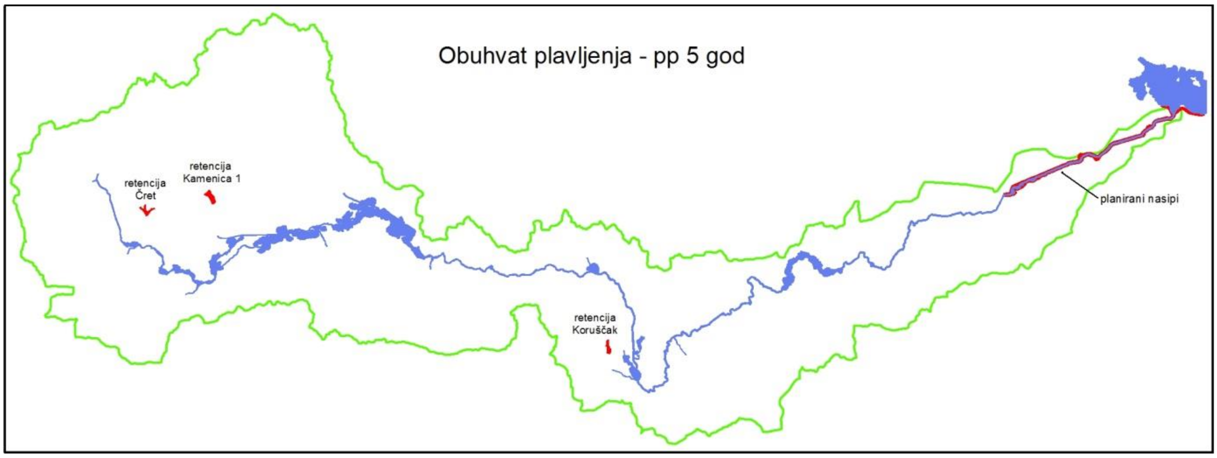


Figure 25. Hydrological state with 5 year return period flood.

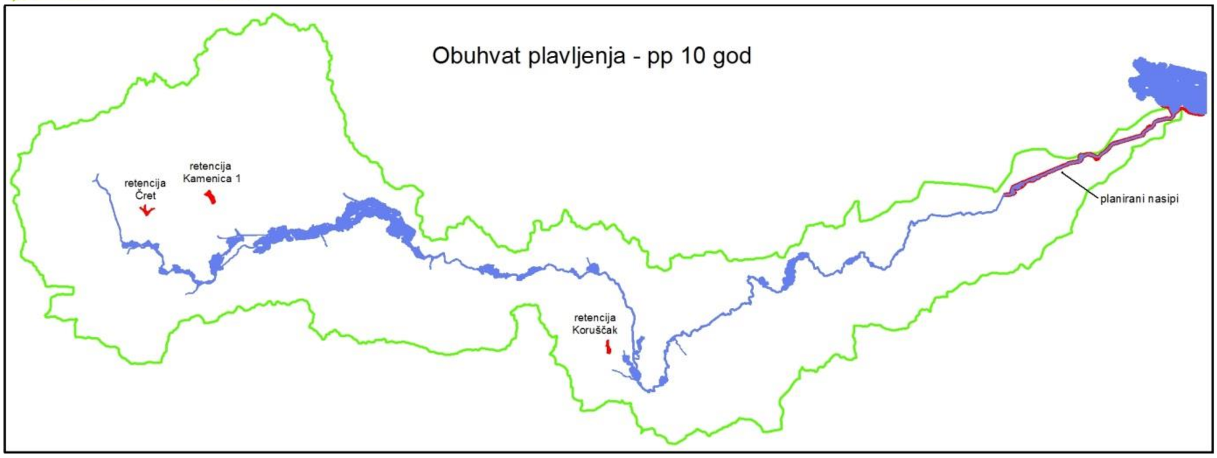


Figure 26. Hydrological state with 10 year return period flood.

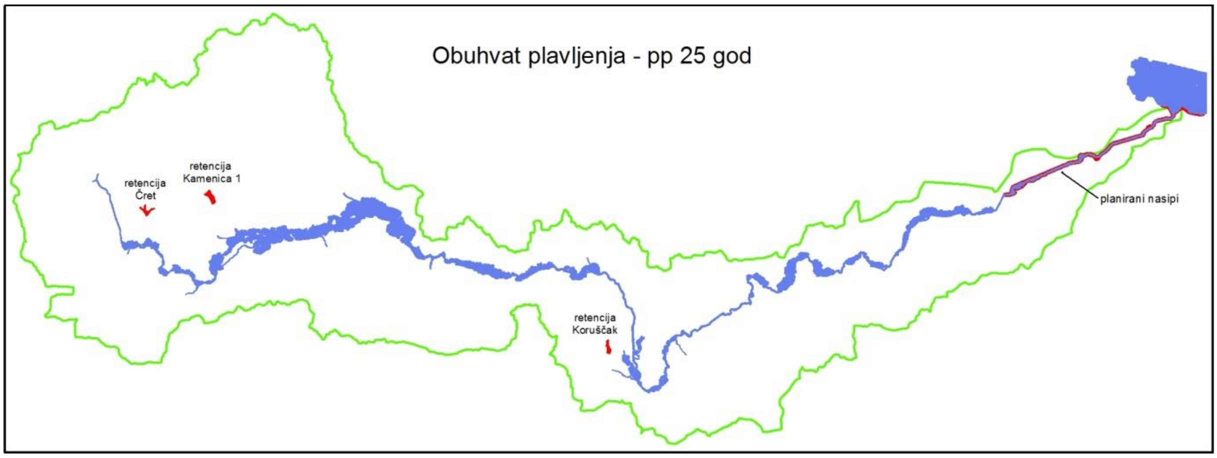


Figure 27. Hydrological state with 25 year return period flood.

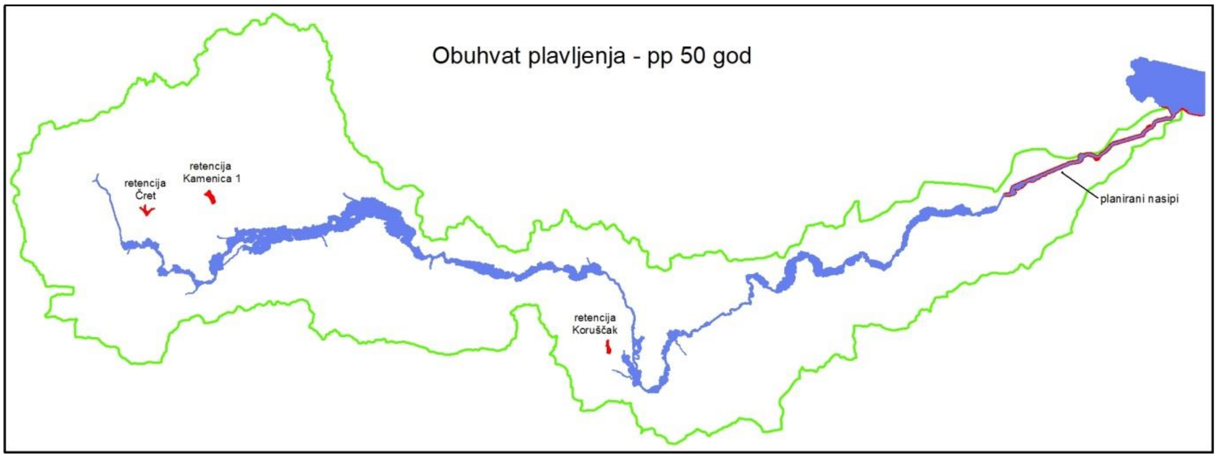


Figure 28. Hydrological state with 50 year return period flood.

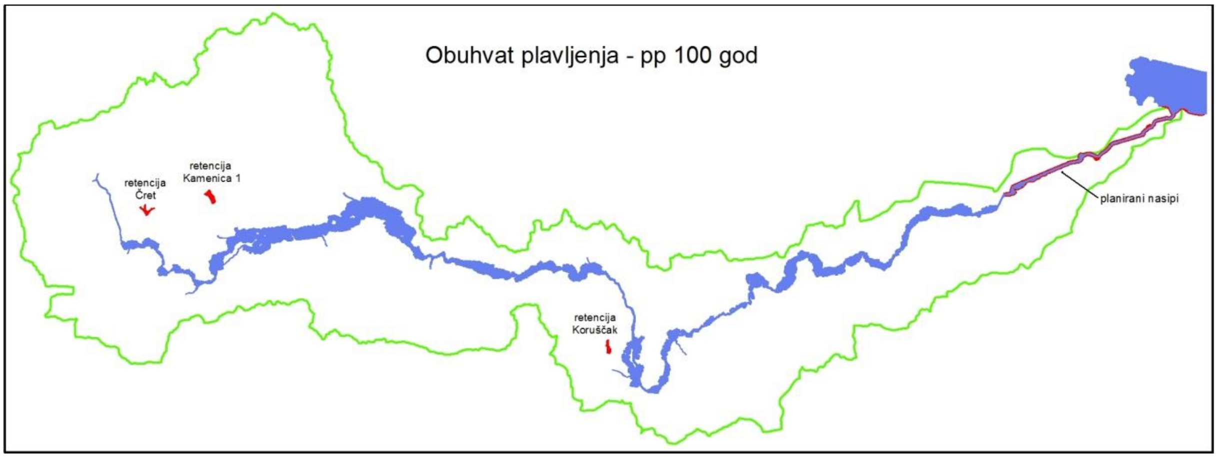


Figure 29. Hydrological state with 100 year return period flood.

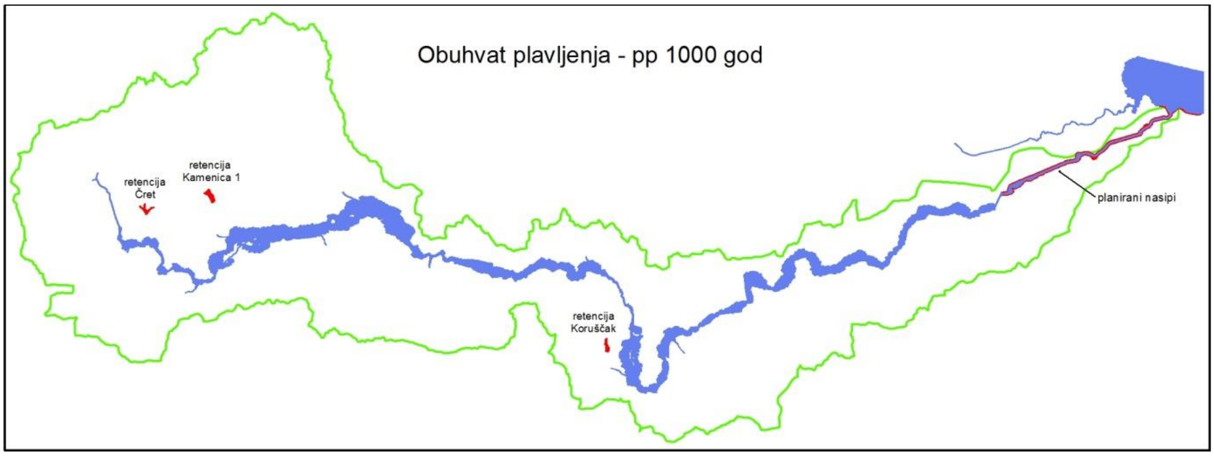


Figure 30. Hydrological state with 1000 year return period flood.

By comparing the results presented in the figures, it is clear that the effect of reducing floodplains is the largest in the area along the Bednja dikes in the downstream part of the basin, whereas the effects of retention basins in the upland part of the basin are present only locally, through the reduction of individual flooding depths caused by the retention of water volumes in the retention basins.

5. CONCLUSIONS

Models for Bednja catchement were calibrated and validated.

The goal was to test the dynamic models with the purpose of assessing effectiveness of measures (retention basins and dikes).

A hydrological-hydraulic analysis of the Bednja basin has been made for 3 upstream retention basins (Čret, Kamenica and Koruščak) and a dike on both sides downstream of Ludbreg for the hydrological state with 2, 5, 10, 25, 50, 100 and 1000 year return period floods.

By comparing the results it is clear that the effect of reducing floodplains is the largest in the area along the Bednja dikes in the downstream part of the basin, whereas the effects of retention basins in the upland part of the basin are present only locally, through the reduction of individual flooding depths caused by the retention of water volumes in the retention basins.