Study

Results of Activity 1

of START Project:

12_PA05-C2,

Quantification of morphological changes in river channels and its impact on flood risk, MORCHFLOOD

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Content

1 Introduction

Floodplains are the low-relief sedimentary surfaces adjacent to river channels, which are more or less frequently inundated during high flow events. It is widely recognised that the storage of floodwater on floodplains can reduce flood magnitude downstream (Acreman et al. 2003). We generally speak about flood transformation, when except the flood peak reduction we can also observe a delay in the peak time of the flood wave. The rate of transformation depends on the planar shape, the character and the land use of the floodplain area, i.e. on its retention capacity (Valentová et al. 2010). In addition, active floodplains increase and maintain biodiversity, preserve and recharge groundwater supply and affect water quality by filtering sediments, nutrients and impurities. Regular flooding also support reproduction of some fish species, e.g. pikes (Wohl 2014).

However, channelisation works represented by channel narrowing, bank stabilisations, removal of bank vegetation and gravel mining lead to channel degradation during 20th century. Narrow incised channels continuously increase flow velocities and unit stream power associated with given discharges. Nowadays, considerable alterations to physical structure of river ecosystems resulting from direct human impacts are common. Deeply incised channels interrupt hydraulic connectivity of floodplains, which has been documented in many European regions including the Western Carpathians (Wyżga 1993; Galia et al. 2012; Wyżga et al. 2012; Škarpich et al. 2013). Decreased or interrupted connectivity between the main channel and adjacent floodplains in unbuilt areas significantly affects the ability of flood transformations and may increase a flood risk for downstream urbanised areas. As for example, the magnitude of the 1994 floods on the Rhine was blamed partly on loss of floodplain storage in upstream part of the river. As component of the succeeding flood alleviation strategy of the lower Rhine, embankments were removed to restore channel-floodplain connectivity (Schropp and Jans 2000). The floodplain retention of the upper part of Lužnice River (Czech Republic) was examined in several papers, when flood transformation accompanied by lowering of peak discharge (ca. 5 %) and a delay in the peak time of the flood wave (5.5-8.5 h) was simulated by a hydraulic model for 10 km long meandering channel-reach and flood magnitudes Q_5, Q_{20} and Q_{100} (Valentová et al. 2010). On the other hand, Turek and Grill (2011) directly observed increased peak discharges in the same channel-reach for low magnitude flood events in 2009 as a consequence of large lateral subsurface inflow contribution from previous precipitations. Thus, floodplain soil saturation is another important aspect influencing flood transformations. It is also notable, that surface storage capacity represented by the retention in depressions (e.g. lakes, old meanders) is able to storage only 0.41 % of total water volume for Q_{20} flood and 0.26 % for Q_{100} flood in this channel-reach of the Lužnice River (David and Dostál 2012).

Main aims of this project are to quantificate morphological changes in two Carpathian river channels (Bečva in Czech Republic and Topľa in Slovakia) including channel-floodplain connectivity and its impact on flood risk. Data collected during the field works and actual digital elevation models were used as a base for development of present scenario for hydraulic models. Study of historical data took place in both rivers and methodology was developed to use these data as base for various scenarios of river channel geometry. Afterwards these scenarios were used in 2D hydraulic models and simulations were analysed with respect to the quantification of changes on flood risk. An important part of the project was sharing of obtained results with the institution involved in catchment management on workshops and the establishment of the network as base for future cooperation.

2 Studied rivers

2.1 Bečva River

The Bečva River is a gravel-bed stream with a length of 61.5 km. The river starts as the Bečva R. after the confluence of the Vsetínská Bečva R. (considered its main source) and the Rožnovská Bečva R. Vsetínská and Rožnovská Bečva R. (see Fig. 2.1.1 and 2.1.2) flow from the Moravskoslezské Beskydy Mts., Hostýnsko-vsetínská hornatina Mts., Javorníky Mts., Vizovická vrchovina Mts. to the relatively flat piedmont. The highest and lowest sites within the Bečva R. basin are, respectively, Čertův Mlýn (Devils Mill) Mt., at 1205 m a.s.l., and the mouth to the Morava R., at 195 m a.s.l. The drainage area of the Bečva R. is 1620 km^2. The annual precipitation in the basin ranges from 500, at the lower parts of the basin, to 1200 mm, at the highest parts of the river basin.

The mean annual discharge of the river amounts to 17.30 m^3/s (data source: Czech Hydrometeorological Institute) at the Dluhonice gauging station (where the basin area is 1592.81 km^2) close to the mouth to the Morava R. Basic hydrological characteristics are showed in Table 2.1.1. The Bečva R. is characterised by the occurrence of frequent floods of moderate magnitude, due to snow melting and rare, large floods caused by summer rains connected to cyclones.

The study areas are the 23.5-km length river reach of the Bečva R. that runs from the 38.0 to 61.5 r. km, 4.0-km length river reach of the Vsetínská Bečva R. that runs from 0.0 to 4.0 r. km and 2.0-km length river reach of the Rožnovská Bečva R. that runs from 0.0 to 2.0 r. km. The study area is presently characterised by some distinctive reaches of dissimilar development from the originally anabranching gravel-carrying stream. The Bečva R. channel reaches from 38.0 to 45.5 r. km, from 47.5 to 53.0 r. km, from 54.5 to 61.5, the Vsetínská Bečva R. channel reach from 0.0 to 4.0 r. km and the Rožnovská Bečva R. channel reach from 0.0 to 2.0 are characterised by regulated single channel pattern with bank stabilisation structures. The Bečva R. channel reaches from 45.5 to 47.5 r. km and from 53.0 to 54.5 r. km are characterised by partially anabranching channel pattern with lateral migration and occurrence of gravel bars. The whole studied channel reach is affected by incision up to 3-4 meters.

The Bečva River draining the Czech part of the Flysch Carpathians was characterised by an anabranching channel pattern in the piedmont zone with a large amount of sediment movement. The main reason affected sediment balance is a particular lithological predisposition of flysch sedimentary rocks with changing layers of claystones and sandstones. Especially layers of claystones are water erosion-susceptible and determined slope instabilities. These slope instabilities, e.g., slope deformations, debris flow and gully erosion (sensu e.g. Pánek et al. 2011; Šilhán and Pánek 2010; Šilhán et al. 2011), have impact on the sediment supply to river channels. In particular, gully network development was related to slope deforestation several times throughout the course of history, during the colonisation of the mountains from the second half of the 16th century to the 19th century.

In the 20th century, a large part of the territory started to be newly afforested, which helped to reduce sheet and gully erosion. The state of contemporary sediment balance is also affected by the stabilising of sediment sources close to the channel (channelising, bank protection by riparian vegetation or regulating works) (sensu Škarpich et al. 2011; 2013).

Tab. 2.1.1: Basic hydrological characteristics: mean annual discharge, N-year recurrence interval discharge and basin area of selected gauging stations in the Bečva R. basin (data source: Czech Hydrometeorological Institute).

Gauging station	**River/Stream**	**Basin area of given gauging station [km^2]**	**Mean annual discharge (Q_a) [m^3/s]**	**N-year recurence interval discharge (Q_N) [m^3/s]**				
				Q_1	**Q_5**	**Q_{10}**	**Q_{50}**	**Q_{100}**
Dluhonice	Bečva	1592.81	17.30	239	466	564	792	892
Teplice nad Bečvou	Bečva	1275.32	15.50	219	452	555	799	908
Kelč	Juhyně	86.12	0.83	9.03	31.5	43.6	79.8	98.8
Rajnochovice	Juhyně	20.31	0.26	2.88	10.4	15.1	30.4	39
Rožnov pod Radhoštěm	Rožnovská Bečva	160.24	2.72	42.8	99.1	134	241	301
Valašské Meziříčí	Rožnovská Bečva	252.45	3.79	66.5	161	214	364	441
Ústí	Senice	134.59	1.65	32.3	71.2	91.5	147	174

Jarcová	Vsetínská Bečva	723.87	9.39	151	274	333	479	547
Velké Karlovice	Vsetínská Bečva	68.5	1.21	17.9	38	49.5	82.8	100
Vsetín	Vsetínská Bečva	505.81	6.79	126	234	279	378	420

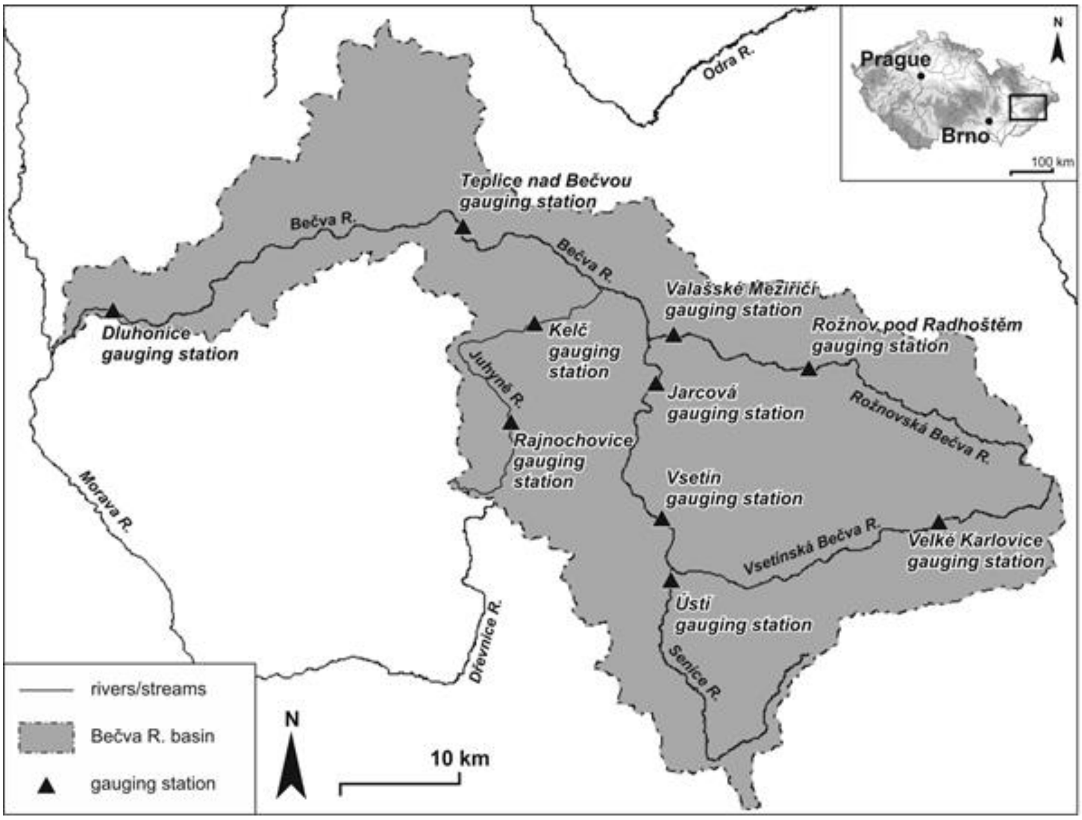

Fig. 2.1.1: Schematic map of the Bečva R. basin with localisation of the gauging stations (data source: T. G. Masaryk Water Research Institute, public research institution).

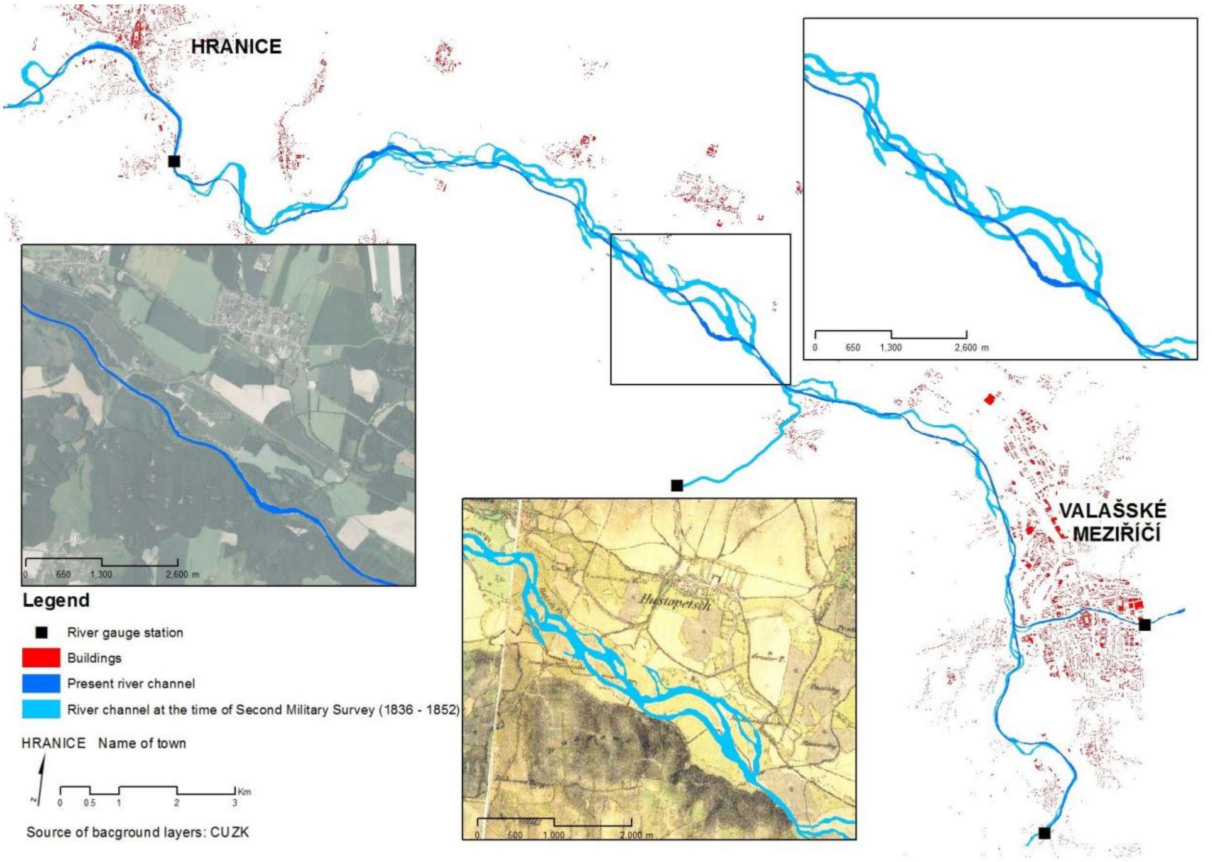

Fig. 2.1.2: Schematic map of the studied part of the Bečva River.

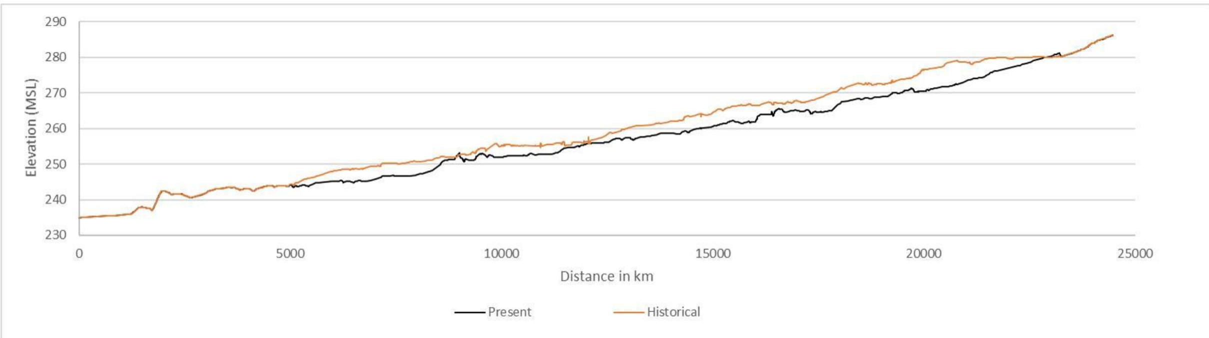

Fig. 2.1.3: Longitudinal profile of the studied part of the Bečva River.

2.2 Topľa River

The sinuous gravel-bed Topľa River (115 km long, catchment area 1506.4 km^2) springs in the Čergov mountain range at 930 m above sea level (Fig. 2.2.1). Long term mean daily discharge of the Topľa R. moves at the station of Bardejov on the level of Q_a = 3,018 m^3.s^{-1} (Q_{max} = 350 m^3.s^{-1} from 4th of June, 2010, Fig. 2.2.2). The shape of the basin is elongated in the northsouthern direction. The river system of river is part of the Bodrog River basin, which drains the Eastern part of Slovakia. The Northern border of basins is also part of the European main watershed between the Baltic and the Black Sea.

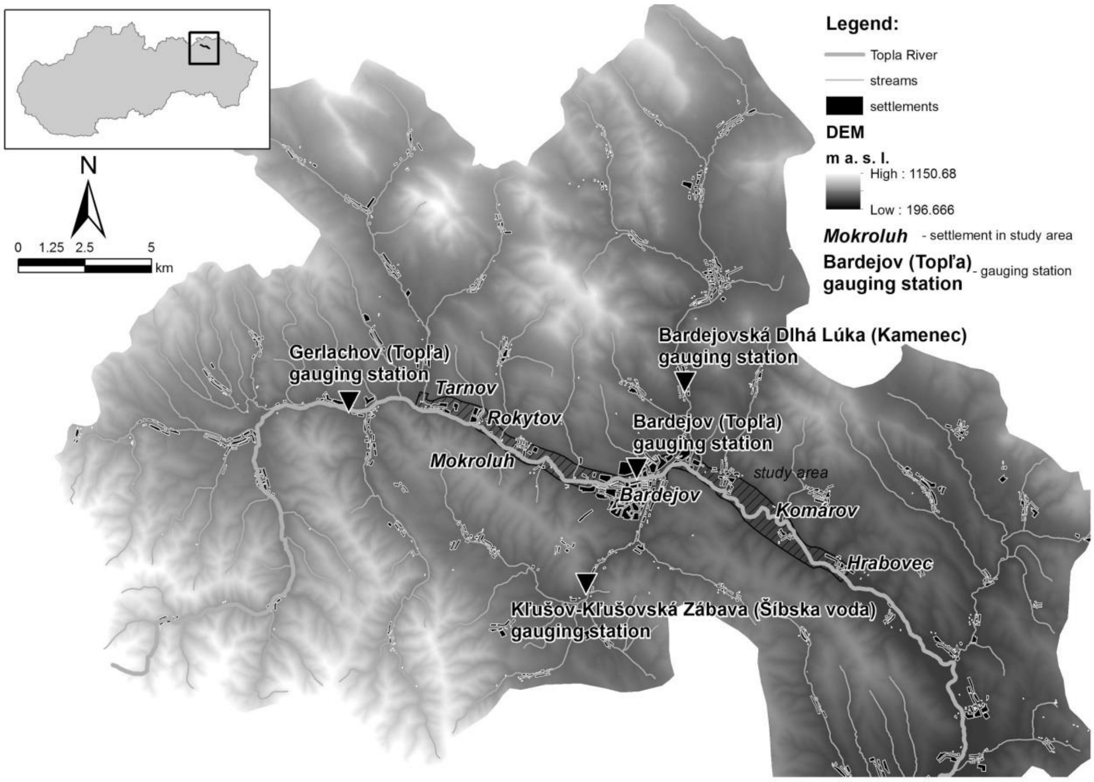

Fig. 2.2.1: Schematic map of the Topľa R. basin with localisation of the gauging stations (data source: Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012)).

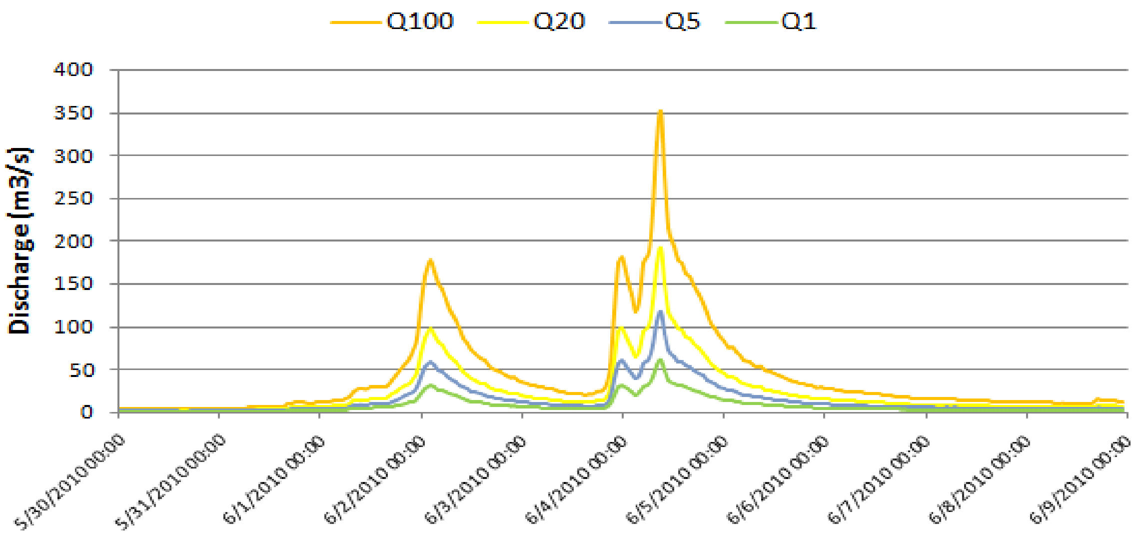

Fig. 2.2.2: Hydrographs of selected N-year recurence interval discharge used for hydraulic modelling in Bardejov gauging station (source: Slovak Hydrometeorological Institute, 2016).

The research has been carried out at the central reach of 21.5 km gravel-bed of less-regulated channel of the Topľa River (Fig. 2.2.3) in the outer Carpathians flysch setting in Eastern Slovakia (Central Europe). River is located in the northern part of eastern Slovakia in the central parts of Ondavská vrchovina Highlands. The valley of the Topľa River is filled with Holocene gravels and sandy gravels. Here the stream flows over flysch environment consisting of the Eocene clay, sandstone and conglomerates. The valley is filled with fluvial gravel and fluvial loam. Their thickness moves between 2 and 8 metres. The average air temperature for Bardejov is 7.8°C. Maximum monthly rainfall are reached in the summer months (June, July) and the highest water level is achieved in the spring (melting snow) with a peak in March, while secondary maximum is in August and is mainly the result of extreme summer rainfall events.

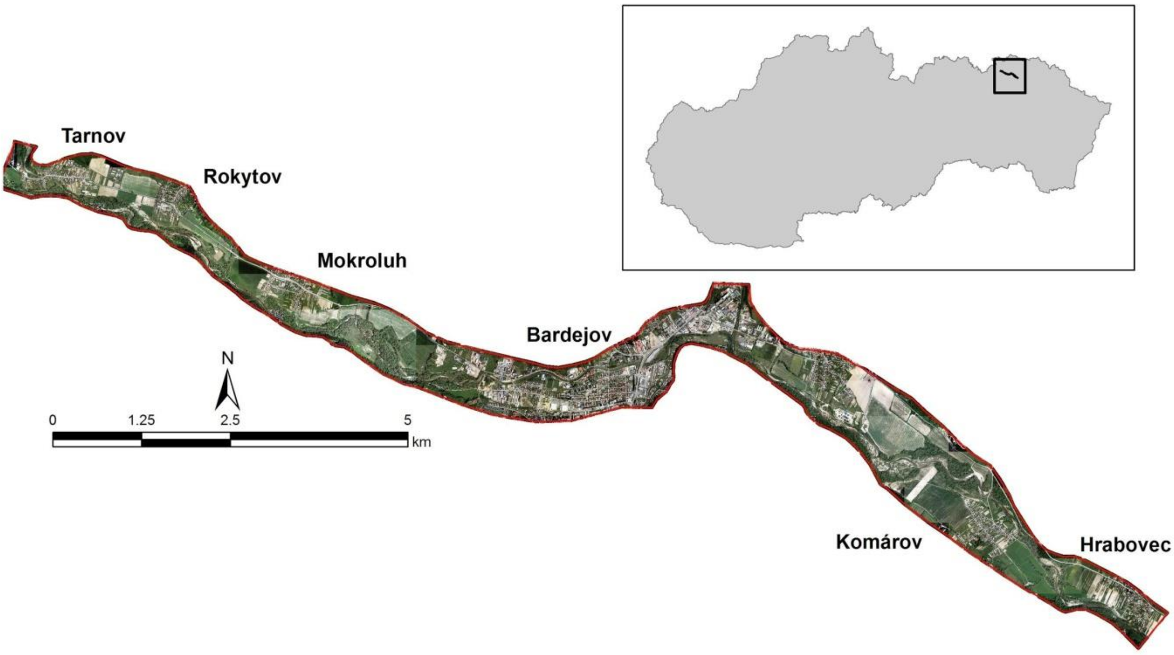

Fig. 2.2.3: Localisation of study reach of the Topľa River (flow direction from left to right) on orthophoto from year 2013 (©EUROSENSE, s r. o.).

3 Methods

3.1 Hydrologic data

For hydraulic modelling of the Bečva River were used hydrographs of flood event from 2010 with recurrence interval 50 years. Data about automatic hourly discharges in time span between 5/11/2010 (00:00) and 06/10/2010 (23:00) were obtained from the Czech Hydrometeorological Institute for 4 gauging stations (Fig 3.1.1). Teplice gauging station is situated 1 km above Hranice town and is the place of model calibration, with the maximum discharge of 799 $m^3.s^{-1}$. Second gauging station - Valašské Meziříčí is placed directly at the town with the same name as the station. Third station is placed closed to the village Jarcová. Last station is at the tributary of the Juryně River directly at Kelč town. For recurrence interval (R.I.) modelling of selected flows (N=1, 5, 20 and 100 R.I.) the data from Teplice station were used and edited according to values of recurrence interval showed in Table 2.1.1 (Fig. 3.1.2).

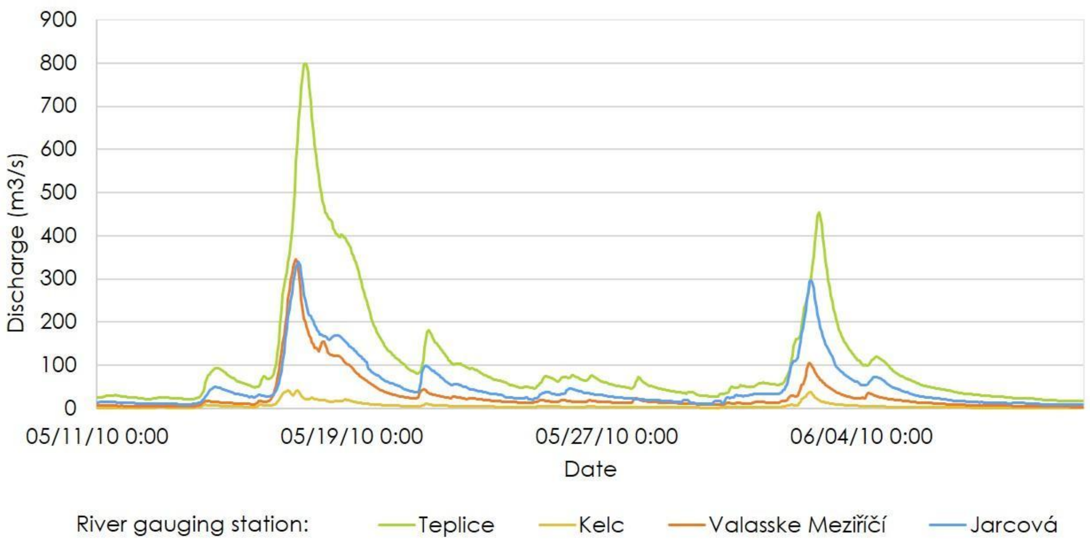

Fig. 3.1.1: Hydrographs of 4 gauging stations from the Bečva River and main tributaries used for hydraulic modelling (source: Czech Hydrometeorological Institute, 2016).

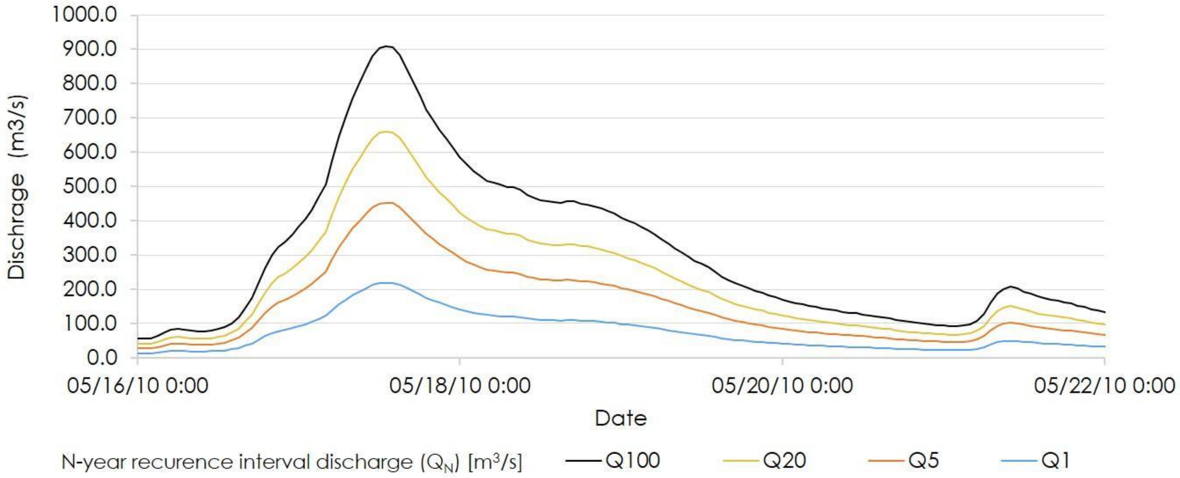

Fig. 3.1.2.: Hydrographs of selected N-year recurrence interval discharge used for hydraulic modelling. (source: Czech Hydrometeorological Institute, 2016).

For hydraulic modelling of Topľa River were used hydrographs of catastrophic flood event from year 2010 with recurrence interval 100 years. Data about automatic hourly discharges in time span between 5/30/2010 (00:00) and 06/08/2010 (23:00) were obtained from the Slovak hydrometeorological institute for 4 water gauging station (Fig.3.1.3). First one (Gerlachov, Topľa River) is situated approximately 3 km above the beginning of study reach on the Topľa river with maximal discharge 78.94 $m^3.s^{-1}$ (flood event in 2010). Second one is situated in the middle part of study area in the town Bardejov (Topľa River) with mean daily discharge around 3.018 $m^3.s^{-1}$ and 2010 flood discharge 351.2 $m^3.s^{-1}$. The two following are located on main tributaries. Šíbska voda creek (Kľušov - Kľušovská Zábava gauging station) is right side tributary with maximal discharge 65.48 $m^3.s^{-1}$ in 2010 flood event and last one is left side tributary Kamenec creek (Bardejovská Dlhá Lúka gauging station) with flood discharge in 2010 on the level 42.29 $m^3.s^{-1}$.

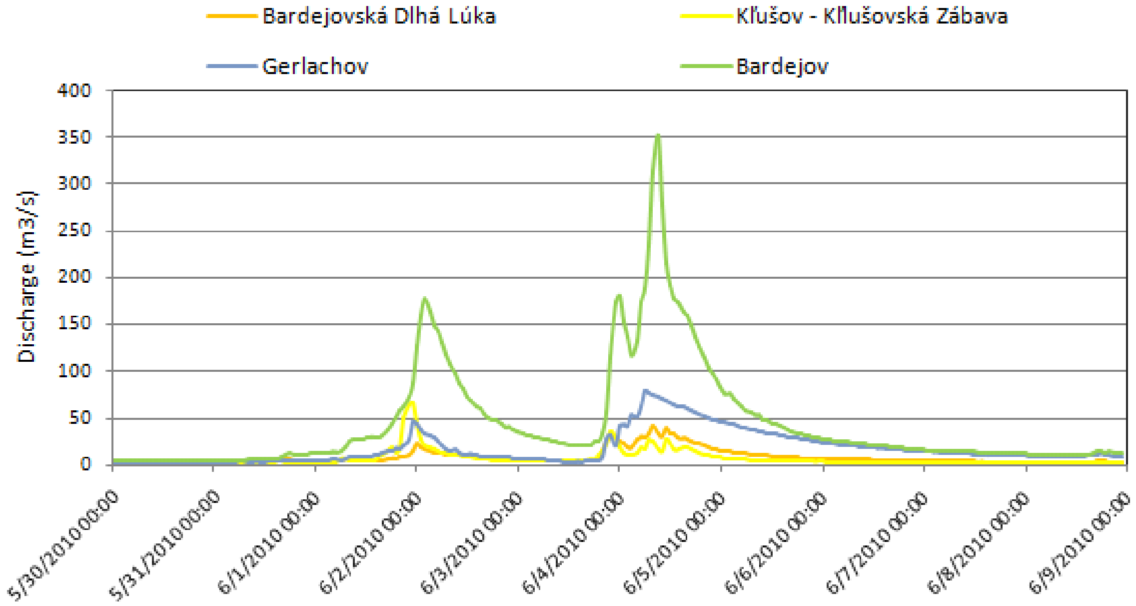

Fig. 3.1.3: Hydrographs of 4 gauging stations from the Topľa River and main tributaries used for hydraulic modelling (source: Slovak Hydrometeorological Institute, 2016).

3.2 Field measurements

Channel cross-sections were geodetically measured during low flow stage at appropriate positions within the studied river reaches, when a higher density of cross-sections was obtained in irregular channel-reaches (i.e. in river bends or in the case of presence of local anabranching pattern). Every single cross-section was taken with respect to the bank and bed morphology, usually accounting 10-20 measured points. Water surface levels were noted together with related discharges at gauging stations for future model calibrations. Mean channel slope between individual cross-sections was taken from digital elevation model. At total, 52 cross-sections were collected for the Bečva River and 95 for the Topľa River. In addition, parameters of occurred bridges (height, width, spacing between individual pillars) were geodetically measured.

3.3 Historical reconstruction of morphology of studied river channels

The Bečva River has been systematically channelized since the beginning of 20th century (Hrádek 2005). Thus, the reconstruction of historical river geometry and thus, close-to-natural state, was focused on i) the assessment of the maps of the Second Military Survey (1836-1852, 1:28 000 scale) and ii) present digital elevation model of fourth generation produced by Czech State Administration of Land Surveying and Cadastre. While the first source provided us by information about planar geometry of studied river (Fig. 3.3.1), the floodplain cross-sections constructed on the basis of digital elevation model demonstrated the intensity of channel incision since the river channelization. There was an evidence of channel incision up to four meters in several cross-sections together with the channel narrowing due to past human interventions when compared to historical channel width (Fig 3.3.2). The historical cross-sections were reconstructed in positions reflecting the locations of present cross-sections geodetically measured in the field. In general, historical cross-sections were much wider and shallower than present cross-sections, which also reflected extinct wandering pattern (i.e., the presence of more channels and channel bars in cross-sectional geometry). In addition, artificial levees were removed during reconstructions to allow hydraulic reconnection of the main channel with adjacent floodplain areas. The cross-sectional geometry of channel-reach in Hranice town remained preserved due to the assessment of present local flood risk; in densely inhabited area is absolutely not possible to restore the channel width corresponding to the historical state. The final channel elevation model interpolated from cross section was inserted to elevation model from for hydraulic modelling of historical scenario in HEC-RAS 5.0.1 software (Fig. 3.3.3).

Fig. 3.3.1. An example of the Bečva River near Milotice on the map of the Second Military Survey (1836-1852) (source: 2nd Military Survey, Section No. O-7-VII, Austrian State Archive/Military Archive, Vienna).

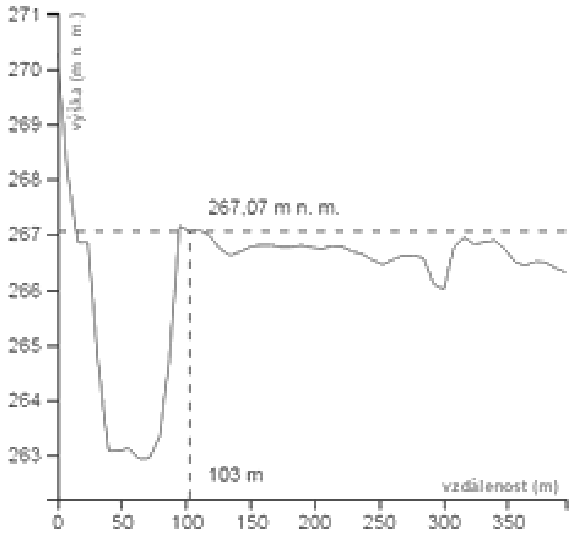

Fig. 3.3.2 Evidence of the channel incision based on floodplain cross-section (data source: DEM 4G, State Administration of Land Surveying and Cadastre).

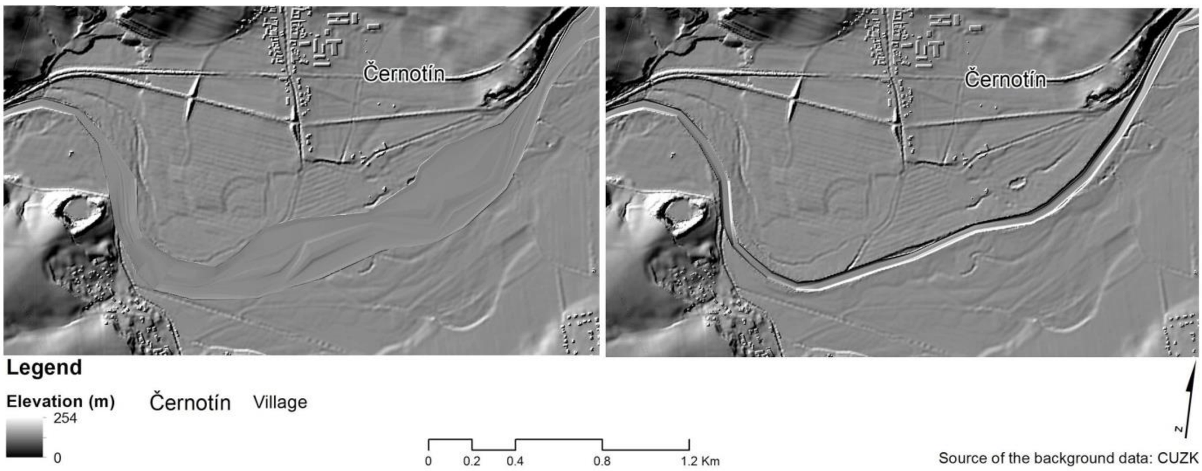

Fig. 3.3.3: Comparison of present (right) and historical (left) river channel (data source: DEM 4G, State Administration of Land Surveying and Cadastre).

The Topľa River represents less regulated gravel-bed river in Slovakia. Typical for the Topľa River channel is its lateral dynamics and distinct bank erosion (Rusnák and Lehotský 2014). In the last 60 years apparent reduction of river channel zone was evident. Average channel width shows the strong decrease from 1949 (62.1 m) to 2009 (37.2 m). This trend is proved also by the decrease of in-channel bar structures (gravel bars) in study area (Fig.

3.3.4). Anthropogenic impact and regulation led to channelization of 5 km long reach in the town Bardejov (Fig.3.3.5). Result of historical changes is straight meandering channel and in contrast to 1949 is river surrounded by riparian vegetation, which was extended around channel on the ends of 80th. The area close to channel was intensively used to agriculture as a mosaic of private plots in the past.

Fig. 3.3.4: Straight meandering channel of the Topľa River near Rokytov with the riparian forest belt on the aerial photo from 2013 (a) (©EUROSENSE, s r. o.) and wide channel on the historical aerial photo from 1949 (b) (Historical orthophotos provide Technical university in Zvolen; Historical orthophoto ©GEODIS SLOVAKIA, s r. o. EUROSENSE, s r. o.; historical aerial photo ©Topographic institute Banská Bystrica).

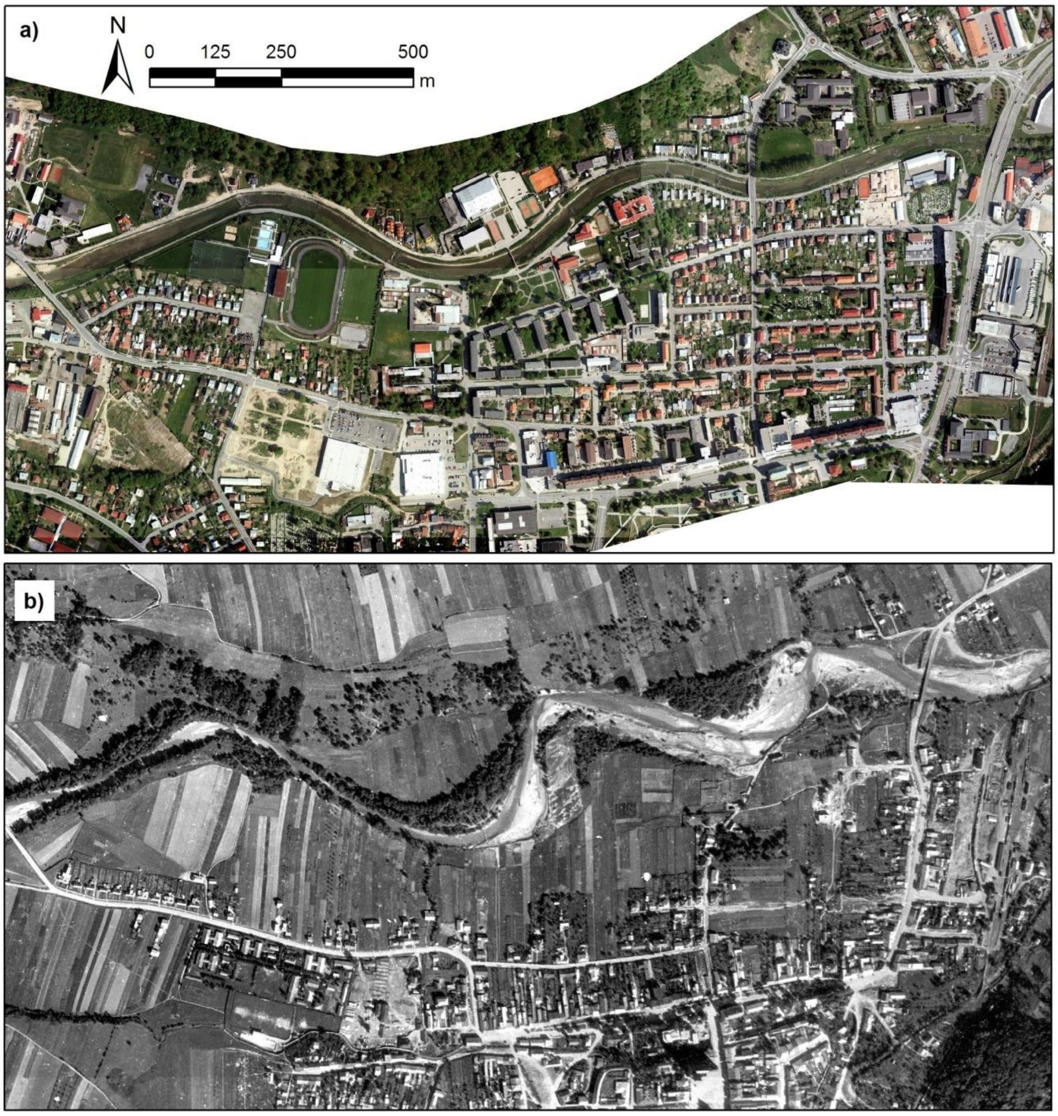

Fig. 3.3.5: Channelized Topľa River in the Bardejov on the aerial photo from 2013 (a) (©EUROSENSE, s r. o.) and sinusoids river channel on the historical aerial photo from 1949 (Historical orthophotos provide Technical university in Zvolen; Historical orthophoto ©GEODIS SLOVAKIA, s r. o. EUROSENSE, s r. o.; historical aerial photo ©Topographic institute Banská Bystrica).

The data about present channel geometry was gathered from geodetically measured cross section, which was used only for reconstruction channel bathymetry. Floodplain geometry was identified from photogrammetrically derived digital surface model, which was created from aerial photos with 10 cm pixel resolution and provided by EUROSENSE company. Data for historical scenario was reconstructed from 1949 aerial photos, where channel cross section was adapted to historical state based on historical channel planform identification. On the Topľa River (in contrast to Bečva River) was not identified channel incision. Relative small incision up to 0.5 - 1 m was taken into account for cross section reconstruction due approximation to historical wide and shallow channel. The final channel elevation model interpolated from cross section was inserted to elevation model from 2013 for hydraulic modelling of historical scenario in HEC-RAS 5.0.1 software (Fig. 3.3.6).

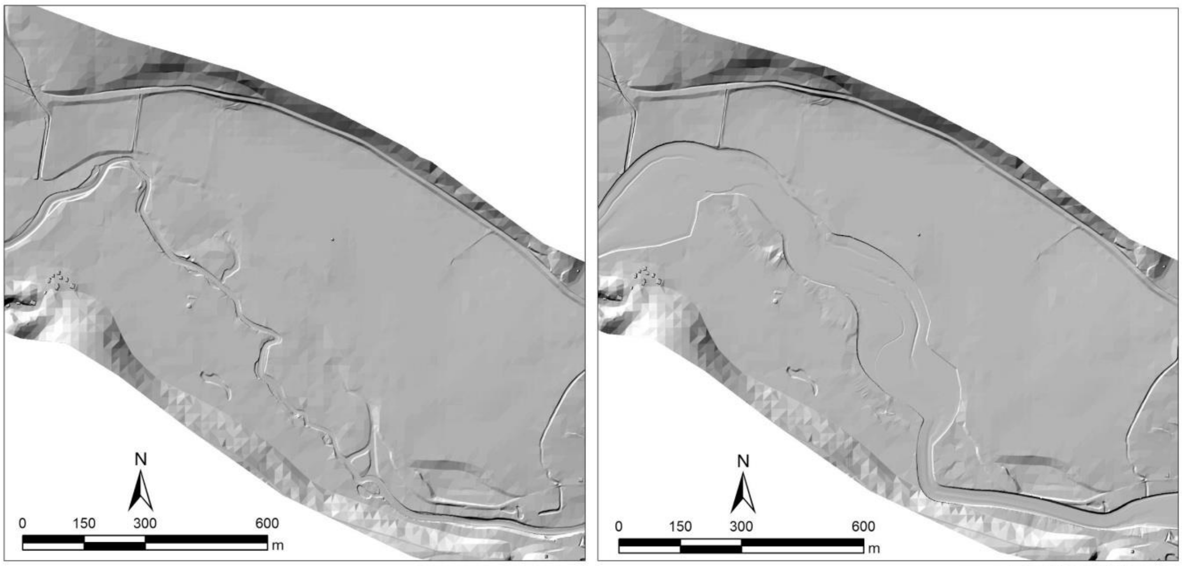

Fig. 3.3.6.: Comparison of present (left) and historical (right) river channel.

3.4 Hydrodynamics simulations

Hydraulic modelling consist from several crucial steps and first one is preparing input geometric data. In case of Bečva River, LIDAR based digital elevation model in raster format with spatial resolution 5x5 m and mean altitude accuracy 0.3 m was obtained and used. Basic source of spatial data of Topľa R. area was digital elevation model in TIN format, which was photogrammetrically derived from aerial photos with pixel resolution 10 cm (provide by EUROSENSE s r. o. company). Although, the photogrammetry and LIDAR based digital elevation models are not able to capture terrain under water surface, bathymetry information was added from geodetically measured cross sections.

Information about buildings as obstacles for water flow was added as a shape layer and uniform height of 6 m was linked to every building in case of Bečva River.

Obstacles for water flow on the floodplain was obtained from ZB GIS geodatabase (source: Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012)), where was used polygon layer buildings ("*budova*") with attribute height for generation 3D model of real buildings.

The final elevation model was created for both rivers by combination of raster elevation model with pixel resolution 0.5 m generated from TIN, raster elevation model of channel interpolated from cross section and 3D models of buildings in HEC RAS 5.0.1 software (Fig.3.3.7).

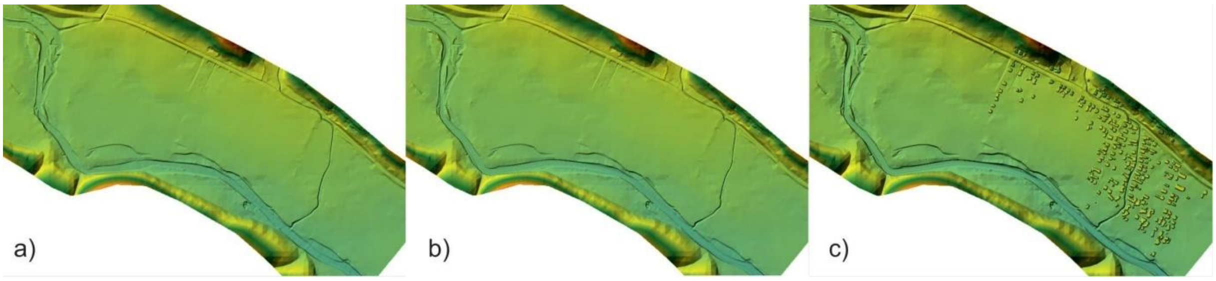

Fig. 3.3.7. Comparison of photogrammetry derived DEM for present scenario (a), photogrammetry derived DEM combined with channel bathymetry (b) and DEM combined with channel bathymetry and buildings (c) for Topľa River (source data: ©EUROSENSE, s r. o. and Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012)).

Basic spatial dataset for historical scenario was created in the same way in HEC RAS from raster models of floodplain (from TIN) and buildings, whereas channel raster was generated from reconstructed cross section based on historical aerial photos from 1949 (Fig. 3.3.8).

Land cover and land use spatial information was vectorized in ArcGIS software from present photos and historical time horizon. Overall, 14 land cover category was identified: bare area, swimming pool, buildings, road, urban area, channel, shrubs, gravel bar, forest, arable land, car park, grassland, gardens and railway.

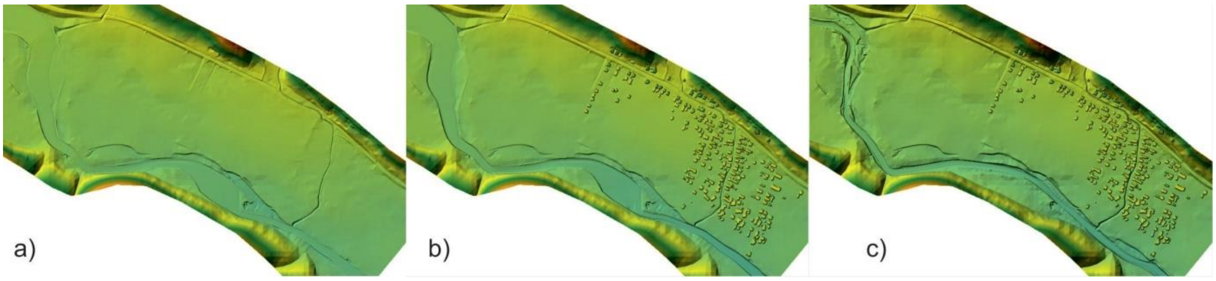

Fig. 3.3.8. Comparison of photogrammetry derived DEM combined with reconstructed channel cross sections (a), DEM combined with channel bathymetry and buildings for historical scenario (b) and for present scenario (c) for Topľa River. (source data: ©EUROSENSE, s r. o. and Geodesy, Cartography and Cadastre Authority of Slovak Republic (122-24-99-2012)).

Second important type of input data were hydrological records, described in detail in chapter 3.1. For hydrodynamics simulation HEC RAS 5.0.1. software was used, which contains analysis components for 2D modelling. For spatial data preparation, the ArcGIS extension HEC-GeoRAS was used, while the data were exported to HEC-RAS afterwards. Data were analyzed in S-JTSK (Krovak East North) coordinate system and elevation models (present and historical) with land cover rasters (present and historical) were imported with pixel resolution 0.5 m.

Next step in geometric editor was creation the 2D flow area with computation mesh spacing 25 m (cell size) and imported breaklines in places of channel and terrain edges with spacing 10 x 10 m. Manning values was set to land cover category in Manning's *n* table.
Bridge and dams in Hranice town were added to the model. No bridges were modelled in case of Topľa River.

Methodology for calibration was identical for both rivers and was done only for present scenario. Overall 3 boundary condition were selected at the mesh (3 of type Flow Hydrograph) at the positions of gauging stations and one downstream at the mesh (of type Normal Depth) for calibration on timing of flood peak. Two boundary conditions were created, one upstream of the mesh (of type Flow hydrograph) and one downstream of the mesh (of type Normal Depth).

Unsteady flow analysis was performed with computational step of 10 second. This time step was the same for both scenarios (I. and II.) and for N-year recurrence interval discharge Q_1, Q_5, Q_{20} and Q_{100}. Cell size and computational time step was selected based on Saint Venant Equations (full momentum):

$$\Delta T \leq \frac{\Delta X}{V} \; (with\; C = 1.0)$$

where

C = Courant Number

V = Flood wave velocity (m/s)

ΔT = Computational time step (s)

ΔX = Average cell size (m).

Model was calibrated by adjusting manning's n model parameters. Simulated discharge was calibrated for timing of flood peak and for value of maximum flood peak with the Manning's n-values and compared with observed flood hydrograph in gauging station Teplice (Bečva) and Bardejov (Topľa).

4 Results

4.1 Bečva River

The calibrations of present scenarios for the Bečva River were finished with the parametrization of model described in chapter 2. The results showed the best values of manning n-values for river as follows: river channel 0.035, floodplain 0.06. The hydrographs describing the flood are shown in Fig 4.1 and 4.2. Lower flows observed during the calibration for timing of flood peak on Fig. 4.1 is caused by missing information about the inflows from not gauged tributaries. Shifts of hydrographs on Fig. 4.2 is caused by flood attenuation from the beginning of modelled reach to the end.

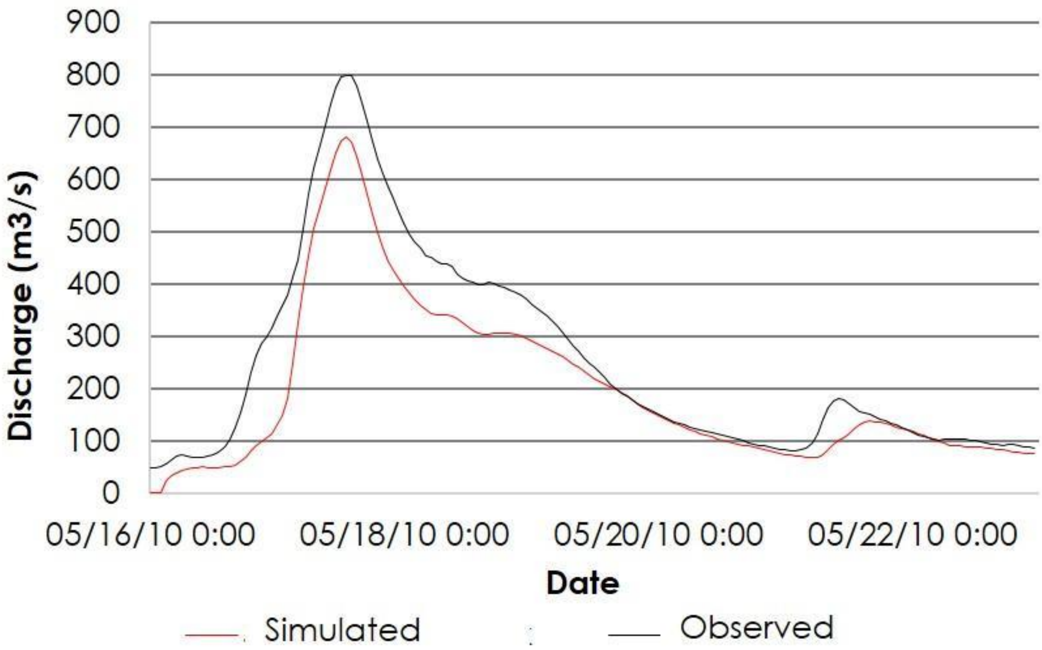

Fig. 4.1: Calibration for timing of flood peak for the Bečva River.

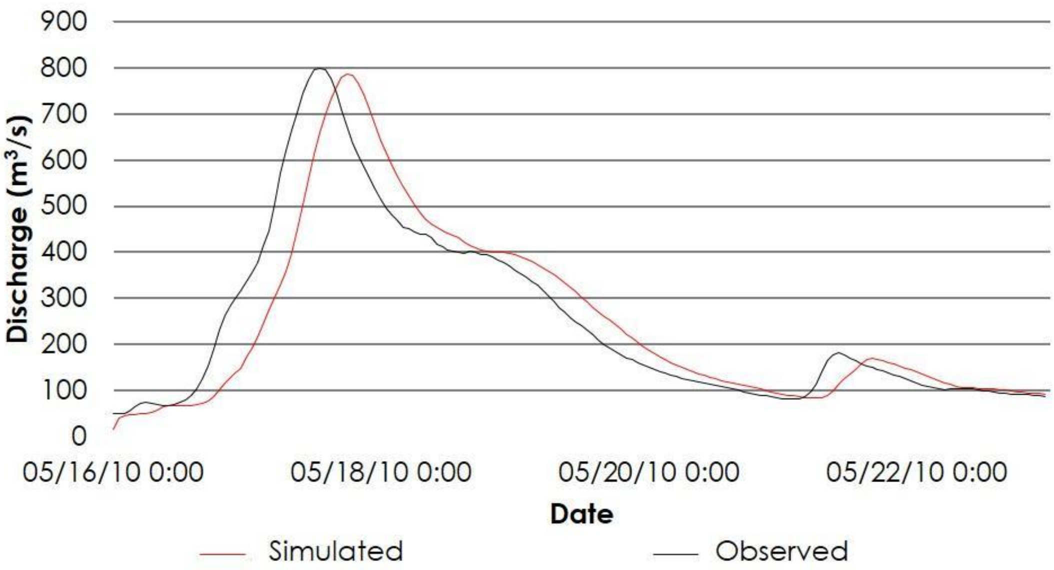

Fig. 4.2: Calibration for value of maximum flood peak for the Bečva River.

Hydraulic modelling for present and historical scenario and for recurrence interval of N=1,5,20 and 100 was performed with the Manning n-values found by calibration. The results are described by Fig. 4.3 – 4.6 and in Table 4.1.1. The highest difference between the present and historical scenario was found in the recurrence interval N=1, where flood attenuation of 5 hours was observed, together with small decrease of flow (Table 4.1.1) as a result of floodplain storage. Next recurrent interval of N=5 showed flood attenuation of two hours and river storage is still remarkable. The small increase of maximum peak is observed. Recurrence interval N=20 shows only a hour attenuation, but higher increase of maximum discharges in historical scenario. The highest flood of recurrence interval equal to 100 has the same time of maximum peak time and again higher number of maximum peak discharge in historical scenario. The higher numbers of discharges are highly negative and can cause higher flood risk.

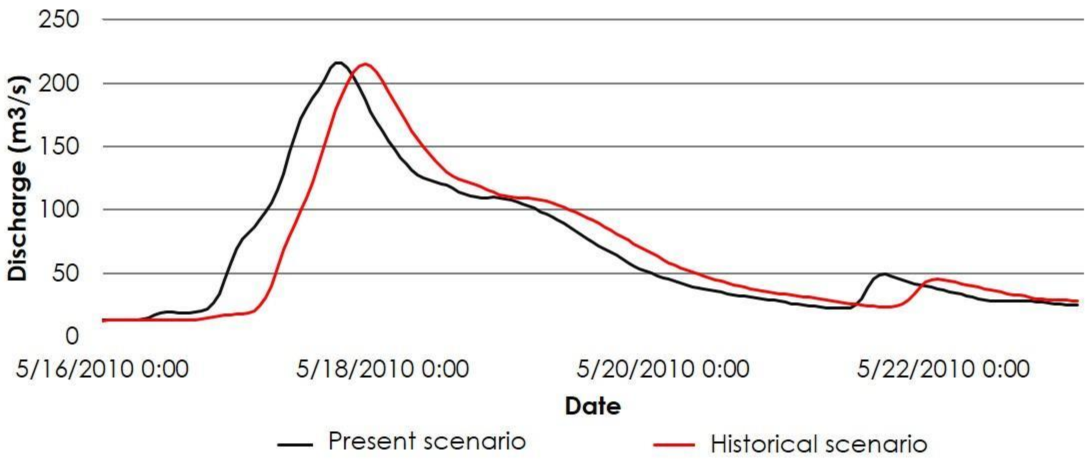

Fig. 4.1.3: Comparison of present and historical scenario of recurrence interval N=1 for Bečva River.

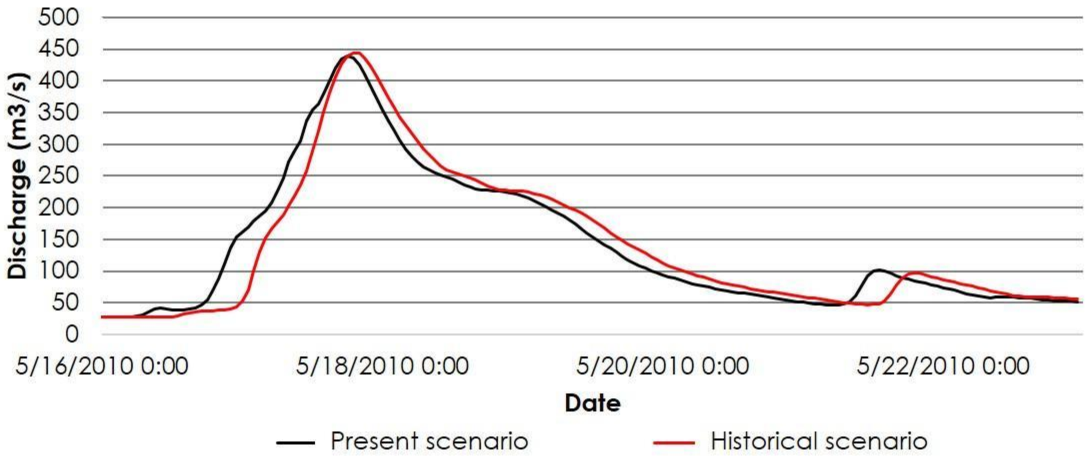

Fig. 4.1.4: Comparison of present and historical scenario of recurrence interval N=5 for Bečva River.

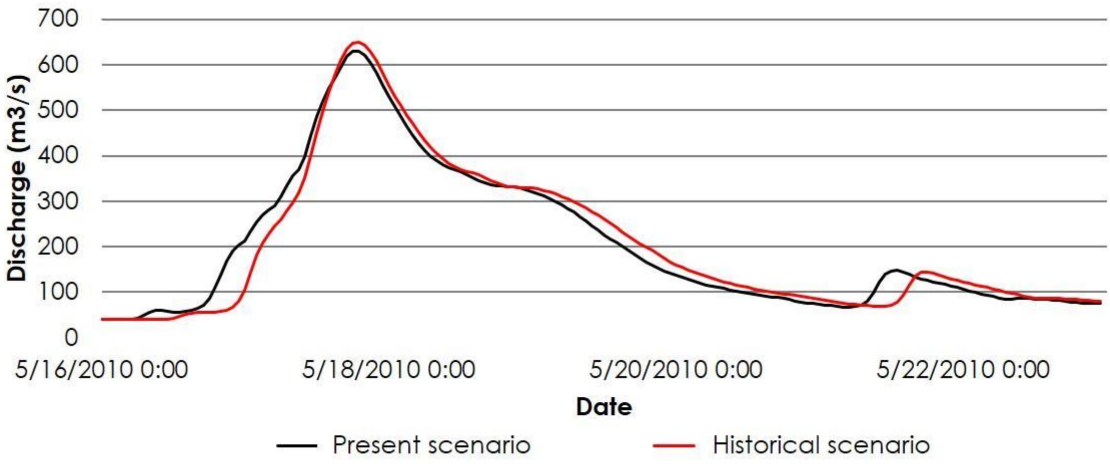

Fig. 4.1.5: Comparison of present and historical scenario of recurrence interval N=20 for Bečva River.

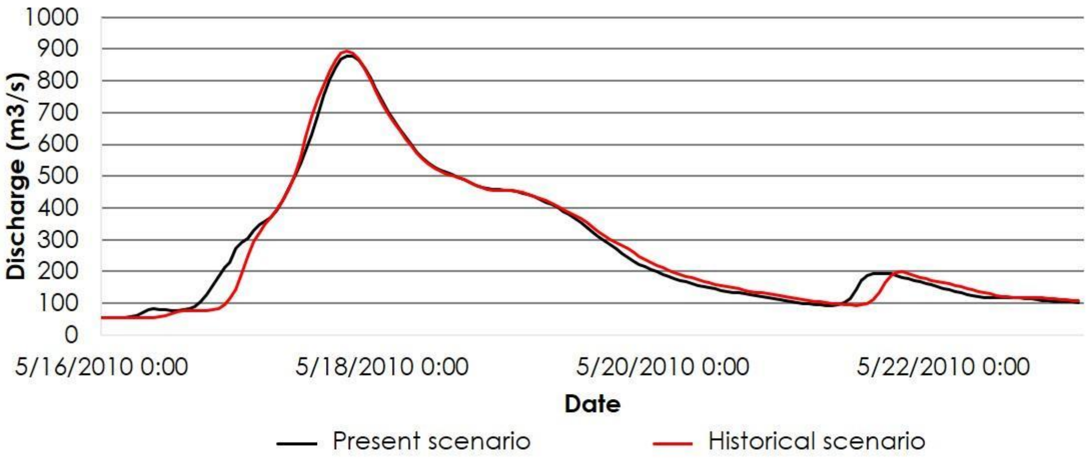

Fig. 4.1.6: Comparison of present and historical scenario of recurrence interval N=100 for Bečva River.

Tab. 4.1.1: Results of present (I.) and historical (II) scenario modelling for selected N-year recurrence interval discharge for Bečva River.

N-year recurence interval discharge	Q_1		Q_5		Q_{20}		Q_{100}	
Scenario	I.	II.	I.	II.	I.	II.	I.	II.
Inundated Area (km²)	2.45	10.63	6.56	13.43	10.63	14.33	15.59	20.38
Time of maximum peak flow	16:00	21:00	18:00	20:00	18:00	19:00	18:00	18:00
Maximum peak (m³/s)	216	215	439	443	631	650	878	894

Because the upper and lower part of the reach was left to the present state (Fig. 3.1.3), highest depths are the same in both scenarios. However by looking at the flood extent there is clearly correlation between the flood attenuation described previously in N=1 (Fig. 4.13) and flood extend showed at Fig. 4.17). During this flood, the inundated area in present scenario is almost everywhere in the channel and no interaction between the floodplain is observed. This is a result of high channel depth in present scenario comparing the historical one. This fact is demonstrated by Table 4.1.1, where the inundated area is almost tripled in historical scenario. In N=5 we can still observed the doubled inundated area, however the ratio is decreasing by increasing the flood magnitude.

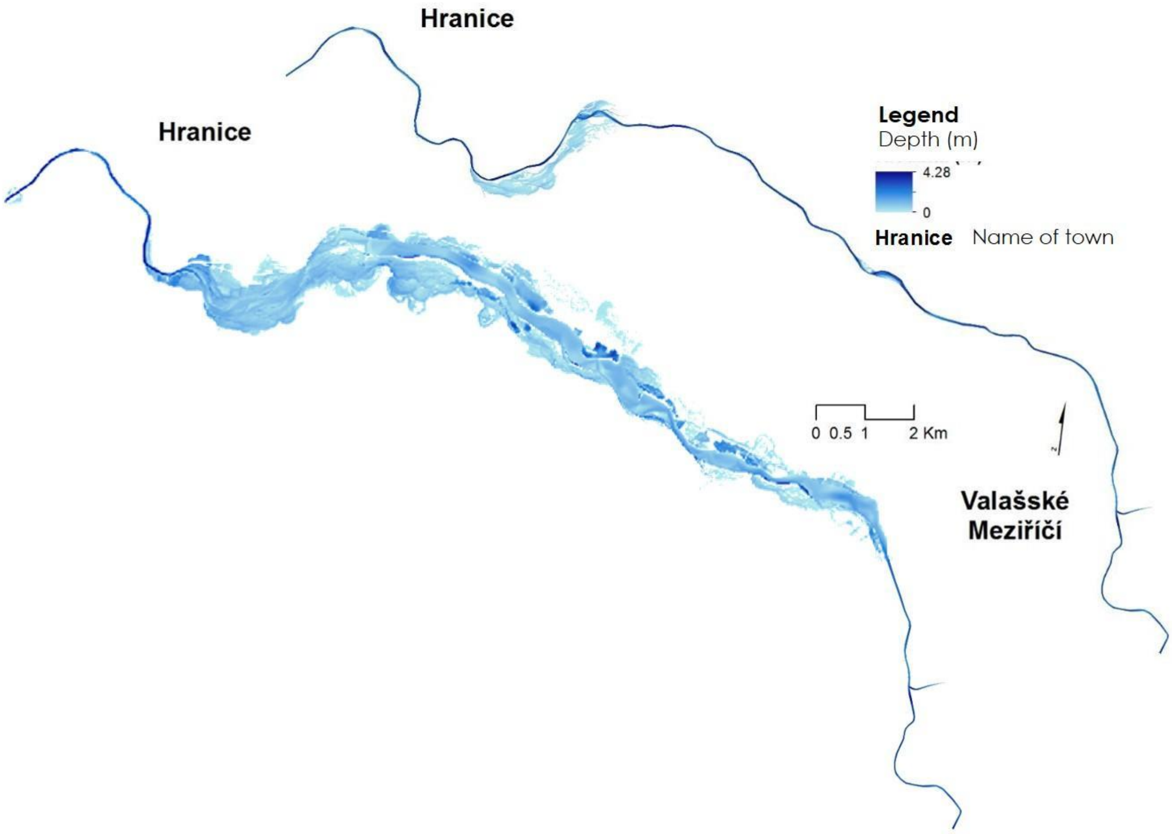

Fig. 4.1.7: Depth of water occurred during the flood of Q_1 for present (upper) and historical (lower) scenario.

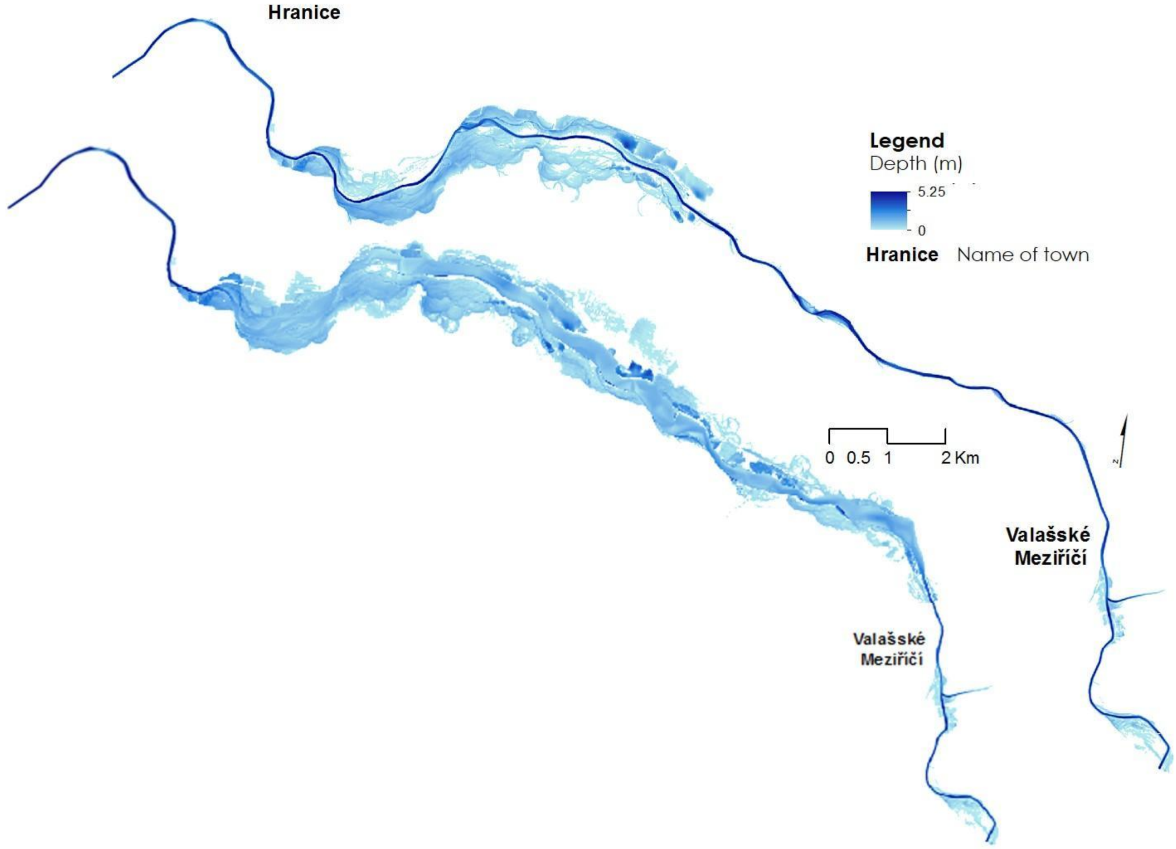

Fig. 4.1.8: Depth of water occurred during the flood of Q_5 for present (upper) and historical (lower) scenario.

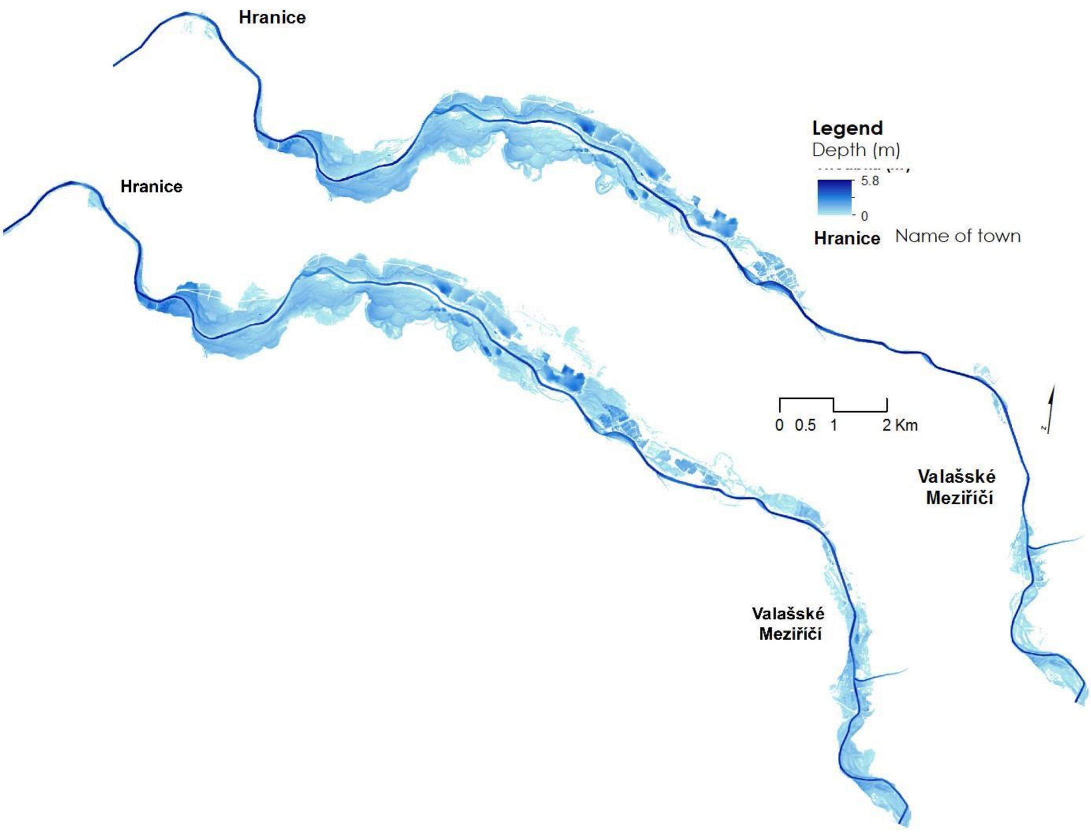

Fig. 4.1.9: Depth of water occurred during the flood of Q_{20} for present (upper) and historical (lower) scenario.

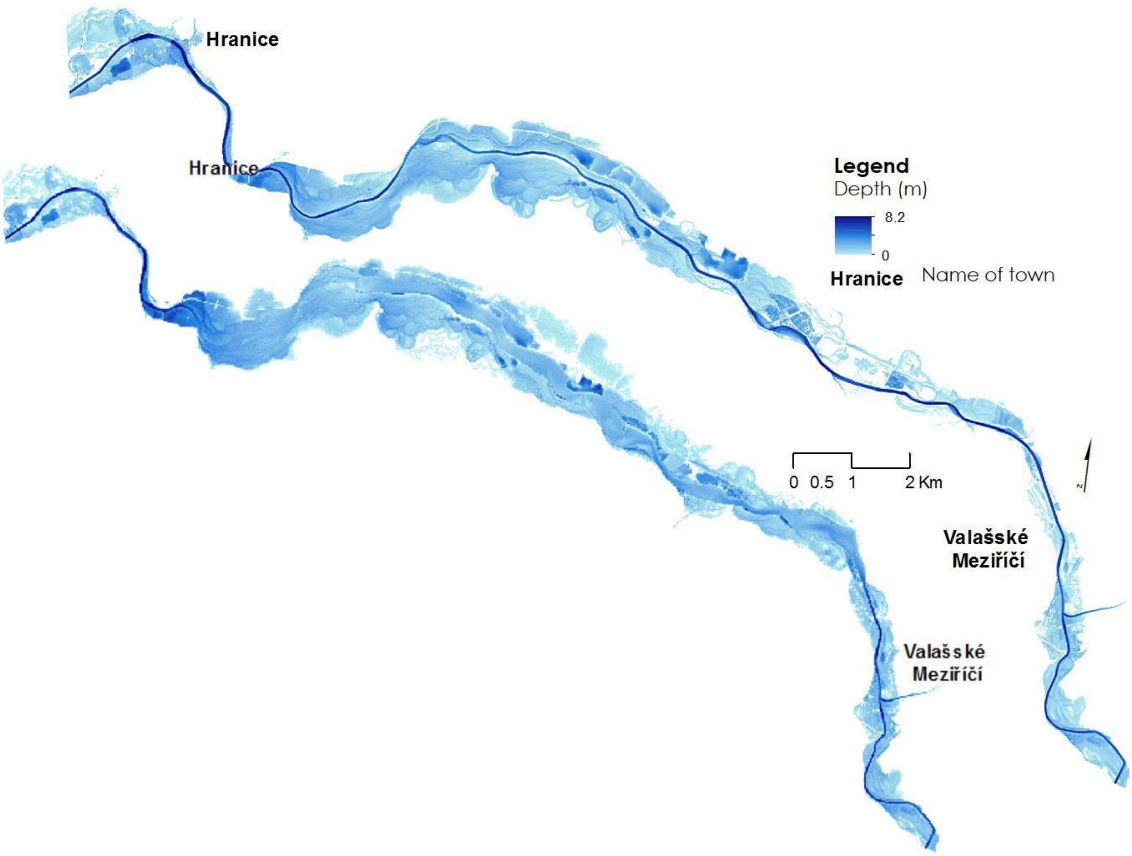

Fig. 4.1.10: Depth of water occurred during the flood of Q_{100} for present (upper) and historical (lower) scenario.

4.2 Topľa River

The calibrations of present scenarios for the Topľa River were finished with the parametrization of model described in chapter 2. The results showed the best values of manning n-values for river as follows: river channel 0.035, floodplain 0.06. The hydrographs describing the flood are shown in Fig 4.2.1 and 4.2.2. Lower flows observed during the calibration for timing of flood peak on Fig. 4.1 is caused by missing information about the inflows from not gauged tributaries. Shifts of hydrographs on Fig. 4.2.2 is caused by flood celerity through the channel and floodplain.

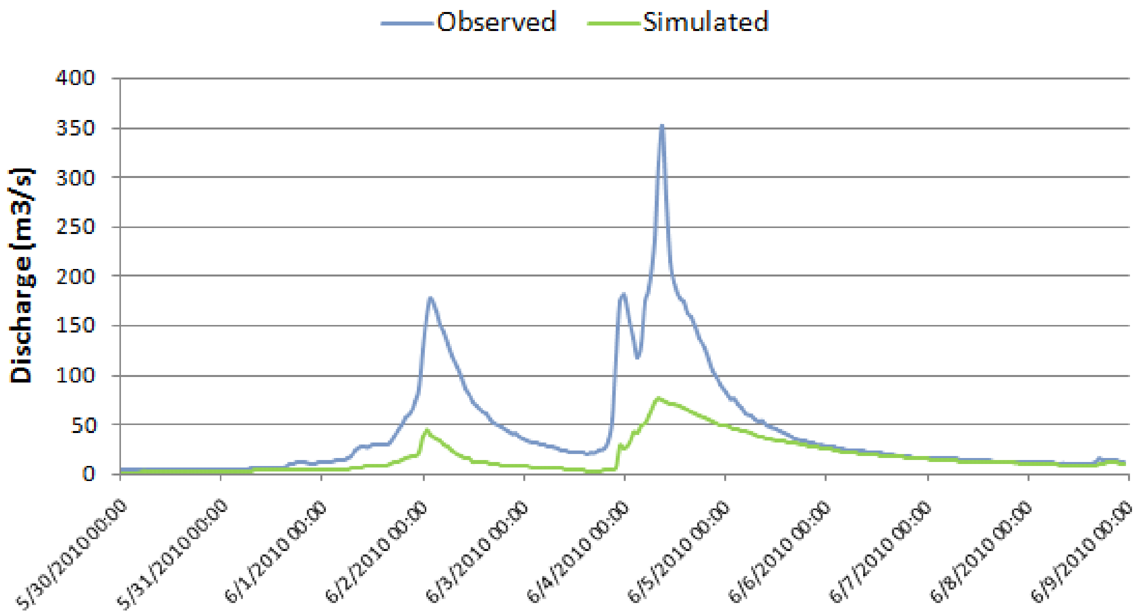

Fig. 4.2.1: Calibration for timing of flood peak for Topľa River.

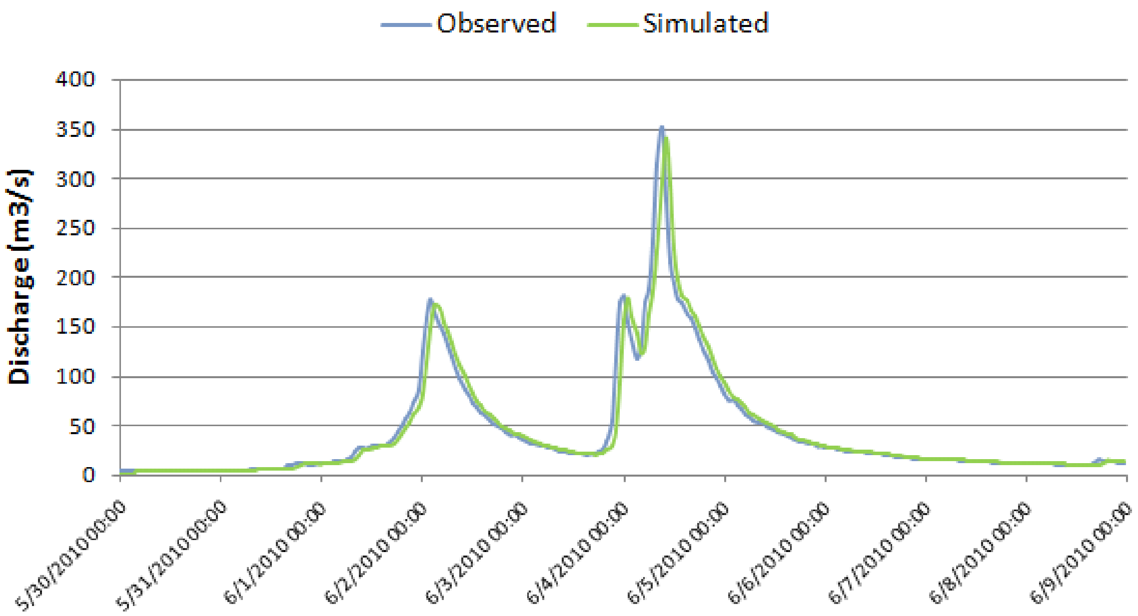

Fig. 4.2.2: Calibration for value of maximum flood peak for Topľa River.

Hydraulic modelling was performed for 2 scenarios (present and historical) for 4 different discharges defined base on N-year recurrence interval (Q_1, Q_5, Q_{20} and Q_{100}). For comparison of present and historical scenario we focus on changes in inundation area and changes in hydrographs on the end of the study area. Evident is similar graph pattern between historical and present modelling of flood events (Fig. 4.2.3 – 4.2.10). Variations in graphs are negligible between I. and II. scenario and differ only in the maximum peak discharge in the each individual recurrence interval. Similarly like notes Table 4.2.1, shift in the time of maximum peak flow was not proved.

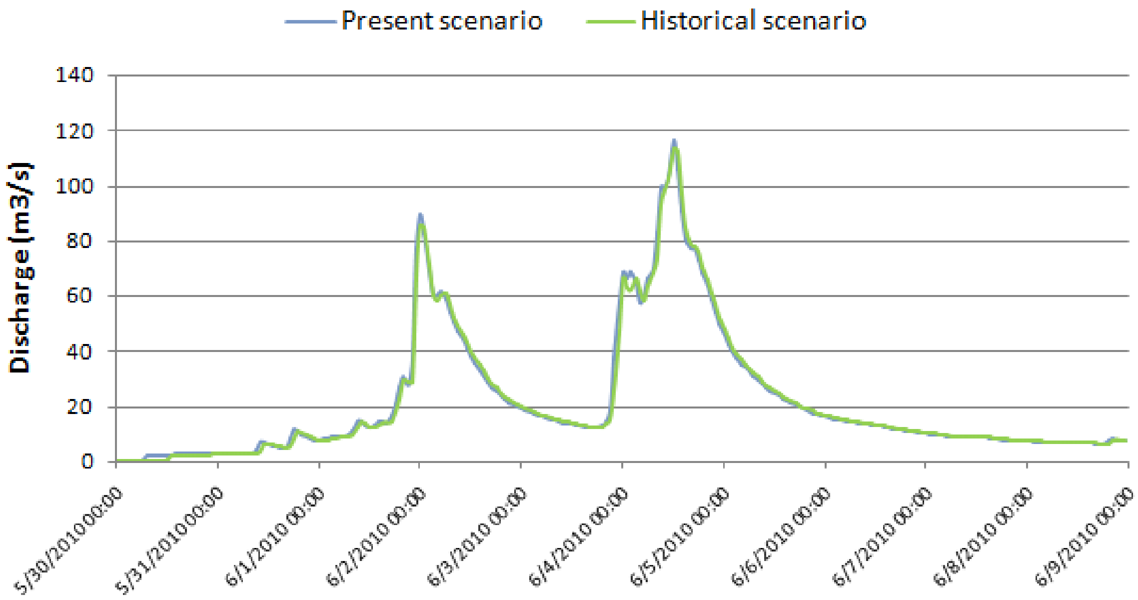

Fig. 4.2.3: Flow hydrograph of N-year recurrence interval discharge Q_1 modelled for present and historical scenario.

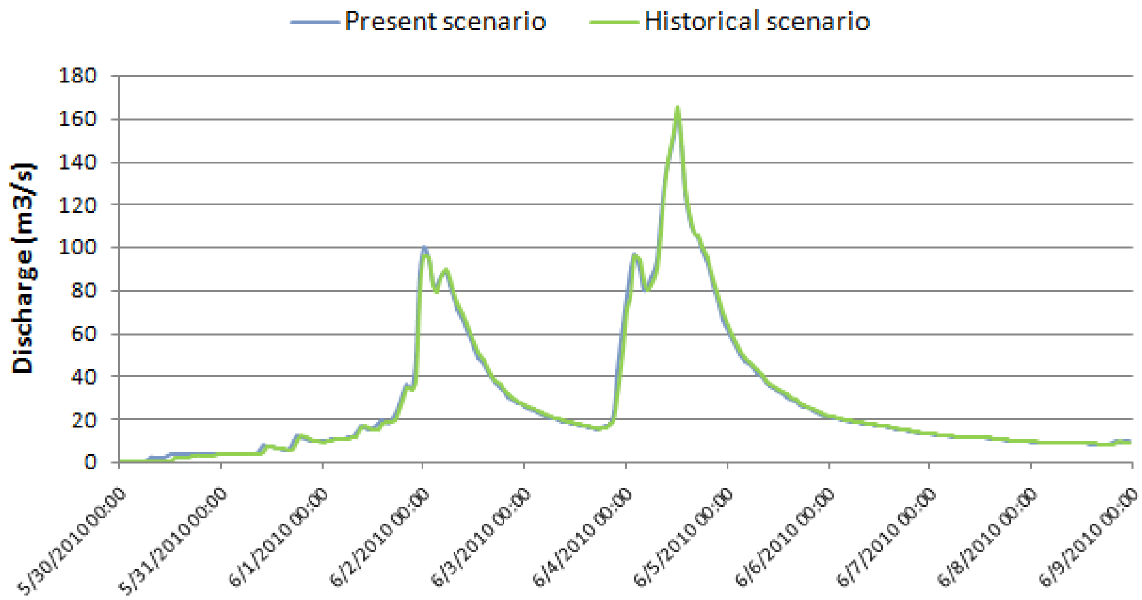

Fig. 4.2.4: Flow hydrograph of N-year recurrence interval discharge Q_5 modelled for present and historical scenario.

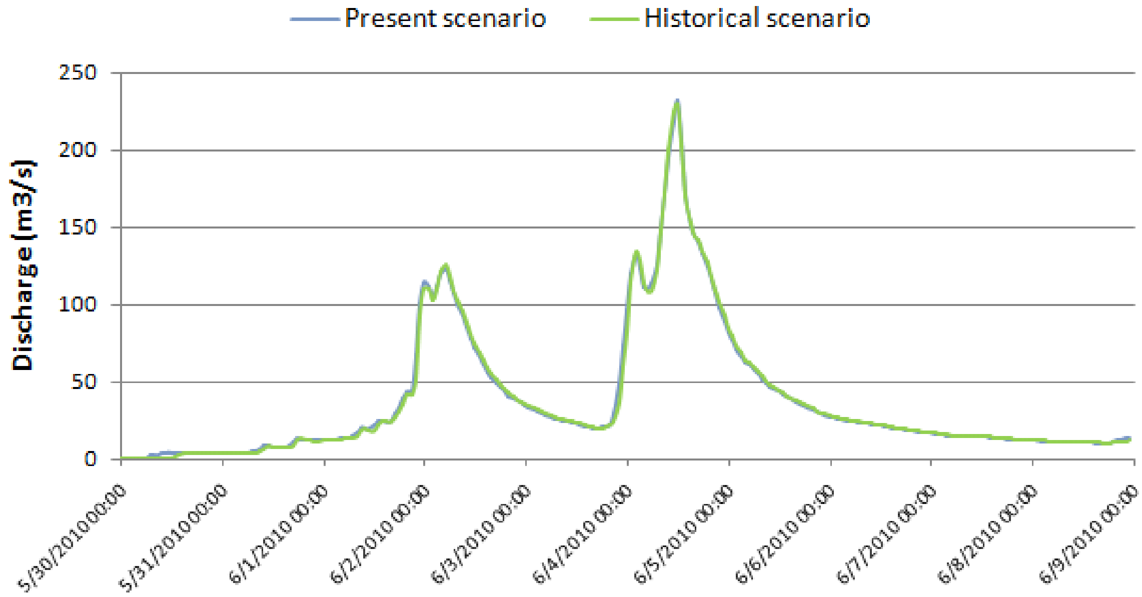

Fig. 4.2.5: Flow hydrograph of N-year recurrence interval discharge Q_{20} modelled for present and historical scenario.

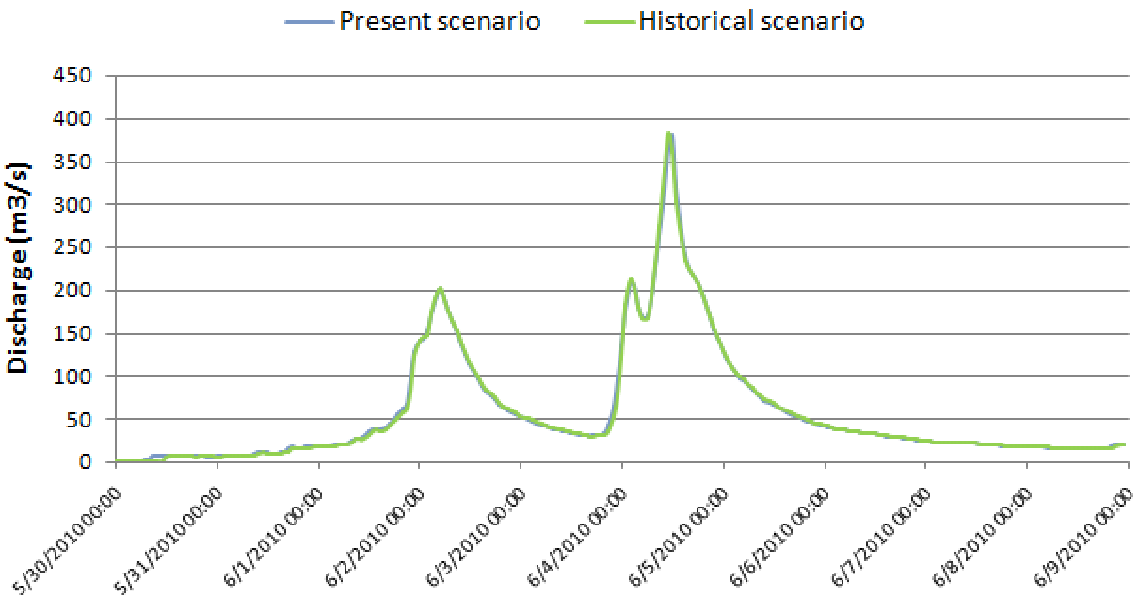

Fig. 4.2.6: Flow hydrograph of N-year recurrence interval discharge Q_{100} modelled for present and historical scenario.

Tab. 4.2.1: Results of present (I.) and historical (II) scenario modelling for selected N-year recurrence interval discharge for Topľa River.

N-year recurrence interval discharge	Q_1		Q_5		Q_{20}		Q_{100}	
Scenario	**I.**	**II.**	**I.**	**II.**	**I.**	**II.**	**I.**	**II.**
Inundated area (km^2)	1.61	2.55	2.52	2.93	3.43	3.50	4.68	4.48
Time of maximum peak flow	12:00	12:00	12:00	12:00	12:00	12:00	12:00	11:00
Maximum peak (m^3/s)	116	113	163	165	231	230	378	383

Major differences are observed in inundation area changes between present and historical scenario. Flooded area is smaller for present scenario when recurrence interval of peak discharges is less than 50-year. For 1-year recurrence interval discharge is inundation area 1.61 km^2 for scenario I. and 2.55 km^2 for historical scenario what representing 158 % of flooding area in 2013. For 5-year recurrence interval is it only 116 % and for 20-year recurrence interval are flooding area approximately equal (3.43 km^2 for scenario I. and 3.50 km^2 for scenario II.). Unexpected is, that inundation area during high magnitude floods (Q_{100})

is higher for present scenario. Flooded area in 2013 is 4.68 km^2 and 4.48 km^2 in 1949 simulation.

Identification of inundation area in longitudinal directions is important for flood hazard and flood risk assessment. Necessarily is evaluation not only extent of inundation but also complex vulnerability of systems based on combination hazard, vulnerability and sensitivity research of individual system components. For 1-year recurrence interval is flooding located mainly in the zone of channel (Fig. 4.2.7) and only the areas on floodplain near village Mokroluh and north from village Komárov are affected by flooding in present scenario. In historical scenario is flooded area at the confluence of Kamenec creek and the Topľa River. Inundation area expands with the increasing magnitude of flood events for each N-year recurrence interval (Fig. 4.2.7- 4.2.10). During floods with 100-year recurrence interval in scenario I. as well as scenario II. is mostly affected zone between village Mokroluh and Komárov (Fig. 4.2.10). Noticeable is a change in the spatial distribution between inundation simulated for year 1949 and 2013. In 1949 reaches flooded area larger extent in the zone of city Bardejov and vice versa in the area above and under this zone is inundation smaller and inundation boundary are closer to the channel. It is important to note that in the project was flooding in the town Bardejov modelled without artificial embankment, which was omitted for the simulation in scenario I.

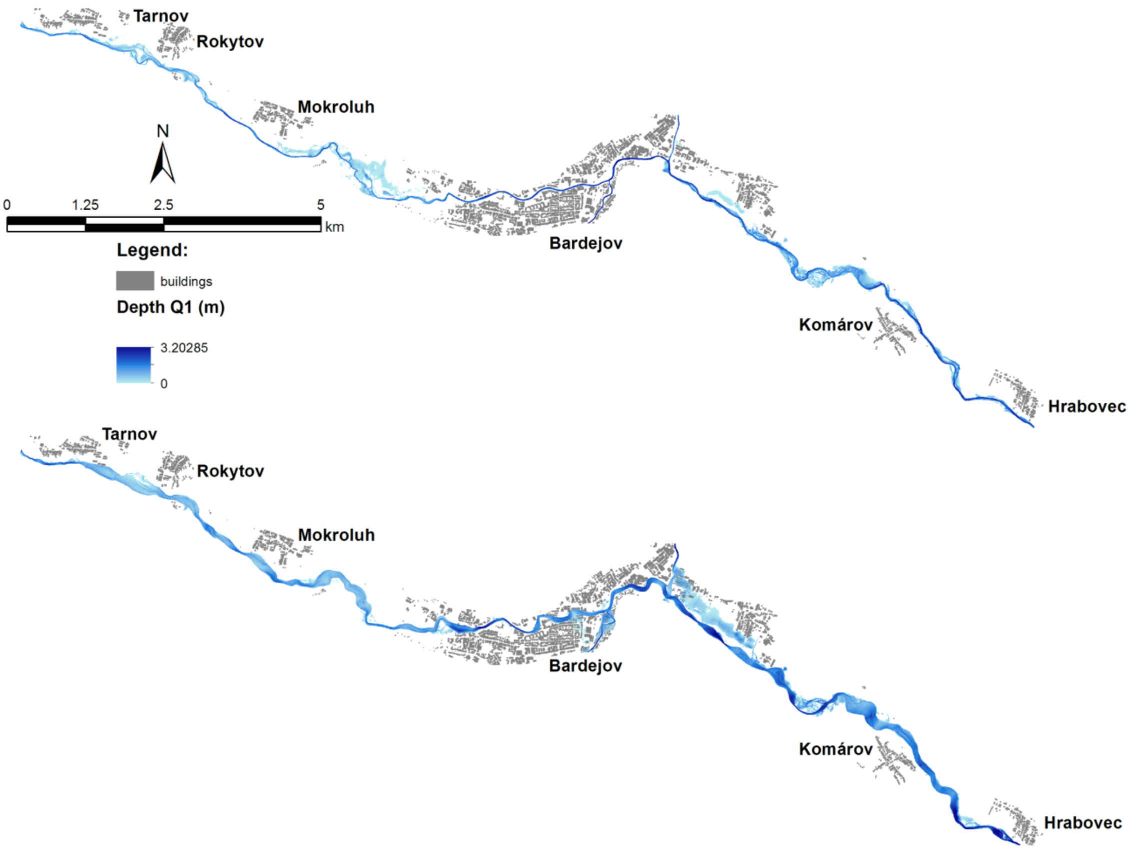

Fig. 4.2.7: Depth of water occurred during the flood of Q_1 for present (upper) and historical (lower) scenario.

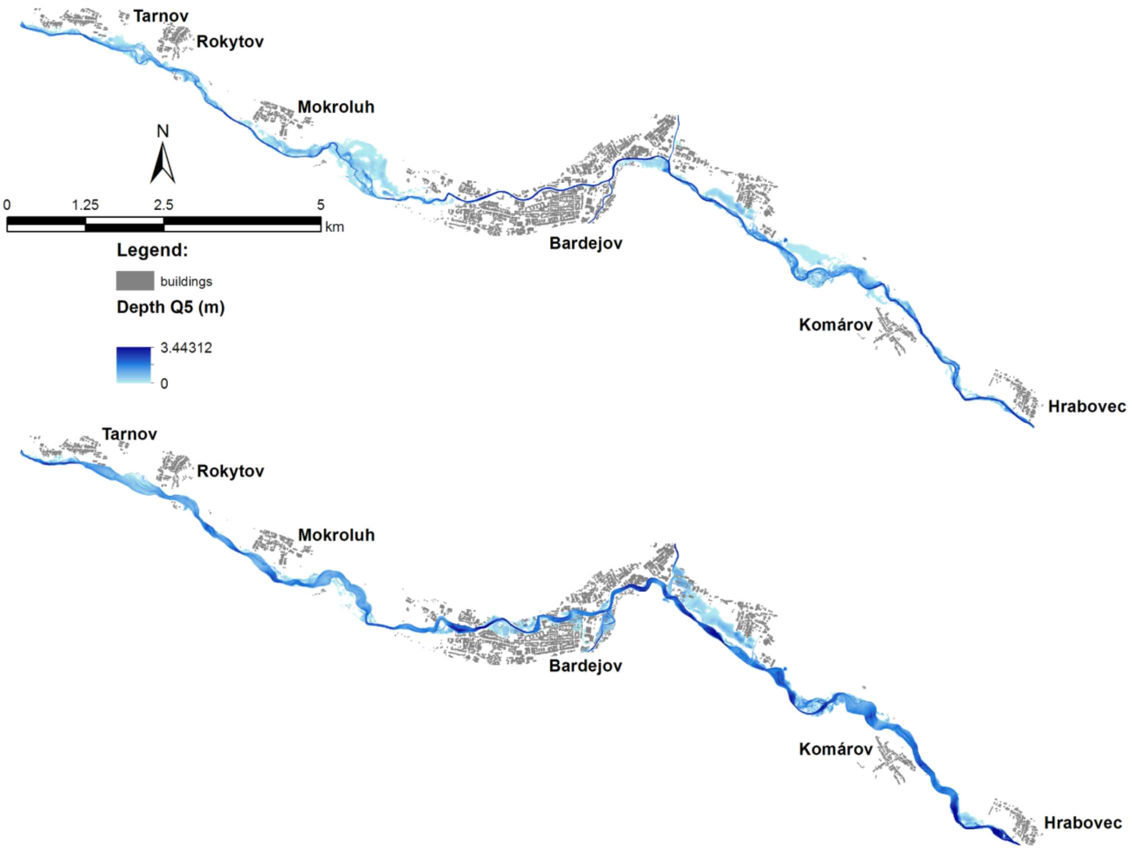

Fig. 4.2.8: Depth of water occurred during the flood of Q_5 for present (upper) and historical (lower) scenario.

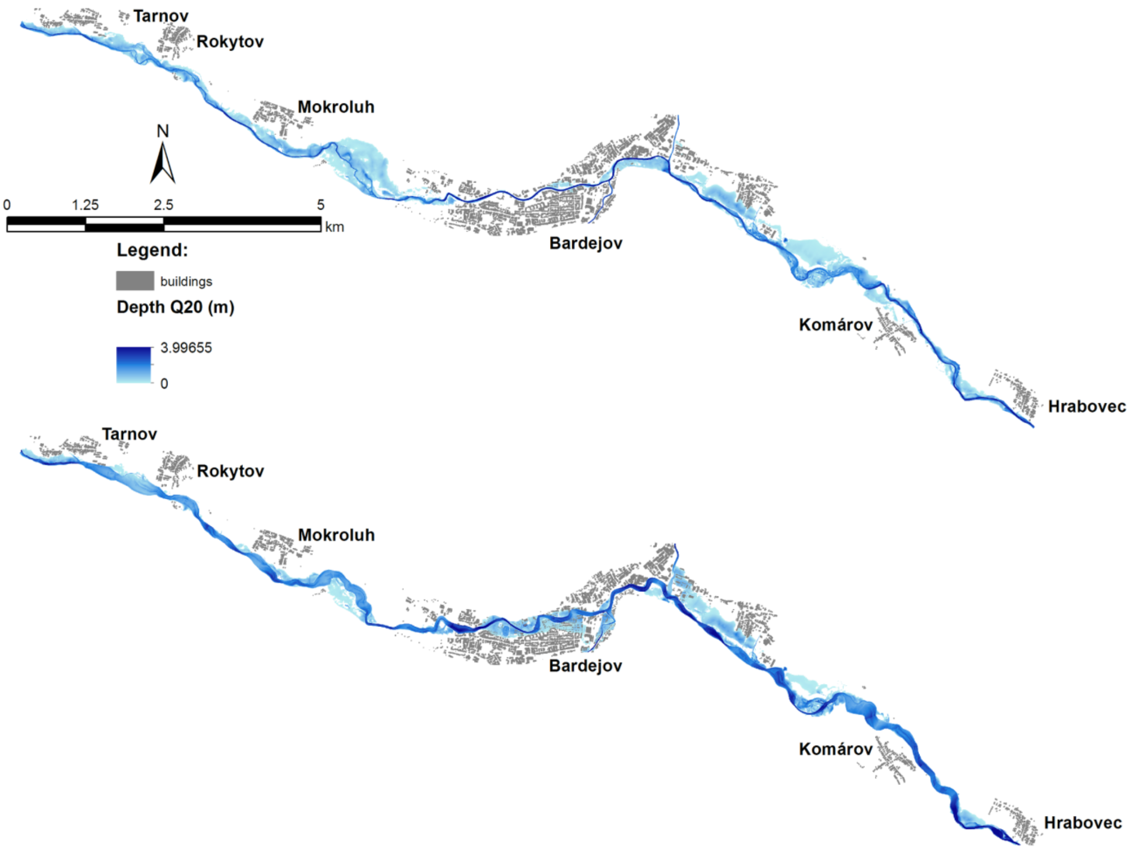

Fig. 4.2.9: Depth of water occurred during the flood of Q_{20} for present (upper) and historical (lower) scenario.

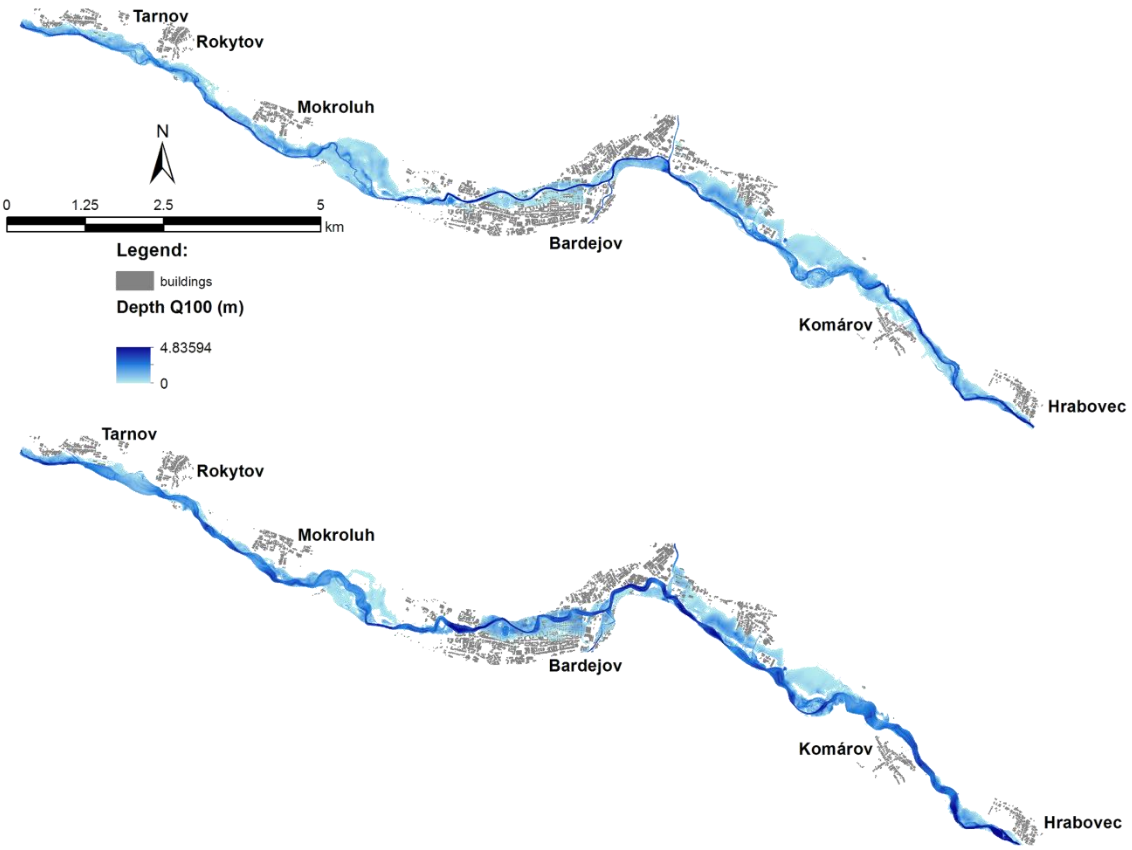

Fig. 4.2.10: Depth of water occurred during the flood of Q_{100} for present (upper) and historical (lower) scenario.

5 Discussion

5.1 Implication of results

Understanding the river system in their natural environment in the context of other components of landscape makes it possible to predict the future development of the stream and minimize flood hazard, what lead to simplify the co-existence of humans and the river and to limit the negative man-made interferences into streams. The Topľa River reach as the unconfined gravel bed river system is typical for its migratory behaviour and dynamic. But it is still one of the few scarcely trained river reach in the Slovak Republic and, therefore, ideal for contemporary monitoring. It is also necessary to bear in mind that flooding is natural processes. "Green" approach is now preferred worldwide which avoids technical interventions into the channels and the rivers are left to meander in the certain area (Piégay et al., 2005) or in certain reaches freely (Piégay et al., 1997). Piegay et al. (1997) also point out that active restrictive interventions in channels are expensive and result in a spiral effect leading to degradation of streams and increased flood risk.

Channel incision in case of the Bečva River caused smaller innundation area in everry recurrence intervals modelled. The main effect was found in the scenario N=1. The others shows flood attenuation (except the N=100, where the timing is the same) and negative effect of increased maximum discharges.

Identical hygrograms of flood wave from year 2010 modelled in scenario I. and scenario II. point to similar character of channel morphology. Although is recorded channel width reduction in the last 60 years from average 62.1 m in 1949 to 37.2 m in 2009, river is preserved its natural state with minor anthropogenetic interventions. Thus, the Topľa R. as a meandering river is deemed to be „robust" if, over decades, it steadily migrates creating bars/point bars, which, in turn, are incorporated into a new floodplain, but yet retains its characteristic morphology of pools, riffles, undercut banks and bars/point bars. But this can be described as "robust" behaviour within existing intrinsic thresholds, rather than "responsive" behaviour crossing extrinsic thresholds (Werritty and Leys, 2001). Length of the stream centreline in 1949 was 22.3 km, in 2013 it was 21.5 km and index of sinuosity remained similar, too. Effect of morphological changes, which do not affect "robust" behaviour of the channel, on hydrological regime during flood events can be small.

It is necessarily to note, that for historical scenario modelling in HEC-RAS was used data from present flood events and not historical flow data.

Differences are observed in inundation area in both rivers. Much higher are present in case of the Bečva River, due to high channel incision. For the case of Topľa River, flooded area is smaller for scenario I. when recurrence interval of peak discharges is less than 50-year and larger for 100-year flood. When evaluating differences in area of flooding is it important to consider, that channel area in historical scenario was larger than now, because channel width (area) is larger. In low magnitude events (scenario II) factor of channel area has more influence to flooding extent. With the capacity of channel are linked differences between inundation in the town Bardejov and in natural channel above and under the town. For recurrence interval 100-year was flooded area smaller only in the town Bardejov (present scenario), because artificial channel has sufficient capacity for transfer of flood wave. Outside channelized area changes in channel morphology (narrowing the channel) led to decreasing of channel capacity and floods have larger extent.

Changing morphology and their aspect to hydraulic properties of channel is important for good assessment of hydromorphological quality of river with a identification of general trend and behaviour with emphasise to environmental changes in landscape. Knowledge of long-term history of river and communication between local or government water authorities, municipalities, non-government organisation and scientist was identified as a main challenge for properly management of river ecosystem at the workshop: Morphological changes in the riverbed and their impact on flood risk hold in Bardejov. Closer cooperation is important for application such interventions, that will have minor effects to channel morphology and ecosystem quality. We and all participants presented that cooperation (established at the workshop) will continue in the future.

5.2 Uncertainties

Modelling of river processes and flood hazards provides an opportunity to quantify and interpretation of the process-response relationship in the river system and enable precise spatial-temporal analysis of riverine landscape. Their accuracy and quality depends on precision of input data, model calibration and model algorithms. Hydrodynamics simulation

(2D simulation) was performed in HEC RAS 5.0.1., which is considered as robust and reliable freely available hydraulic modelling software for both scenarios with identical settings.

Quality of input data depend on precision and resolution DEMs used. The maximal errors occur on vegetated floodplain and areas under the water, because the principal problem of DEMs used in this study is that cannot capture terrain under vegetation cover or water. Bathymetry data was added by geodetic cross section measurement and uncertainty on the floodplain topography are negligible in our research scale. Models were calibrated by timing of flood peak and value of maximum flood peak. Final inundation for scenario I. was manually checked by official government flood hazards map s in both cases and results was identical.

The bridge and a dam was modelled in the Hranice town as a real obstacles during the flooding, however no such structures were in-built into the model of Topľa River. By using these structures, the flood risk can be increased locally, but could not change results of this study significantly.

Most uncertainties resulted from historical scenario, where channel was reconstructed from historical maps and aerial photos, where channel cross section was adapted to historical state based on historical channel planform identification.

6 Main conclusions

- The project represents the pilot study estimating changes in flood risk by restoration of original river patterns and reconnection of floodplains to channels.
- Hydraulic simulations in studied river reaches show, that lowering of peak flood discharges by restoration of the original channel and increased flood inundation is important only for high-frequent, low magnitude flows $<Q_5$.
- Original floodplains were probably not able to significantly transform high-magnitude floods.
- All flood inundations are more intensive in the case of historical scenarios for the Bečva River when compared to present situation. On the other hand, the Topľa River displayed different behaviour with larger inundated areas during present scenario and high-magnitude ($>Q_{50}$) floods; for smaller flood events, the inundations were larger for historical scenarios.
- The differences between two rivers can be found by comparison of levels of anthropogenic changes. While in the case of the Bečva River, the channel in present is much deeper and narrower, compared the past, this is a not case in the Topľa River, where only narrowing of the river was observed along the last 100 years.
- Obtained results are rather untypical for assumed flood wave transformations by floodplains in the European context. We hypothesize that high discharge variations in flysch-based watersheds connected with high water depths in floodplains during large floods probably play important role in decreased ability of floodplains to lower and delay flood culminations.
- Floodplain storage was observed in all modelled hydrographs in the case of the Bečva River, where filling and emptying of floodplain is clearly visible. Such effect was not found in the latter case, where depth of the channel in present and historical scenario is almost the same.
- However, one should assess other benefits of floodplain inundations, e.g. increased biodiversity and water quality in watercourses, preservation of groundwater supply and managing the environmental risk of drought.

- Future accuracy improvement of input data for hydraulic models and estimations of flood hazard (e.g. historical and present land cover with related hydraulic roughness, role of bed and bank stability) is recommended.

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