1D hydraulic model chain along the Danube and tributaries

Deliverable D 4.1.2

Technical document concerning the homogenization of different models, as well as the basin wide assessment of the strategy measures' impact and efficiency as input for D 4.3.4 and D 4.3.2.

WP	WP4: Flood prevention pilots
Activity	Activity 4.1
Deliverable	Technical document concerning the homogenization of different models, as well as the basin wide assessment of the strategy measures' impact and efficiency as input for D 4.3.4 and D 4.3.2.
Activity-leader	TUM
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Involved partners	BAFG, BOKU, VUVH, KOTIVIZIG, EDUVIZIG, JCI, CW, NARW, NIHWM, TUM
Connection with other deliverables/ outputs	D 4.3.2, D 4.3.3 and output 4.1
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List of abbreviations

AFP	Active floodplain (defined in activity 3.1)
BAFG	German Federal Institute of Hydrology, Germany
BOKU	University of Natural Resources and Life Science Vienna, Austria
CS	Current state; simulation of the current situation including all the existing active floodplains
dQ	= ΔQ; Delta Q; difference between RS and CS of the maximum runoff (Qmax) value either in m^3/s or in % change compared to the CS
dt	= Δt; Delta t; difference between the peak time of the RS compared to the CS in hours
EDUVIZIG	North-Transdanubian Water Directorate, Hungary
JCI	Jaroslav Černi Water Institute, Serbia
KOTIVIZIG	Middle Tisza District Water Directorate, Hungary
MRBA	Morava River Basin Authority, Czech Republic
NARW	National Administration “Romanian Waters”, Romania
PFP	Potential floodplain (defined in activity 3.1)
Qmax	Maximum runoff in m^3/s (=peak of the flood wave)
RS	Restoration state; simulation of a restored state with all potential floodplains included
TUM	Technical University of Munich, Germany
VUVH	Water Research Institute, Slovakia

Abstract

The deliverable 4.1.2 of the Danube Floodplain project summarizes the 1D modelling investigations at the Danube and its tributaries Morava, Tisza and Sava. In order to assess and compare the trans-regional effect of flood protection through floodplain restoration, a model chain approach is applied. Project partners simulate the current state (CS) of their river section, which includes all active floodplains, and a restoration state (RS), in which an additional activation of potential floodplains (PFP), delineated in activity 3.1, is implemented.

At the tributaries, three individual hydrological scenarios are applied (HQ_{2-5}, HQ_{10-30} and HQ_{50+}) based on observed gauging data. Along the Danube, three past flood events (2006, 2010 and 2013) are simulated in the current state scenario (CS) and restoration scenario (RS) models of each national river stretch. The results are handed over at gauging stations close to national borders. The downstream partner implements the outputs of the previous upstream partner as input for his modelling section and simulates again two the CS and RS scenario until the next national border.

The results of the simulated flood peak reduction (ΔQ) and the translation of the flood wave (temporal displacement of the peak, Δt) are analyzed quantitatively for each hydrological event for both scenarios. The difference of RS to CS is compared. The shape of the flood peaks during both scenarios are depicted.

In nearly all modeled sections, simulations a flood peak reduction (ΔQ) is shown downstream of a potential floodplain of up to 5 %. Thus, a local effect of flood mitigation can be confirmed by floodplain reactivation. However, the effect further downstream is mainly superposed after the confluence with large tributaries. The generated Δt values are, with only a few exceptions, positive and confirm a temporal displacement of the flood wave peak discharge resulting from the flood retention in the potential floodplains. Both effects are clearly visible in exemplary flood wave figures of the current state scenario (CS) and the restoration scenario (RS).

It can be concluded that the demonstrated 1D model chain is a well applicable tool to investigate the trans-regional effects of floodplain restoration on large scales. The 1D models have a short running time and thus several scenarios can be simulated and compared. For a more detailed analysis of the flood wave propagation and long-reaching effect, it is suggested to extract the ΔQ and Δt values at more locations, to create continuous longitudinal sections. Also, the input hydrographs of tributaries to the investigated river stretch should be analyzed to quantitatively compare the effects of additional potential floodplains and the influence of the tributaries.

1. Introduction and Tasks according to the Application Form

In previous activities and deliverables (Act. 3.2, D 4.1.1, Act. 4.2, Act. 4.3) of the Danube Floodplain project, the activation and restoration of potential floodplains along the Danube and some of its tributaries were assessed individually to determine their hydraulic impact during flood events and other effects like ecosystem services. In the scope of this deliverable, the possible extent of the hydraulic effects of additional potential floodplains and their influence on the flood situation in downstream cities and countries is simulated and evaluated with a hydraulic 1D model chain.

The main questions which are analyzed in this deliverable are:

- What would previous flood events (2006, 2010 and 2013) have looked like, if all potential floodplains were already activated?
- How far downstream can the effects of an additional potential floodplain be detected in terms of peak reduction and translation of the flood wave?
- Which other factors have an impact on the flood wave attenuation?

To assess the effect of restoration measures on floods in the whole Danube Basin, a chain of 1D hydrodynamic models is established from upstream to downstream. In these models, several hydrological events and two scenarios, 1) the current state (CS) scenario and 2) a potential state (RS) scenario, which includes potential floodplains in the modeled area, are applied. National partners use the 1D models at the Danube and at the tributaries Morava, Sava, and Tisza to estimate the trans-regional flood protection efficiency.

Instead of simulating one continuous 1D model along the Danube and the selected tributaries, national existing or – if necessary – newly set up 1D models are applied individually in the respective countries. This ensures that sensitive data is kept with the national authorities and no central data processing or storage of the 1D simulations is required. Instead, the national partners can set up and run the simulations with their local expert knowledge about the simulated river section and its active and potential floodplains as well as use it for further assessments.

2. Delineation of model chain

To set up the model chain, in a first step the WP lead partner requested information about the availability and currentness of data, as well as the delineation of existing national 1D models. After several project meetings it was decided to set the start of the model chain not at the source of the Danube, but at Neu-Ulm Bad Held (DE). A continuous German 1D model is available just from this gauge and a tributary mainly changes the discharge of the Danube at this location. Thus, setting the starting point there is reasonable. The downstream limitation of the model chain is set at the gauge of Calarasi (RO). It is also the limit of the existing 1D model and furthermore, the Danube does not have one-dimensional flow characteristics downstream of Calarasi, due to its multiple side arms towards the Danube delta.

The start of the tributary models is defined by the national partners and determined by data availability and the potential flood hazard to be simulated. The downstream end of the tributary models is set at the confluence with the Danube River.

Figure 1 shows the extent of the 1D models. In general, the national 1D models start and end at gauges close to the national borders. In Austria, no appropriate 1D model is available for this simulation, so it was decided to apply an existing high quality 2D models (Hydro_AS-2D) instead. Between the large hydropower dams Iron Gate I and II, the 1D models are not be applied, because it is considered as a hydraulic border and the upstream restoration effects can be neglected downstream of this highly anthropogenic stretch.

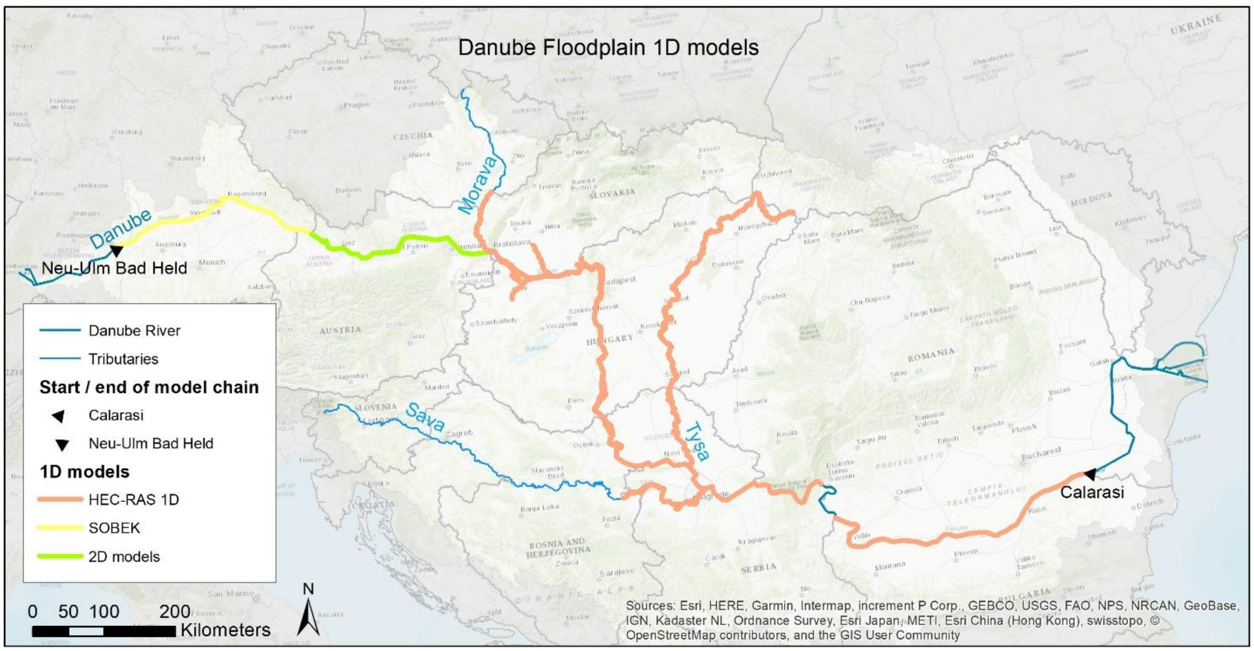

Figure 1: Delineation of the applied 1D models for the model chain approach in the Danube and its tributaries Morava, Tisza (Tysa) and Sava in the Danube Floodplain project

3. Methodology of 1D model chain

In order to assess the trans-regional efficiency of flood protection through restoration measures, national hydrodynamic 1D models along the Danube and the tributaries Morava, Tisza and Sava are applied in two different hydrological approaches:

- **Tributaries Morava, Tisza and Sava:** Modelling the trans-regional effect for different flood magnitudes ($HQ_{2\text{-}5}$, $HQ_{10\text{-}30}$, HQ_{50+}) (chapter 3.3 and 4)
- **Danube:** Trans-regional effect of the three past flood events 2006, 2010 and 2013 (chapter 3.4 and 5)

3.1. Active and potential floodplains

In activity 3.1 of the Danube Floodplain project, the project partners determine existing floodplains (**active floodplains, AFP**) in their national reaches along the Danube and selected tributaries. They also develop – together with other national authorities – potentially restorable areas along the rivers which are then delineated and defined as **potential floodplains (PFP)** (Table 1, Table 2 and Figure 2). In the Romanian and Bulgarian Danube stretch, the partners delineated neighboring PFPs together. Restoration in potential floodplain areas is mainly generated by dike relocations resulting in a reactivation of historical floodplains. Some PFPs are controlled polders but are assumed as uncontrolled polders in this investigation, i.e. are flooded when the river exceeds the riverbank, not at a certain discharge or water level. Furthermore, land use change is implemented in the developed potential floodplain areas, e.g. from crops to pasture or floodplain forest, which changes the roughness of the area. Some of the potential floodplains are extensions of existing active floodplains.

Table 1: Delineated potential floodplains along the Danube and gauges where the 1D model results are handed over to the next downstream partner (in red)

	DFGIS_ID	Location	River km	PFP size ha
DANUBE				
DE	Neu-Ulm Bad Held		2587	-
	DE_DU_PFP01	Oberelchingen - Lech	2491	16698
	DE_DU_PFP02	Lech - Neuburg	2478	3736
	DE_DU_PFP03	Grossmehring	2451	493
	DE_DU_PFP04	Katzau	2437	309
	DE_DU_PFP05	Geisling / Gmuend	2337	2503
	Englhartszell		2201	-
AT	AT_DU_PFP01	Tullnerfeld	1938	16066
	AT_DU_PFP02	Nationalpark Donau-Auen	1880	12139
	Thebnerstrassl		1879	-
SK	Cunovo		1851	-
HU	HU_SK_DU_PFP01	Szigetköz	1797	15711
	HU_DU_PFP06	Paks	1521	2214
	HU_DU_PFP07	Veránka-sziget	1463	16172
	HR_HU_DU_PFP01	Béda-Karapnacsa	1426	5471

	DFGIS_ID	Location	River km	PFP size ha
	Bezdan		1426	-
RS	RS_DU_PFP01	Siga - Kazuk	1409	6059
	RS_DU_PFP02	Vajska	1362	5988
	RS_DU_PFP03	Kamariste	1324	10072
	Drencova		1016	-
RO/ BG	DU_PFP_BG01	Slivata	753	2024
	DU_PFP_RO01-BG02	Bistret-Dolni Tibar	698	18477
	DU_PFP_RO02-BG03	Dabuleni-Potelu-Corabia-Zagrajden	634	14306
	DE_PFP_BG04	Belene	576	5448
	RO_DU_PFP03	Suhaia-Zimnicea	554	6478
	DE_PFP_BG05	Vardim	537	1839
	Calarasi		375	-

A standardized evaluation of each of these individual floodplains is performed in the FEM approach (activity 3.2) by using several hydrological, hydraulic, ecological and socio-economic parameters. This FEM approach is based on HQ_{100} unsteady simulations with hydrodynamic 1D or 2D models for each active and potential floodplain.

In the 1D model chain in activity 4.1, the same predefined floodplains are investigated, however not separately, but in a continuous simulation along the whole river for one flood event. This means, that not a HQ_{100} peak runoff upstream of each floodplain like in the FEM evaluation is evaluated, but a long-distance approach with continuous varying flood magnitudes along the rivers. The delineated potential floodplains are depicted in Figure 2. The corresponding information about the floodplains is specified in Table 1.

Table 2: Delineated potential floodplains along the tributaries Morava, Tisza, and Sava and gauges where the 1D model results are handed over just upstream of the confluence with the Danube River (in red)

	DFGIS_ID	Location	River km	PFP size ha
MORAVA				
SK	SK_M_PFP01	Hodonín	96	745
	SK_M_PFP02	Tvrdonice	90	412
	SK_M_PFP03	Kostice	85	271
	SK_M_PFP04	Brodské	80	290
	SK_M_PFP05	Kuty	72	1484
	Devínska Nová Ves		8	-
TISZA				
HU	HU_T_PFP01	Tisza-Túr köz	724	2089
	HU_T_PFP02	Inerhát	492	3945
	HU_T_PFP03	Dél-Borsod	445	3107
	HU_T_PFP04	Hanyi-Jászság	388	3618
	HU_T_PFP05	Közép-Tisza	337	3997
	HU_T_PFP06	Szolnok-Tiszaug	270	9140
	HU_T_PFP07	Tiszaug-Csongrád	255	5759
	Tiszasziget		167	-
RS	Titel		9	-
SAVA				
RS	RS_S_PFP01	Bosutske šume	8521	187
	Beograd		1	-

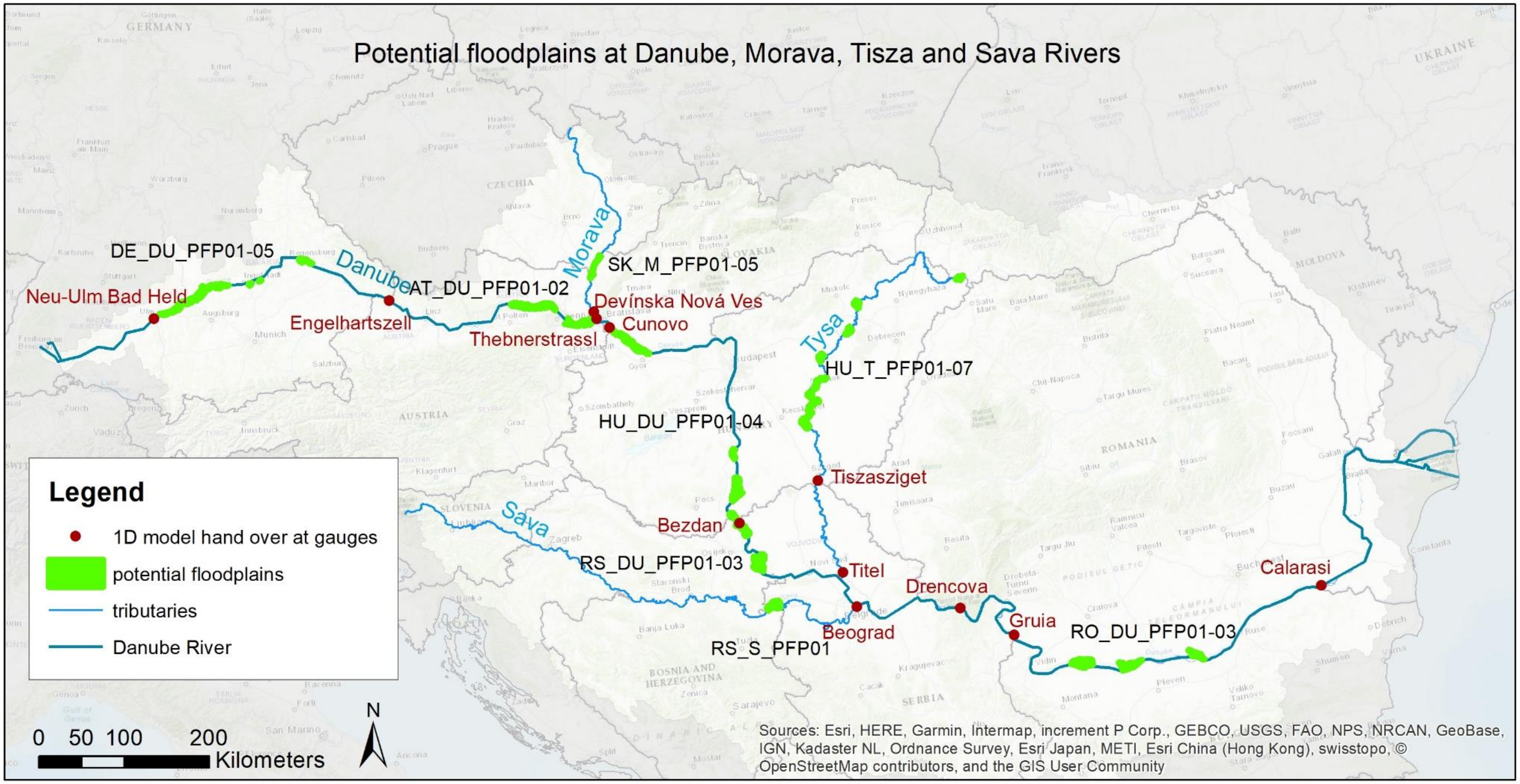

Figure 2: Location of the potential floodplains of Danube, Morava, Tisza (Tysa) and Sava Rivers in the Danube basin

3.2. 1D simulations of active and potential floodplains

Two 1D models are developed in each of the simulated reaches:

- one model for the current state (CS, active floodplains) and
- one model for the restoration state (RS, potential floodplains).

The models are applied for the active (CS) and potential floodplains (RS) of the proposed restoration project list from activity 3.1. Measured streamflow input time series are applied along the Danube for three specific past flood events (2006, 2010 and 2013) and the results are transferred from up- to downstream partners after the upstream partner has finished the simulations. In the tributary models (Morava, Sava, and Tisza) gauging data for different flood magnitudes (HQ_{2-5}, HQ_{10-30} and ca. HQ_{100}) are chosen by the national partners. The Tisza tributary model is implemented by two countries (Hungary and Serbia). As no potential floodplains are determined in Serbia, the results from the Hungarian partner are transferred downstream in one model. Besides, for each reach 6 simulations are performed, considering three different hydrological scenarios, the CS and the RS scenario. The results are compared regarding the trans-regional effect of peak reduction and the temporal displacement of the flood wave.

Figure 3 shows exemplarily the modelling section analyses: In the CS model, the broader cross sections of the existing active floodplains are included in the 1D model, while in the RS 1D model, the potential floodplains are additionally implemented. The 1D RS model has broader cross sections at the potential floodplains. This enables the spread and retention of the flood wave discharge. At the downstream border of the modeled section, the output hydrographs of the CS and RS are compared for each flood event. The difference in Q_{max} (ΔQ) and the difference in t (Δt) between the two hydrographs after each potential floodplain is analyzed.

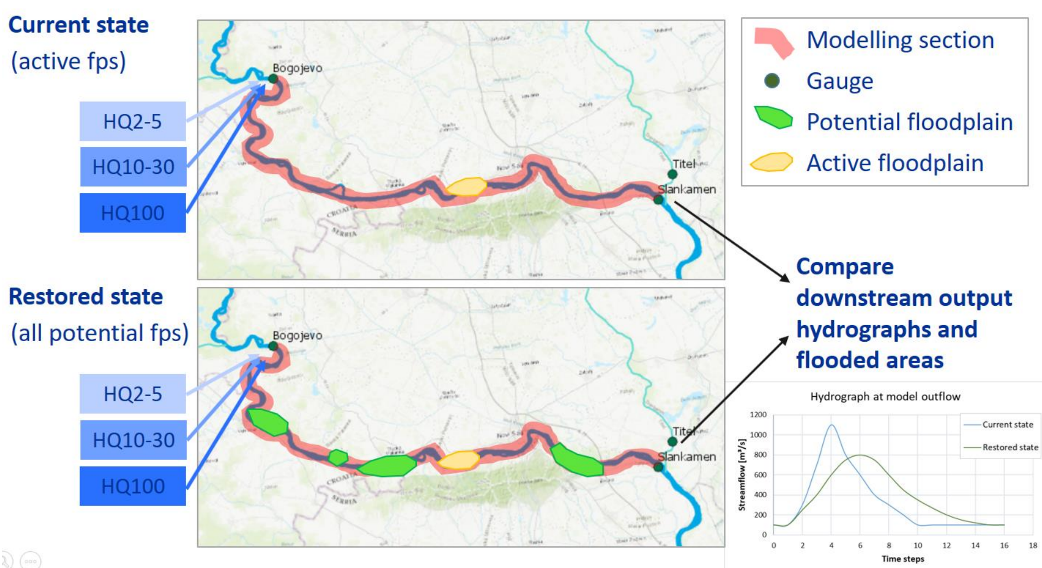

Figure 3: Example of current state and restored state 1D models in the sections with input and output analysis

Model output hydrographs of the current and the restored state at the downstream model border and at cross sections right behind each potential floodplain are compared.

3.3. Simulations of different HQs at the tributaries

Different flood events are simulated with existing 1D models in the three tributaries Morava, Tisza and Sava. Table 3 shows details on the modeled river stretches. The Morava and the Sava model are run by a single partner from the start to the confluence with the Danube. At the Tisza, the Hungarian section is simulated by the KOTIVIZIG partners, the lower reach on Serbian territory is investigated by JCI. However, there are no potential floodplains on the Serbian stretch, so the two generated hydrographs (CS and RS) are forwarded downstream in one Serbian CS model to the confluence with the Danube.

Table 3: 1D model delineation at the tributaries Morava, Tisza and Sava

River	Country	Responsible PP	1D section	from	to	1D model
Morava	CZ/ SK	MRBA VUVH	M_01	Hodonin	Devínska Nová Ves	1D HEC RAS
Tisza	HU	KOTIVIZIG	T_01_HU	Tiszabecs	Tiszasziget	1D HEC RAS
	RS	JCI	T_02_RS	Tiszasziget	Titel	1D HEC RAS
Sava	HR/RS	JCI	S_01	HR border	Beograd	1D HEC RAS

The project partners perform the simulations in their respective national modelling section with 3 hydrological scenarios:

- a 2-5 year flood event,
- a 10-20 year flood event, and
- a 50+ year flood event (mostly HQ_{100}).

The input for these hydrological scenarios is derived from past real events at the tributaries. In some cases, the observed flood waves are up- or downscaled to generate the appropriate return period. The necessary input data for the model start and all lateral tributaries is obtained from national hydrological authorities.

3.4. Simulations of past real floods at the Danube River

To analyze a trans-regional effect of floodplain restoration at the Danube River and to investigate the propagation of possible floodplain restoration effects downstream, it was decided to commonly examine the three past flood events of 2006 (Figure 4), 2010 (Figure 5) and 2013 (Figure 6) with data of the respective gauges in the Danube basin (Table 4). For the gauge Mohács (HU) the nearby station Bezdan (RS) is visualized due to data availability. The three selected past events, have different magnitudes (HQ of flood peaks) in each Danube section, ranging from HQ_2 to larger than HQ_{100} events.

The length of the events is set as follows in order to ensure that the flood wave is proceeded, and the peak already declined in Calarasi.

- 2006: from 08.03.2006 to 04.06.2006
- 2010: from 13.05.2010 to 04.08.2010
- 2013: from 13.05.2013 to 20.07.2013

Table 4: Hydrological data availability of the three Danube flood events 2006, 2010 and 2013 from national partners

	Gauge	River km	Peak time	Peak [m³/s]	~HQ peak	No. of upstream gauges	Temporal resolution
2006							
DE	Passau-Ilzstadt	2225	29.03.2006	4820	HQ2-5	21	15 min
AT	Thebnerstrassl	1879	31.03.2006	7728	HQ10		15 min
SK	Devín	1880	31.03.2006	8024	HQ10	1	1 h
HU	Mohács	1447	07.04.2006	8050	HQ50	15	1 h
RS	Smederevo	1116	16.04.2006	14800	HQ100	4	1 d
RO	Calarasi-Chiciu	375	24.04.2006	16210	>HQ100	9	1 h
2010							
DE	Passau-Ilzstadt	2225	03.06.2010	4850	HQ2-5	21	15 min
AT	Thebnerstrassl	1879	05.06.2010	7944	HQ10		15 min
SK	Devín	1880	05.06.2010	8071	HQ10	1	1 h
HU	Mohács	1447	10.06.2010	7500	HQ20	15	1 h
RS	Smederevo	1116	29.06.2010	12700	HQ10-20	4	1 d
RO	Calarasi-Chiciu	375	07.07.2010	14620	>HQ20	9	1 h
2013							
DE	Passau-Ilzstadt	2225	03.06.2013	10000	>HQ100	21	15 min
AT	Thebnerstrassl	1879	06.06.2013	10640	HQ50-100		15 min
SK	Devín	1880	07.06.2013	10572	HQ100	1	1 h
HU	Mohács	1447	11.06.2013	8300	HQ50-100	15	1 h
RS	Smederevo	1116	17.-18.6.2013	10500	HQ2-5	4	1 d
RO	Calarasi-Chiciu	375	22.06.2013	10840	HQ2	9	1 h

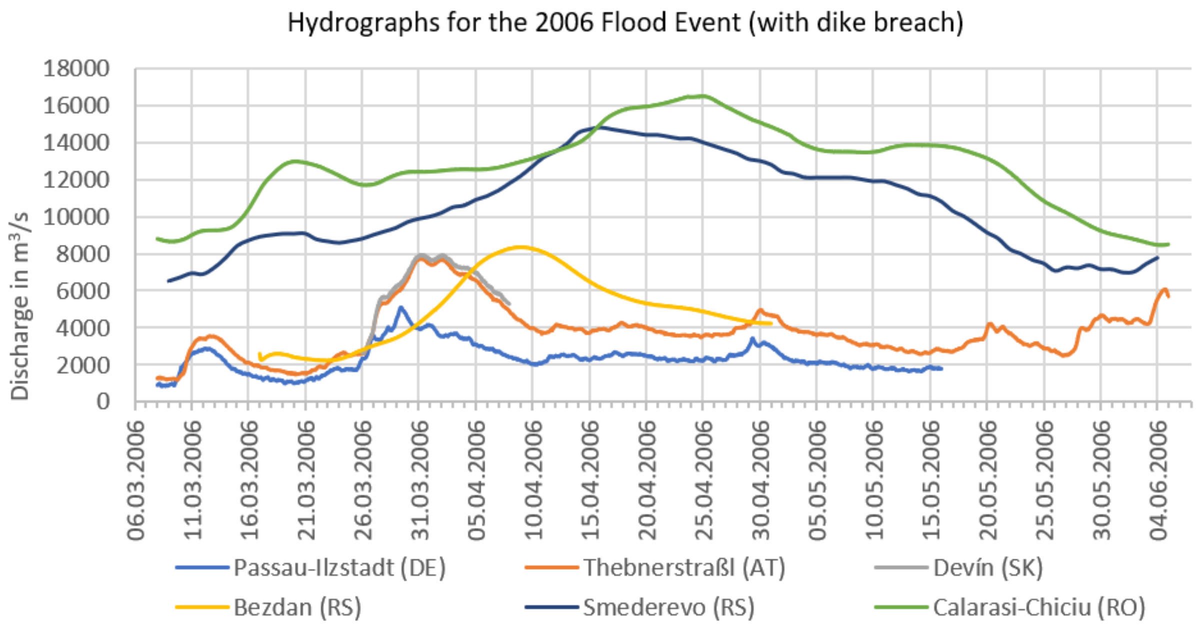

Figure 4: Development of the flood discharge (hydrographs) from Passau-Ilzstadt gauge to the most downstream gauge (Calarasi Chiciu) during the 2006 flood event (measured gauge data). The data for the gauge Smederevo was retrieved from http://www.hidmet.gov.rs/latin/hidrologija/povrsinske_godisnjaci.php (Hydrology Year Books of the Republic Hydrometeorological Service of Serbia).

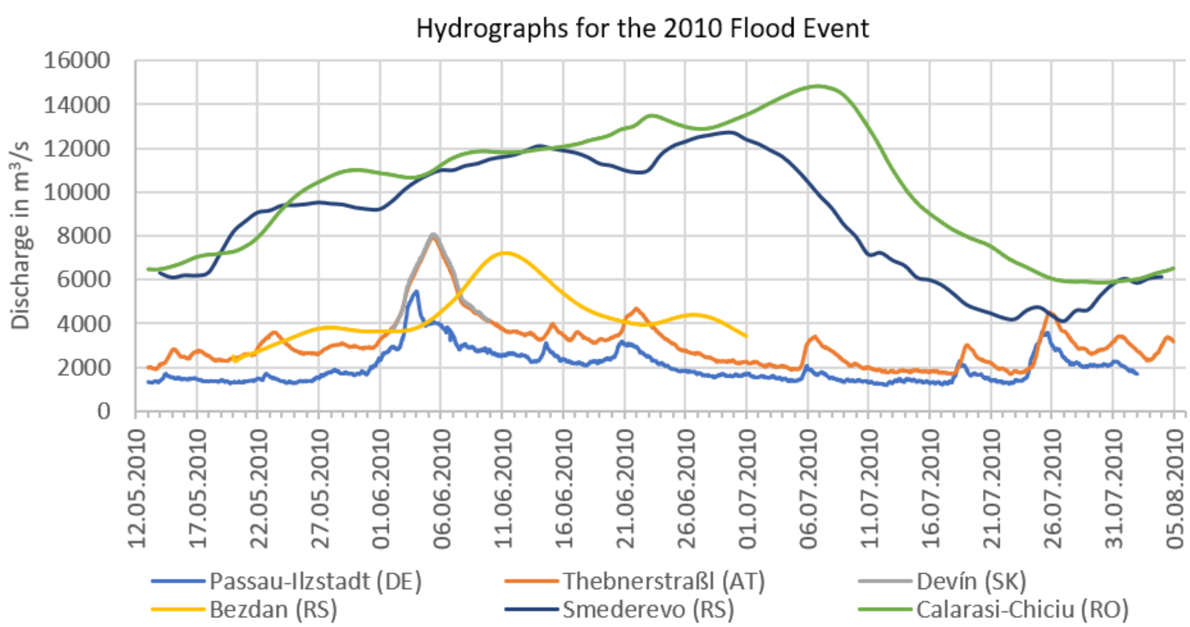

Figure 5: Development of the flood discharge (hydrographs) from Passau-Ilzstadt gauge to the most downstream gauge (Calarasi Chiciu) during the 2010 flood event (measured gauge data). The data for the gauge Smederevo was retrieved from http://www.hidmet.gov.rs/latin/hidrologija/povrsinske_godisnjaci.php (Hydrology Year Books of the Republic Hydrometeorological Service of Serbia).

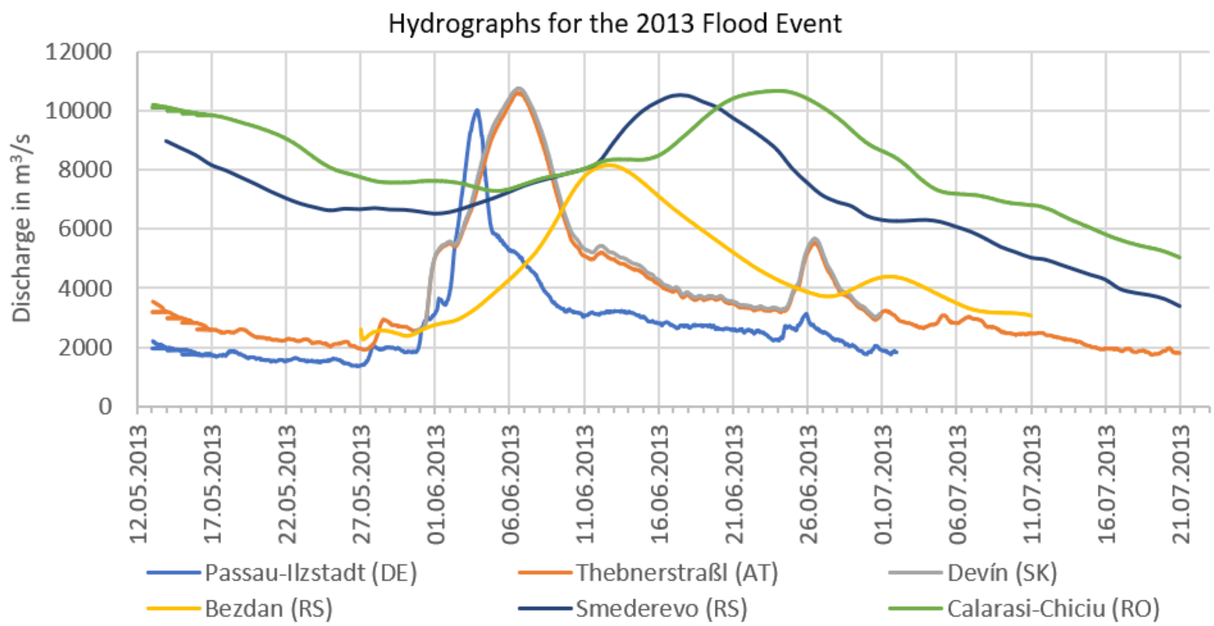

Figure 6: Development of the flood discharge (hydrographs) from Passau-Ilzstadt gauge to the most downstream gauge (Calarasi Chiciu) during the 2013 flood event (measured gauge data). The data for the gauge Smederevo was retrieved from http://www.hidmet.gov.rs/latin/hidrologija/povrsinske_godisnjaci.php (Hydrology Year Books of the Republic Hydrometeorological Service of Serbia).

The most upstream partner, Germany, obtains measured hydrographs of the Danube from the upstream model border gauging station, Neu-Ulm Bad Held, for the identified, required time series length. With the provided time series, the simulations are run and transferred step by step to each downstream partner. The national partners provide time series of measured tributary streamflow data as lateral input for their national reaches when necessary.

Like for the tributaries' simulations (Figure 3), two model variations are simulated (CS and RS). The resulting discharge time series of the current state (active floodplains) and the restored state (potential floodplains) are then compared. The most upstream partner (Germany) hands over both model results (current and restoration state) time series for each event to the next partner (Austria) who uses it as input.

The tributaries' inflow runoff for each modelling stretch is derived from observed data at their respective gauges. After simulating the three events for both scenarios, the results are handed over to the next downstream partner and so forth.

The simulated runoff time series are analyzed regarding their peak discharge value of the flood wave (in m³/s) and the translation (temporal displacement) of the flood peak (in hours). The CS and RS are compared at the end of each national modelling stretch and after each potential floodplain.

Table 5: 1D model delineation at the Danube 1D models

River	Country	Responsible PP	1D section	from	to	1D/2D model
Danube	DE	TUM / BAFG	D_01_DE	Neu-Ulm	Engelhartszell	SOBEK 1D
	AT	BOKU	D_02_AT	Engelhartszell	Thebnerstrassl	Hydro_AS-2D
	SK	VUVH	D_03_SK	Thebnerstrassl	Cunovo	1D HEC RAS
	HU	EDUVIZIG	D_04_HU	Cunovo	Bezdan	1D HEC RAS
	RS	JCI	D_05_RS	Bezdan	Drencova	1D HEC RAS
	RO	JCI / NARW	D_06_RO	Drencova	Gruia	Iron Gates section: will not be modeled
	RO	NARW	D_07_RO	Gruia	Calarasi	1D HEC RAS

4. Results of the tributaries

4.1. Results at Morava

Figure 7 shows the hydrograph for a flood event of magnitude HQ_{20} at the downstream model border in Devínska Nová Ves, illustrating the effects of the floodplain restoration, i.e. a later approach of the flood wave and the decrease of the peak discharge. Those effects are also visible in many other modeled sections. The less steep decline of the flood wave after the peak discharge in the RS scenario refers to the retention of water.

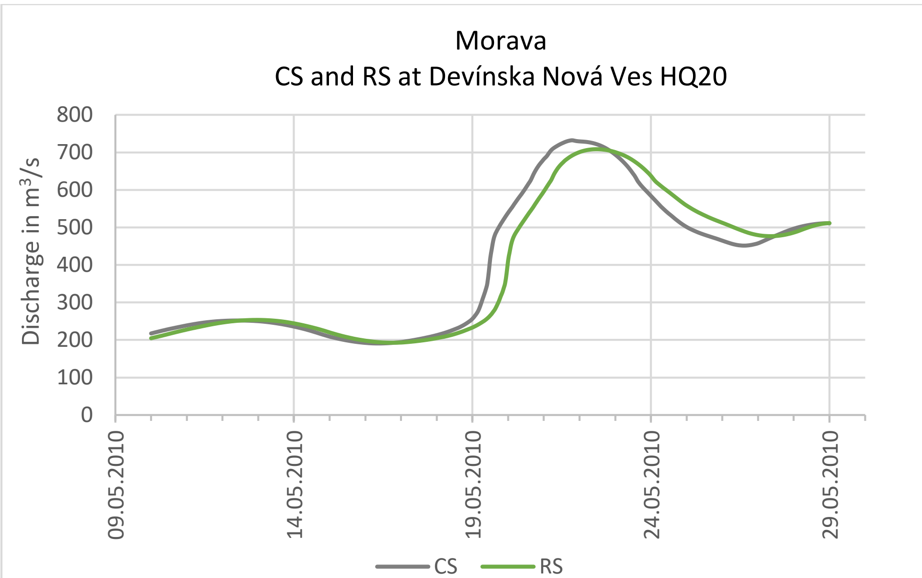

Figure 7: Simulated HQ_{20} hydrographs (CS and RS) at Devínska Nová Ves gauge which shows exemplarily for all investigated PFP and modeled sections the effects of floodplain restoration.

The simulated maximum peak discharge of the different flood events at the Morava River in the CS and RS scenario, as well as the difference (ΔQ) between the two scenarios in m³/s and % are listed in Table 6 to Table 8. In addition, the temporal displacement of the flood peak in hours (Δt) is given in the tables after each potential floodplain and at the hand-over-gauges. In Figure 8 to Figure 10, the hydrological longitudinal sections including the CS and RS Q_{max} values are depicted.

In all three hydrological scenarios, a peak reduction can be achieved by activating the potential floodplains. A maximum ΔQ value of up to 3.25 % is simulated for $HQ_{10\text{-}30}$. Yet, the peak reduction is consistently most considerable during the HQ_{100} event for all potential floodplains. Here most values of ΔQ are larger than 2% with one exception of 0.88% at Devínska Nová Ves, resulting from the confluence with the tributary Dyje just before the junction. Regarding Δt, the temporal displacement of the peak time from +3 to +33 hours is simulated, i.e. the flood wave approaches 3 to 33 hours later compared to the CS scenario. The highest Δt values are achieved in the $HQ_{10\text{-}30}$ scenario simulation downstream of each potential floodplain. At the gauging station Devínska Nová Ves, just upstream of the confluence with the Danube River, Δt is lower than in the upstream PFPs in the $HQ_{10\text{-}30}$ and HQ_{100} event, whereas it is higher in the $HQ_{2\text{-}5}$ scenario.

This can again be explained by the confluence with other tributaries in the section between PFP05 and Devínska Nová Ves and thus a superposition of the flood waves. During events with lower flood magnitudes this effect is less pronounced. However, in the investigated Morava section, with potential floodplains in close succession, the trans-regional efficiency of the activation of potential floodplains (RS scenario) can be confirmed with the applied simulation approach.

Table 6: Morava results of the $HQ_{2\text{-}5}$ event: Q_{max} of current state (CS) and potential restoration state (RS), ΔQ ($Q_{maxRS} - Q_{maxCS}$) and Δt ($t_{maxRS} - t_{maxCS}$) downstream of each potential floodplain and the gauge Devínska Nová Ves

Morava					**$HQ_{2\text{-}5}$**				
	DFGIS_ID	**Location**	**Size ha**	**River km**	**Qmax CS $HQ_{2\text{-}5}$ [m³/s]**	**Qmax RS $HQ_{2\text{-}5}$ [m³/s]**	**ΔQ $HQ_{2\text{-}5}$ [m³/s]**	**ΔQ $HQ_{2\text{-}5}$ [%]**	**Δt $HQ_{2\text{-}5}$ [h]**
SK	SK_M_PFP01	Hodonín	745	96	561	558	-2	-0.41	15
	SK_M_PFP02	Tvrdonice	412	90	408	405	-3	-0.80	9
	SK_M_PFP03	Kostice	271	85	408	405	-3	-0.69	7
	SK_M_PFP04	Brodské	290	80	408	406	-2	-0.60	6
	SK_M_PFP05	Kuty	1484	72	408	406	-2	-0.58	3
	Devínska Nová Ves			8	702	689	-13	-1.91	10

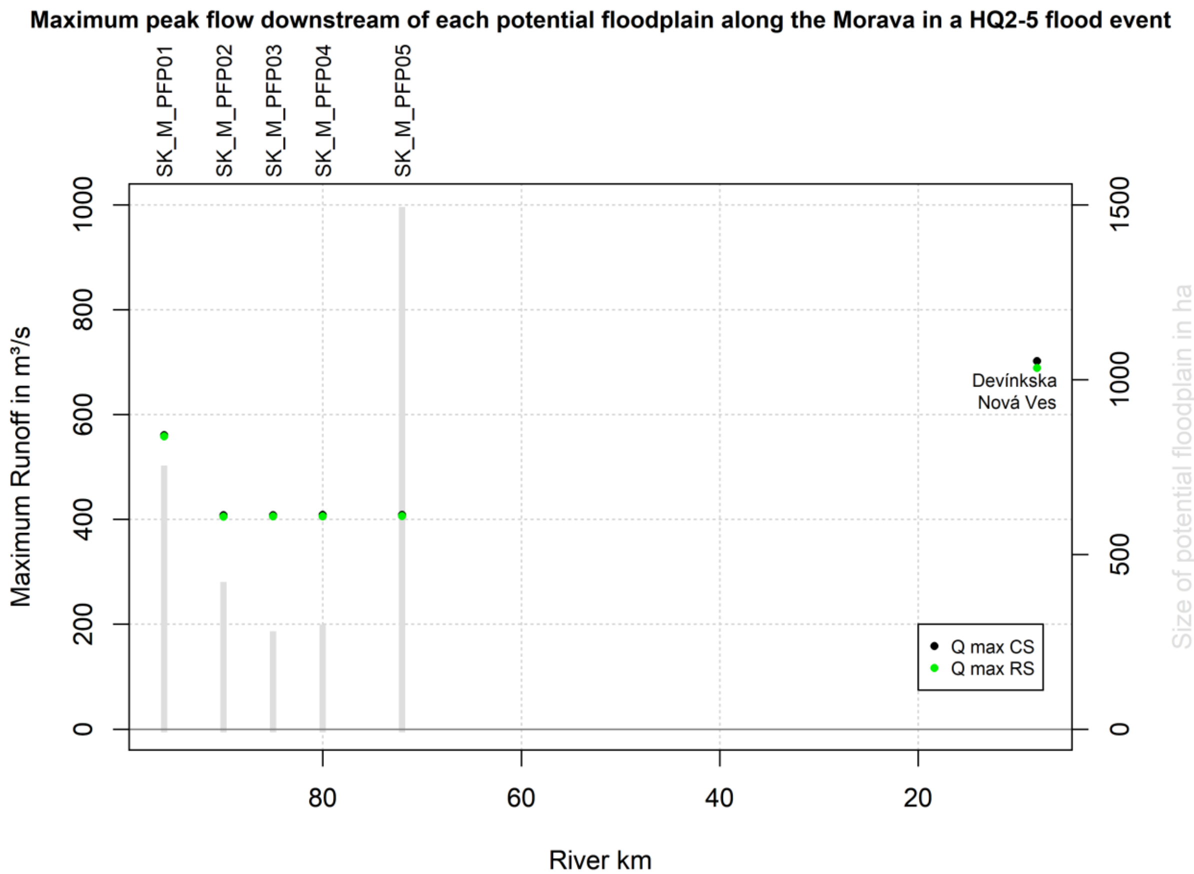

Figure 8: Peak flow of CS and RS simulations in a HQ_{2-5} flood event downstream of the Morava potential floodplains and at the gauge Devínska Nová Ves

Table 7: Morava results of the HQ_{10-30} event: Q_{max} of current state (CS) and potential restoration state (RS), ΔQ ($Q_{maxRS} - Q_{maxCS}$) and Δt ($t_{maxRS} - t_{maxCS}$) downstream of each potential floodplain and the gauge Devínska Nová Ves

Morava					**HQ_{10-30}**				
	DFGIS_ID	**Location**	**Size ha**	**River km**	**Q_{max} CS HQ_{10-30} [m³/s]**	**Q_{max} RS HQ_{10-30} [m³/s]**	**ΔHQ_{10-30} [m³/s]**	**ΔQ HQ_{10-30} [%]**	**Δt HQ_{10-30} [h]**
SK	SK_M_PFP01	Hodonín	745	96	857	853	-4	-0.52	33
	SK_M_PFP02	Tvrdonice	412	90	699	694	-4	-0.62	32
	SK_M_PFP03	Kostice	271	85	699	695	-4	-0.54	29
	SK_M_PFP04	Brodské	290	80	699	695	-3	-0.48	29
	SK_M_PFP05	Kuty	1484	72	699	696	-3	-0.43	25
	Devínska Nová Ves			8	732	708	-24	-3.25	16

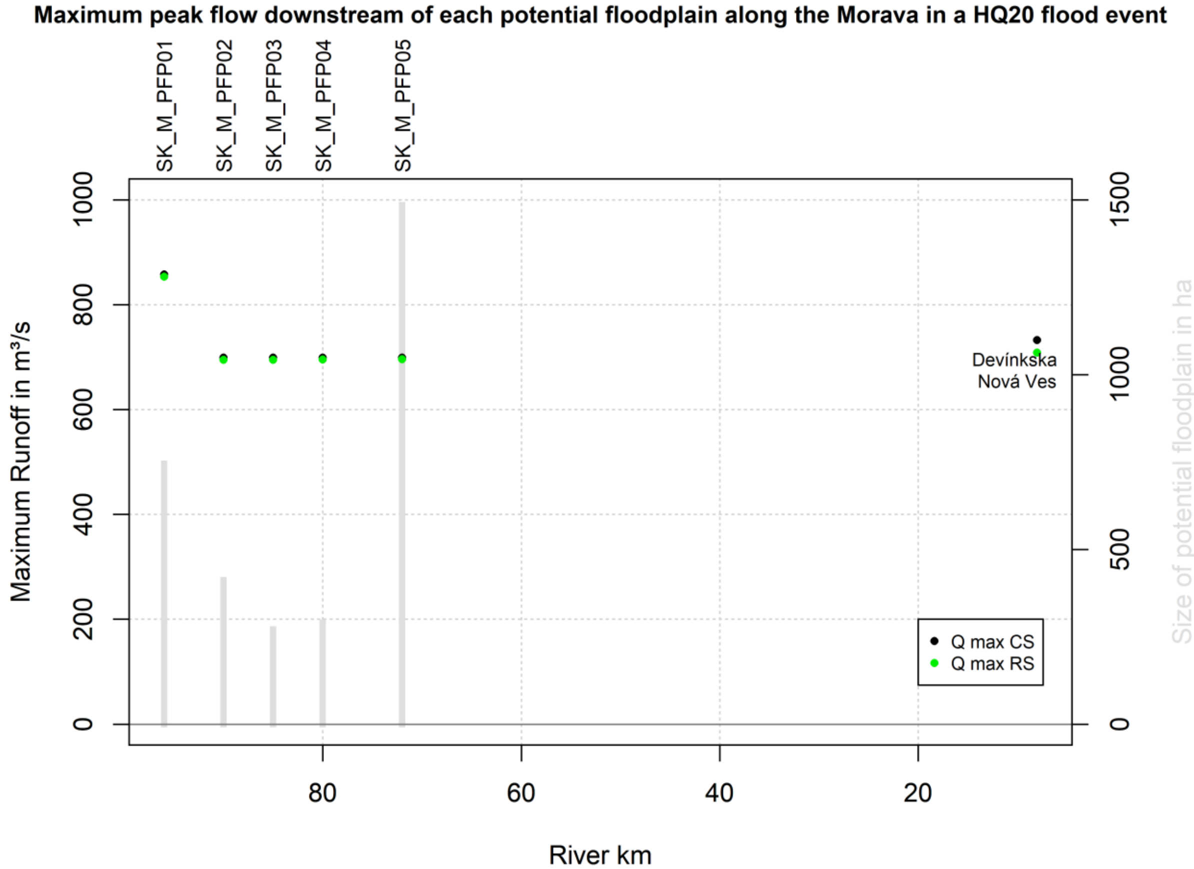

Figure 9: Peak flow of CS and RS simulations in a $HQ_{10\text{-}30}$ flood event downstream of the Morava potential floodplains and at the gauge Devínska Nová Ves

Table 8: Morava results of the HQ_{100} event: Q_{max} of current state (CS) and potential restoration state (RS), ΔQ ($Q_{maxRS} – Q_{maxCS}$) and Δt ($t_{maxRS} – t_{maxCS}$) downstream of each potential floodplain and the gauge Devínska Nová Ves

Morava					HQ_{100}				
	DFGIS_ID	Location	Size ha	River km	Q_{max} CS HQ_{100} [m³/s]	Q_{max} RS HQ_{100} [m³/s]	ΔQ HQ_{100} [m³/s]	ΔQ HQ_{100} [%]	Δt HQ_{100} [h]
SK	SK_M_PFP01	Hodonín	745	96	939	919	-20	-2.12	18
	SK_M_PFP02	Tvrdonice	412	90	790	765	-24	-3.06	18
	SK_M_PFP03	Kostice	271	85	790	767	-23	-2.96	17
	SK_M_PFP04	Brodské	290	80	791	768	-23	-2.89	15
	SK_M_PFP05	Kuty	1484	72	792	769	-23	-2.91	14
	Devínska Nová Ves			8	879	871	-8	-0.88	8

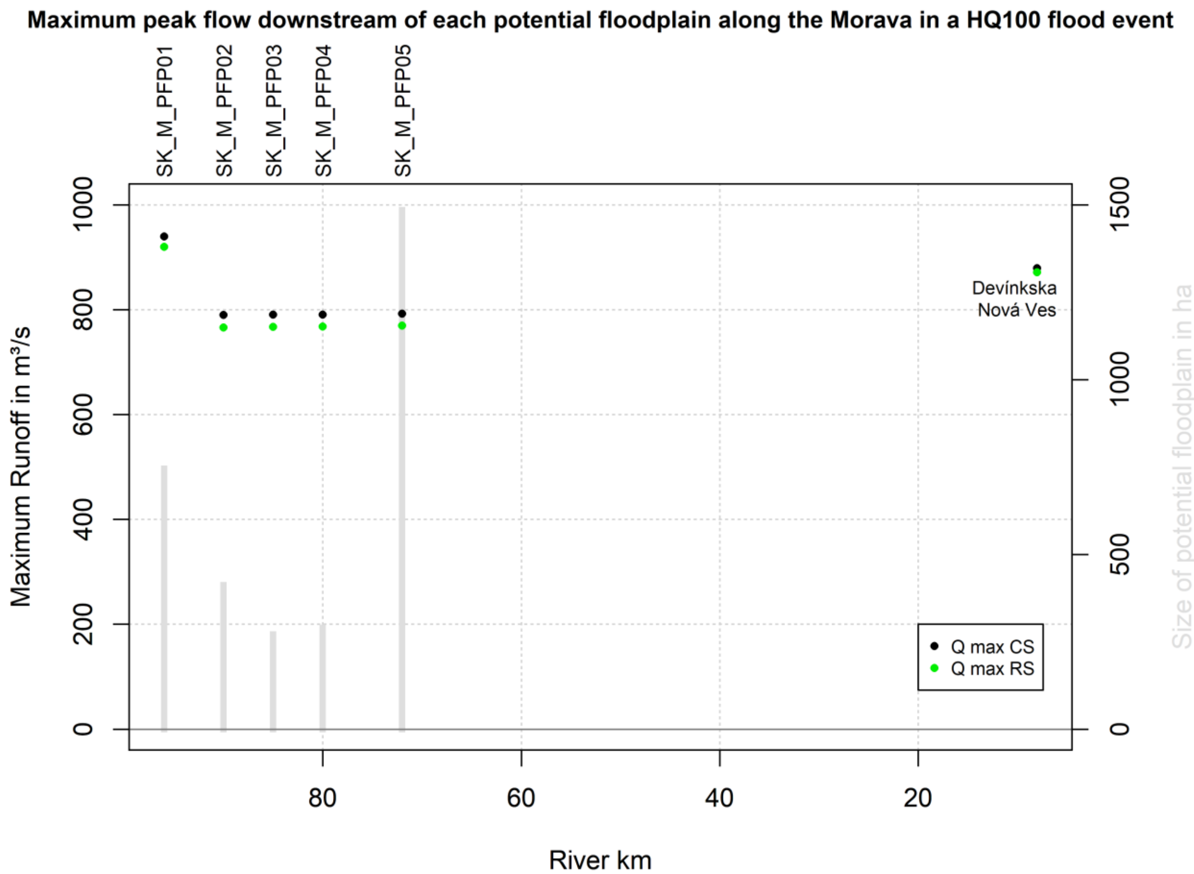

Figure 10: Peak flow of CS and RS simulations in a HQ_{100} flood event downstream of the Morava potential floodplains and at the gauge Devínska Nová Ves

4.2. Results at Tisza

For the Tisza river, the simulated maximum peak runoff of the different flood events for the CS and RS scenario, as well as the reduction of the flood peak (ΔQ) between the two scenarios in m^3/s and % are listed in Table 9 to Table 11. Further, the translation of the flood wave in hours (Δt) is given in the tables after each potential floodplain and at the gauges where the results are given to partners to continue with the simulation. In Figure 12 to Figure 14, the hydrological longitudinal sections including the maximum discharge in the CS and RS scenarios and the size of the potential floodplains are shown.

The simulated ΔQ values are negative (max -7.18%) for all analyzed sections in the three investigated hydrological scenarios, i.e. a reduction of the maximum flood discharge due to the activation of each potential floodplain can be observed. Upstream of the Tiszasziget gauging station the confluence with a larger tributary, the Maros river, lowers the upstream peak reduction in the RS scenario compared to the CS scenario. Yet it is important to evaluate the variable magnitude of the tributaries discharge (i.e. if the main river has a HQ of a certain magnitude, the tributaries discharge does not necessarily have the same magnitude) as the extent of the effect depends on it regardless of the flood magnitude in the main river. However, it is visible, especially in the HQ_{10-30} and HQ_{100} event that the peak reduction effect of all seven potential floodplains is transported downstream and thus, a trans-regional flood mitigation effect can be achieved for the Tisza River.

Regarding Δt, almost all potential floodplains reveal a temporal displacement of the peak of up to +32 hours in the HQ_{2-5} event, up to +48 hours in the HQ_{10-30} event and up to +72 hours in the HQ_{100} event. Only at PFP02 (Inherát) for the simulated HQ_{2-5} and for the gauge Tiszasziget for the simulated HQ_{100} event an earlier approach of two and one hour respectively is found. However, in both cases a confluence with a tributary is given right downstream the potential floodplain. In case of PFP02 (Inherát) the Sajo river and for Tiszasziget the Maros river joins the Tisza river. Thus, an overlay of the flood peak of Tizsa and the respective tributaries can cause a negative flood wave translation, i.e. an earlier approach. PFP04 to PFP07 (Hanyi-Jászság, Közép-Tisza, Szolnok-Tiszaug, Tiszaug-Csongrád) are most effective concerning the temporal displacement of the flood wave.

Based on the results of the simulations, the potential floodplains along the Middle Tisza district (PFP04-PFP07) have the greatest effect on the flood peak. The effect of the PFP04 (Hanyi-Jászság) is the most distinct (Figure 11), followed by the PFP05 (Közép-Tisza) potential floodplain. PFP04 has an area of 3618 ha and is therefore a medium sized floodplain along the course of the Tisza and among the floodplains of the other modelled tributaries. Additionally, no lateral inflow from tributaries is given in this river section (until PFP06). Concluding from that, it is important consider tributary conditions and the areas of the potential floodplains while evaluating the effect of flood waves. Further, the combined effect of potential floodplains is crucial to be noted to achieve an adequate and efficient flood peak reduction.

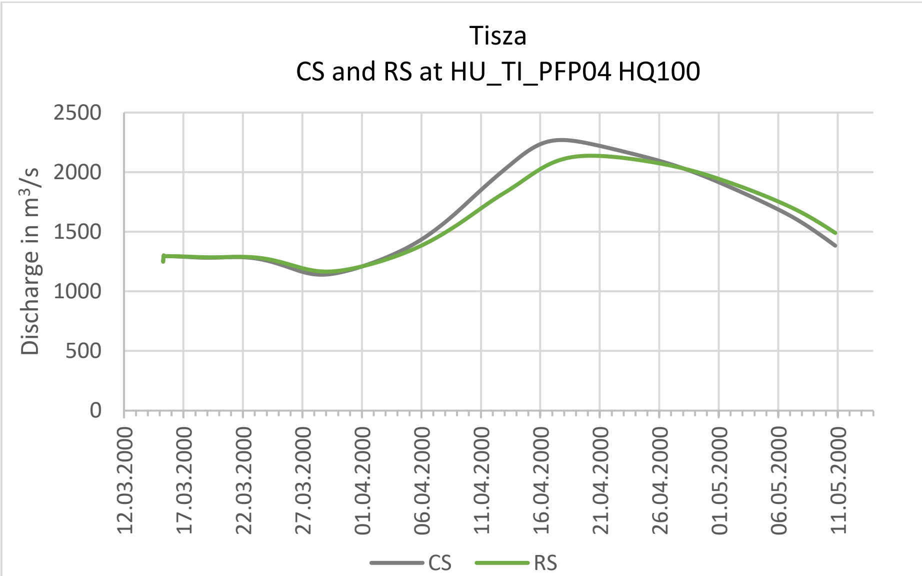

Figure 11: Hydrographs of the CS and RS Scenario downstream of the potential floodplain HU_TI_PFP04 along the Tisza tributary for the HQ_{100} scenario

Table 9: Tisza results of the $HQ_{2\text{-}5}$ (2008 flood event): Q_{max} of current state (CS) and potential restoration state (RS), ΔQ ($Q_{maxRS} - Q_{maxCS}$) and Δt ($t_{maxRS} - t_{maxCS}$) downstream of each potential floodplain and at the hand over gauges

Tisza					**$HQ_{2\text{-}5}$ (2008 event)**				
	DFGIS ID	**Location**	**Size ha**	**River km**	**Q_{max} CS $HQ_{2\text{-}5}$ [m³/s]**	**Q_{max} RS $HQ_{2\text{-}5}$ [m³/s]**	**ΔQ $HQ_{2\text{-}5}$ [m³/s]**	**ΔQ $HQ_{2\text{-}5}$ [%]**	**Δt $HQ_{2\text{-}5}$ [h]**
HU	HU TI PFP01	Tisza-Túr köz	2089	724	1826	1823	-3	-0.19	0
HU	HU TI PFP02	Inerhát	3945	492	1830	1802	-28	-1.54	-2
HU	HU TI PFP03	Dél-Borsod	3107	445	1692	1655	-37	-2.19	5
HU	HU TI PFP04	Hanyi-Jászság	3618	388	1454	1350	-104	-7.18	32
HU	HU TI PFP05	Közép-Tisza	3997	337	1377	1299	-78	-5.65	22
HU	HU TI PFP06	Szolnok-Tiszaug	9140	270	1281	1232	-48	-3.79	14
HU	HU TI PFP07	Tiszaug-Csongrád	5759	255	1261	1219	-43	-3.39	10
HU	Tiszasziget			167	1381	1343	-38	-2.74	1
RS	Titel			9	1401	1370	-31	-2.20	0.00

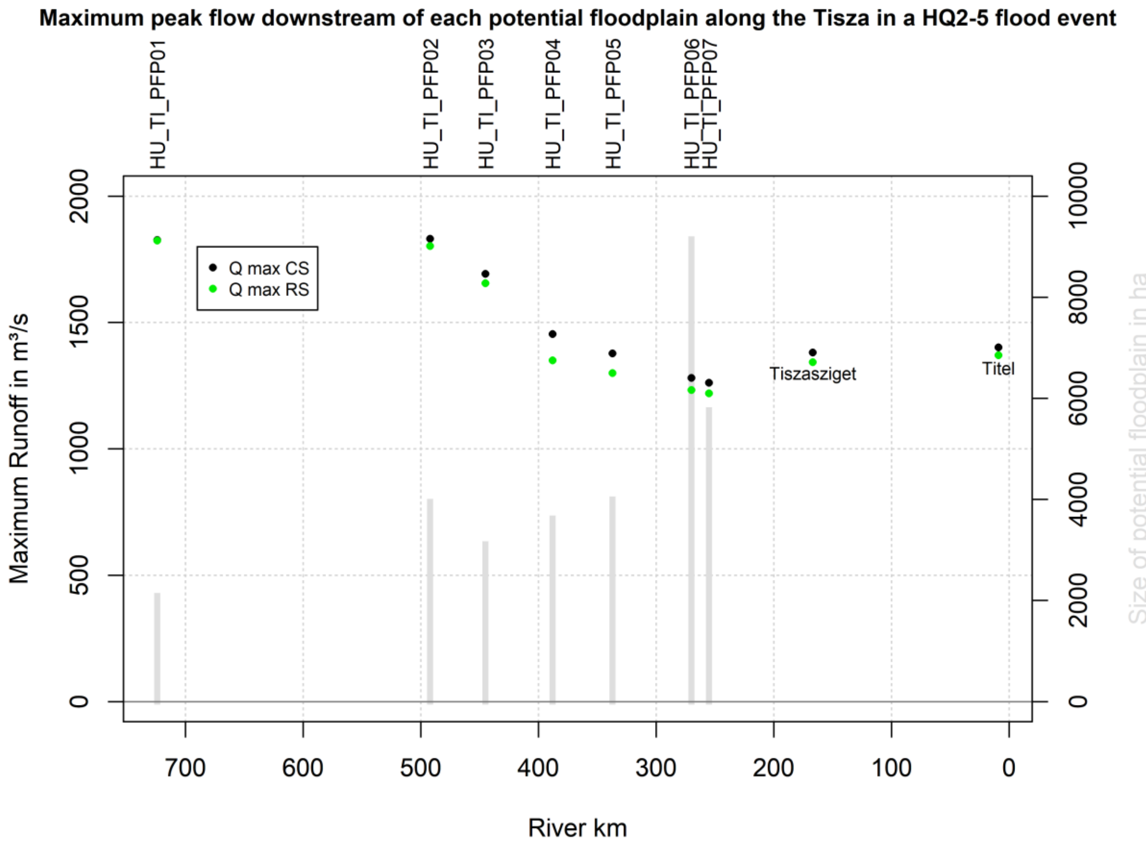

Figure 12: Peak flow of CS and RS simulations in a $HQ_{2\text{-}5}$ flood event downstream of the Tisza potential floodplains and at hand over gauges

Table 10: Tisza results of the $HQ_{10\text{-}30}$ (2013 flood event): Q_{max} of current state (CS) and potential restoration state (RS), ΔQ ($Q_{maxRS} - Q_{maxCS}$) and Δt ($t_{maxRS} - t_{maxCS}$) downstream of each potential floodplain and at the hand over gauges

Tisza					**$HQ_{10\text{-}30}$ (2013 event)**				
	DFGIS ID	**Location**	**Size ha**	**River km**	**Q_{max} CS $HQ_{10\text{-}30}$ [m³/s]**	**Q_{max} RS $HQ_{10\text{-}30}$ [m³/s]**	**ΔQ $HQ_{10\text{-}30}$ [m³/s]**	**ΔQ $HQ_{10\text{-}30}$ [%]**	**Δt $HQ_{10\text{-}30}$ [h]**
HU	HU TI PFP01	Tisza-Túr köz	2089	724	1797	1795	-1	-0.07	0
	HU TI PFP02	Inerhát	3945	492	2317	2270	-47	-2.04	20
	HU TI PFP03	Dél-Borsod	3107	445	2220	2183	-36	-1.64	11
	HU TI PFP04	Hanyi-Jászság	3618	388	2127	2057	-70	-3.30	34
	HU TI PFP05	Közép-Tisza	3997	337	2100	2033	-67	-3.19	39
	HU TI PFP06	Szolnok-Tiszaug	9140	270	2073	2008	-65	-3.13	48
	HU TI PFP07	Tiszaug-Csongrád	5759	255	2073	2008	-65	-3.15	45
	Tiszasziget			167	2446	2365	-81	-3.33	0
RS	Titel			9	2476	2383	-93	-3.77	0

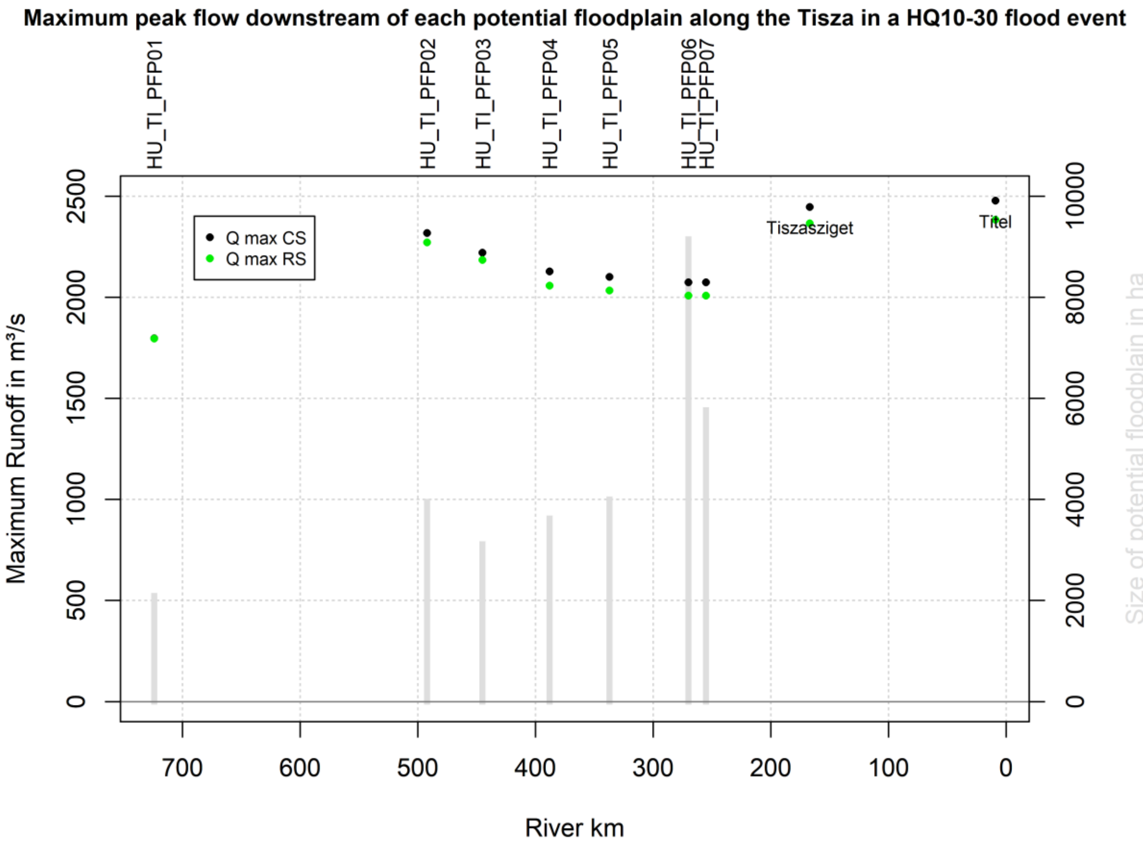

Figure 13: Peak flow of CS and RS simulations in a $HQ_{10\text{-}30}$ flood event downstream of the Tisza potential floodplains and at hand over gauges

Table 11: Tisza results of the HQ_{100} (2000 flood event): Q_{max} of current state (CS) and potential restoration state (RS), ΔQ ($Q_{maxRS} - Q_{maxCS}$) and Δt ($t_{maxRS} - t_{maxCS}$) downstream of each potential floodplain and at the hand over gauges

Tisza					**HQ_{100} (2000 event)**				
	DFGIS ID	**Location**	**Size ha**	**River km**	**Q_{max} CS HQ_{100} [m³/s]**	**Q_{max} RS HQ_{100} [m³/s]**	**ΔQ HQ_{100} [m³/s]**	**ΔQ HQ_{100} [%]**	**Δt HQ_{100} [h]**
HU	HU TI PFP01	Tisza-Túr köz	2089	724	2017	2002	-14	-0.71	0
	HU TI PFP02	Inerhát	3945	492	2687	2575	-112	-4.15	26
	HU TI PFP03	Dél-Borsod	3107	445	2530	2407	-124	-4.89	27
	HU TI PFP04	Hanyi-Jászság	3618	388	2270	2138	-132	-5.82	61
	HU TI PFP05	Közép-Tisza	3997	337	2212	2108	-104	-4.72	72
	HU TI PFP06	Szolnok-Tiszaug	9140	270	2145	2068	-77	-3.59	63
	HU TI PFP07	Tiszaug-Csongrád	5759	255	2142	2062	-80	-3.73	64
	Tiszasziget			167	2901	2859	-42	-1.45	-1
RS	Titel			9	2956	2849	-108	-3.64	0

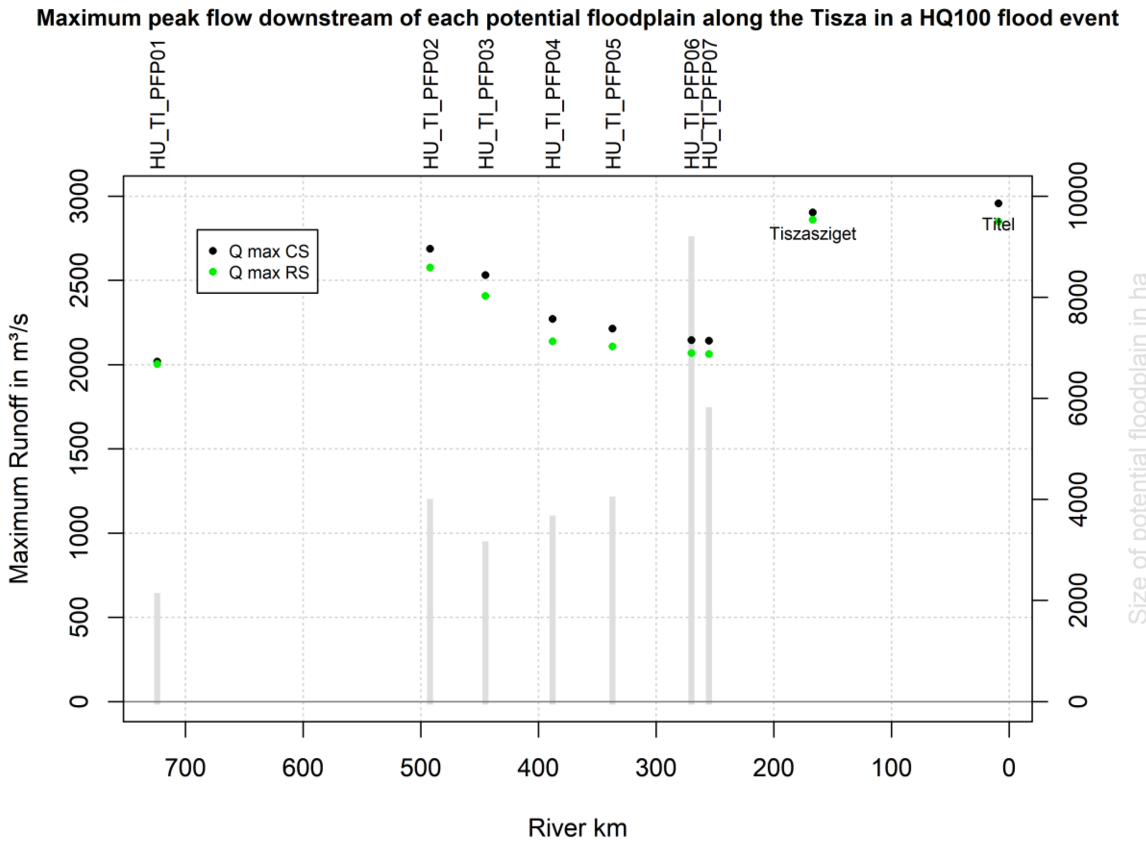

Figure 14: Peak flow of CS and RS simulations in a HQ_{100} flood event downstream of the Tisza potential floodplains and at hand over gauges

4.3. Results at Sava

The simulated maximum peak runoff of the different flood events at the Sava River in the CS and RS scenario, as well as the difference (ΔQ) between the two scenarios in m³/s and % are listed in Table 12 and presented in Figure 15, Figure 17 and Figure 19. In addition, the translation of the flood peak in hours (Δt) is given in the tables after the potential floodplain and at the hand-over-gauge. In Figure 16, Figure 18 and Figure 20, the hydrological longitudinal sections including the CS and RS Q_{max} values are depicted.

Table 12: Sava results of the HQ_5, HQ_{20} and HQ_{100} event: Q_{max} of current state (CS) and potential restoration state (RS), ΔQ (Q_{maxRS} – Q_{maxCS}) and Δt (t_{maxRS} – t_{maxCS}) downstream of the potential floodplain and the gauge Beograd

Sava					**HQ_{2-5} (2010-2011)**				
	DFGIS_ID	**Location**	**Size ha**	**River km**	**Qmax CS HQ_{2-5} [m³/s]**	**Qmax RS HQ_{2-5} [m³/s]**	**ΔQ HQ_{2-5} [m³/s]**	**ΔQ HQ_{2-5} [%]**	**Δt HQ_{2-5} [h]**
RS	RS_S_PFP01	Bosutske šume	8521	187	3156	3002	-154	-4.88	68
	Beograd			1	5053	4648	-405	-8.02	31
Sava					**HQ_{10-30} (2013)**				
	DFGIS_ID	**Location**	**Size ha**	**River km**	**Qmax CS HQ10-30 [m³/s]**	**Qmax RS HQ_{10-30} [m³/s]**	**ΔQ HQ_{10-30} [m³/s]**	**ΔQ HQ_{10-30} [%]**	**Δt HQ_{10-30} [h]**
RS	RS_S_PFP01	Bosutske šume	8521	187	3563	3546	-17	-0.48	88
	Beograd			1	4538	4486	-52	-1.14	101
Sava					**HQ_{100} (2014)**				
	DFGIS_ID	**Location**	**Size ha**	**River km**	**Qmax CS HQ_{100} [m³/s]**	**Qmax RS HQ_{100} [m³/s]**	**ΔQ HQ_{100} [m³/s]**	**ΔQ HQ_{100} [%]**	**Δt HQ_{100} [h]**
RS	RS_S_PFP01	Bosutske šume	8521	187	5078	4626	-451	-8.89	54
	Beograd			1	6865	6056	-810	-11.80	5

Along the course of the Sava river only one additional potential floodplain is implemented in the 1D model. However, this floodplain has a relatively large area of 8521 ha and is thus the second largest potential floodplain determined among the modelled tributaries within the scope of the 1D model chain. The simulations of the current state scenario and the restoration state scenario, including the activation of the predefined potential floodplains, show an overall reduction of the flood peak, i.e. ΔQ is negative for all hydrological scenarios (HQ_{2-5}, HQ_{10-30} and HQ_{100}). The largest effect is achieved during an HQ_{100}, with values of up to 11.8 % relative and 810 m^3/s absolute peak reduction. For the scenario of HQ_{10-30} which corresponds to the magnitude during the flood event in 2013 smaller absolute and total change are obtained (-0.48% and -17m^3/s right downstream of PFP01 (Bosutske šume) and -1.14% and -52m^3/s at the hand-over-gauge Beograd). The smaller changes during a flood event of HQ_{10-30} can be attributed to the shape of the hydrographs and thus the characteristics of the flood events. While the hydrograph for the investigated HQ_{2-5} (Figure 15) and HQ_{100} (Figure 19) shows a pronounced peak, the hydrograph of the HQ_{10-30} (Figure 17) is wider and slower rising. Thus, it is likely that the floodplain is already saturated in the beginning of the event, before the actual peak (maximum discharge of the event) occurs, which then cannot be reduced as much. Yet, a distinct temporal displacement of the flood wave is simulated for the HQ_{10-30} at the Sava river, also resulting from the broad hydrograph shape. A later approach of 101 hours at the hand-over-gauge Beograd is achieved by activating the additional floodplain. Just after PFP01 the temporal displacement is +88 hours. In the other hydrological scenarios Δt is also notable with values between +5 and +68 hours (with a median of +42.5h).

The effects of the potential floodplain at the Sava river are the most pronounced among the modelled tributaries. Knowing the magnitude of the effects and having in mind that the size of the floodplain is comparingly large, the area of potential floodplains should be kept in mind during their determination. However, as seen during the other analyses, the size is not the only influencing factor, as seen during the HQ_{10-30} (shape of hydrograph).

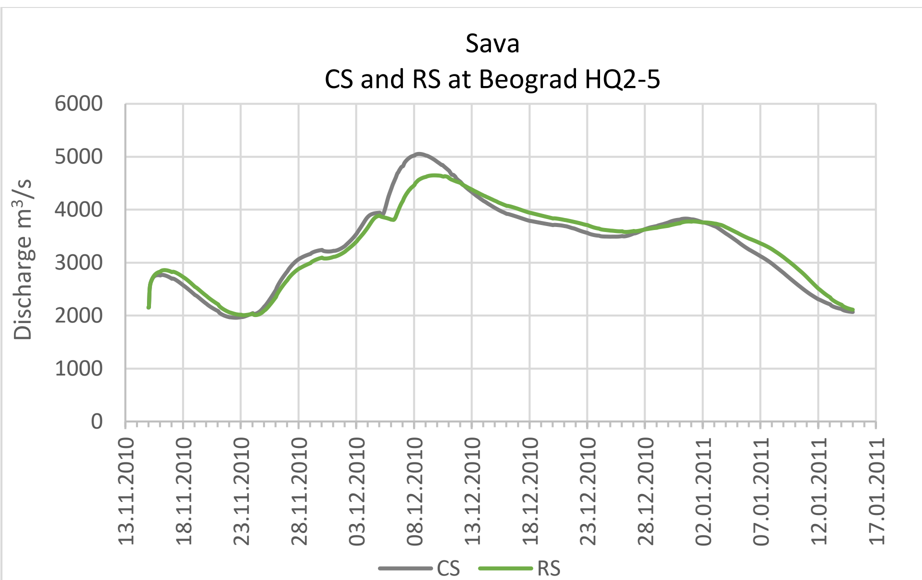

Figure 15: Simulated HQ2-5 output time series (CS and RS) at the hand-over-gauge Beograd

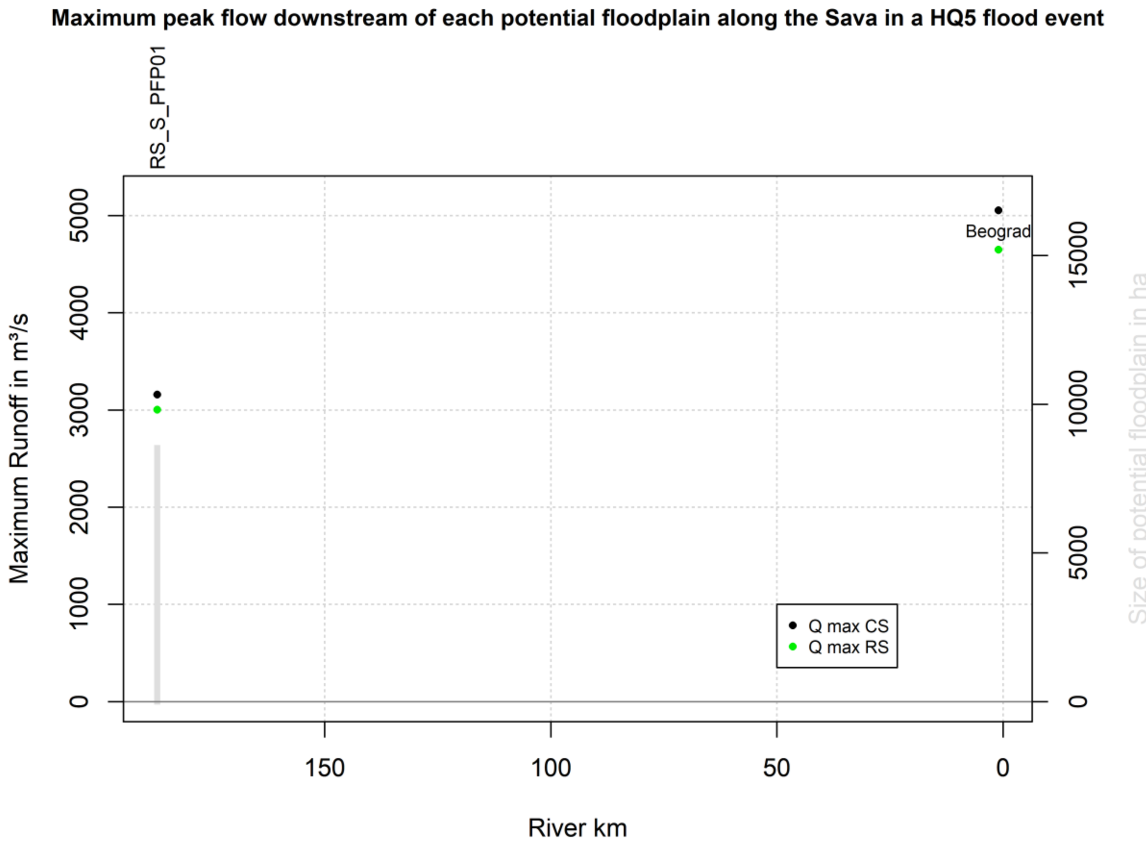

Figure 16: Peak flow of CS and RS simulations in a HQ_5 flood event downstream of the Sava potential floodplain and at the Beograd gauge

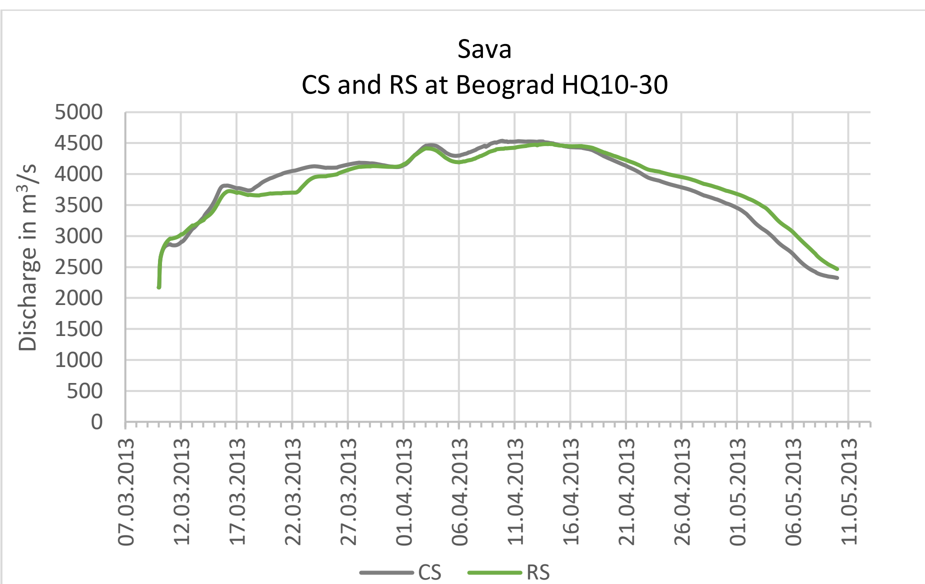

Figure 17: Simulated $HQ_{10\text{-}30}$ output time series (CS and RS) at the hand-over-gauge Beograd

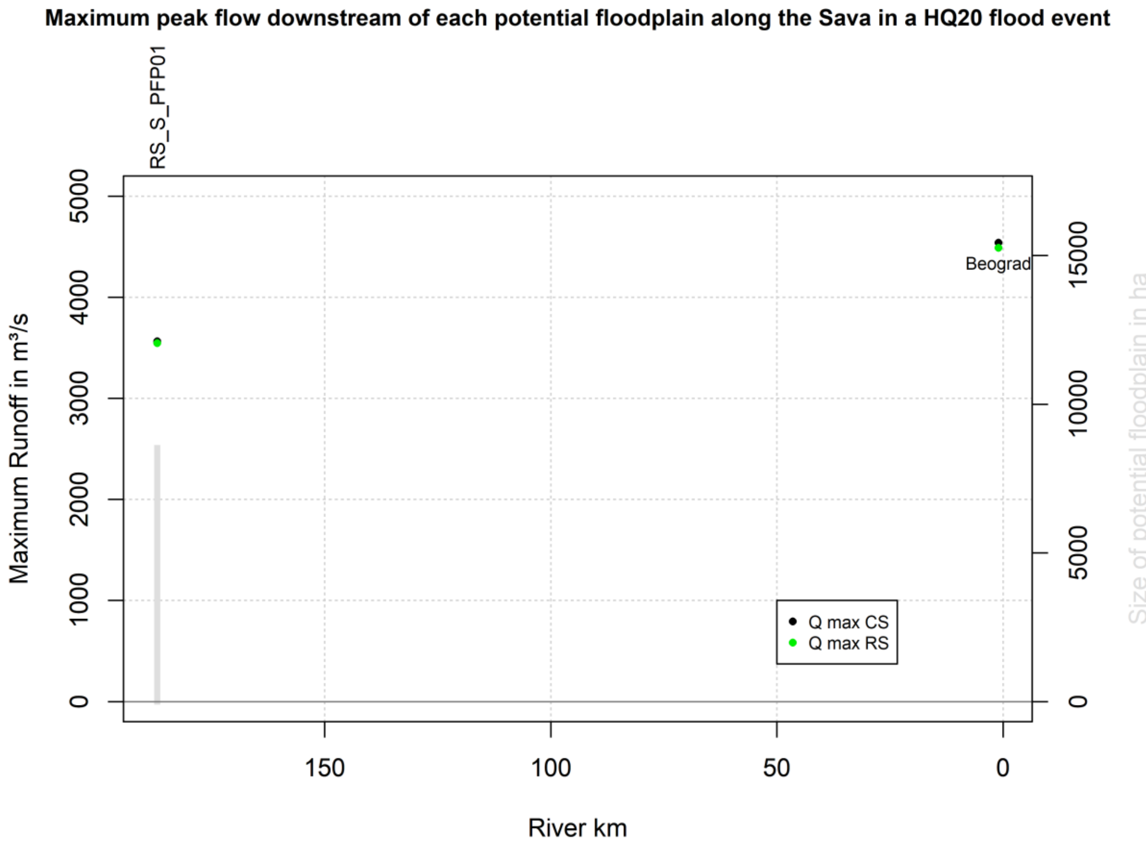

Figure 18: Peak flow of CS and RS simulations in a HQ_{20} flood event downstream of the Sava potential floodplain and at the Beograd gauge

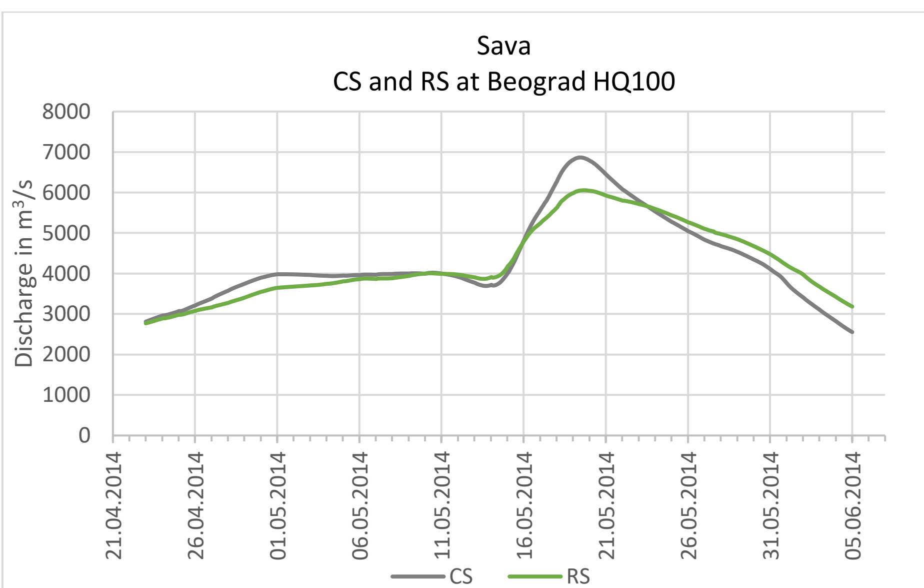

Figure 19: Simulated HQ_{100} output time series (CS and RS) at the hand-over-gauge Beograd

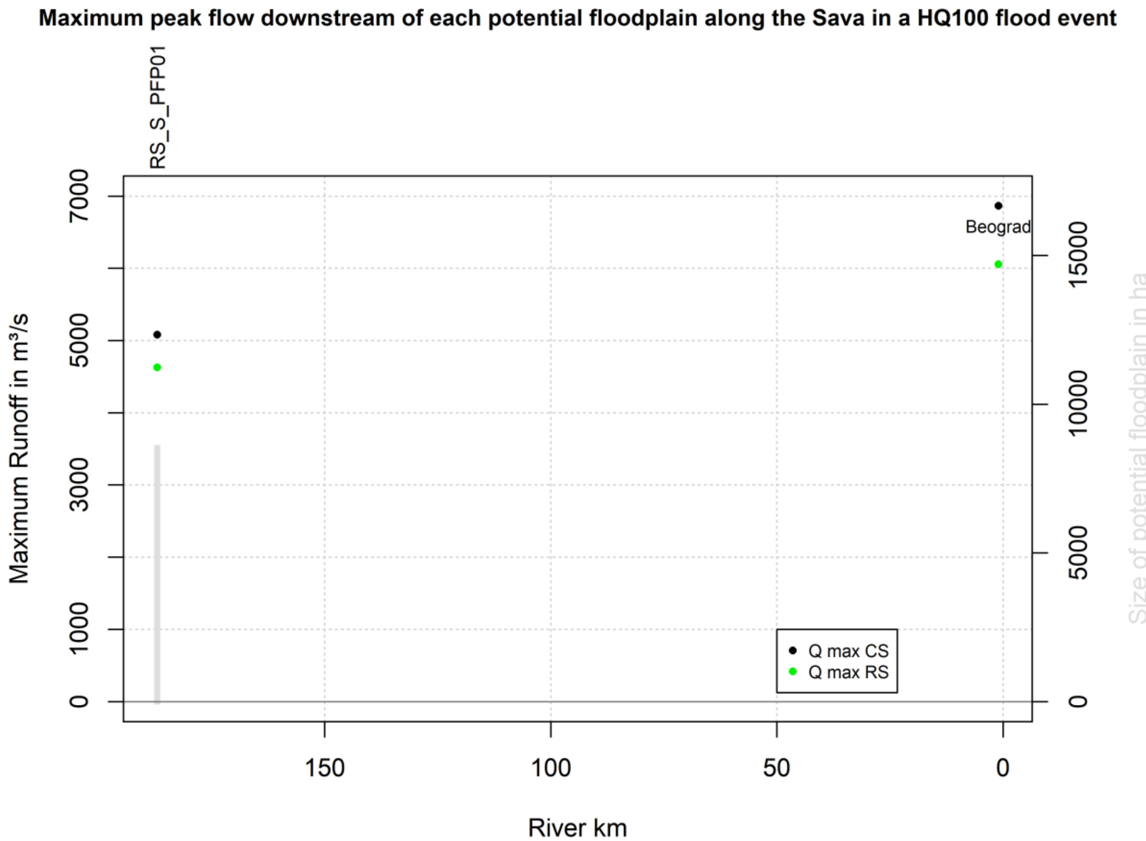

Figure 20: Peak flow of CS and RS simulations in a HQ_{100} flood event downstream of the Sava potential floodplain and at the Beograd gauge

5. Results of flood events at the Danube

Some special features along the Danube model chain should be considered in the simulations and for the results analysis:

- In the Slovakian Danube stretch, the streamflow is separated into the Danube and a bypass channel (Gabčíkovo weir). The simulated runoff is handed over to the downstream Hungarian partners in two time series (Danube and bypass channel). In the channel a maximum runoff of 3950 m³/s during all three flood events is captured. No flood wave translation can be determined in the channel for the RS scenario due to the fixed transfer values. Therefore, in the analysis of Q_{max} the maximum runoff value and time is extracted from the Danube time series and the according value of the same time is added from the bypass channel. For the analysis of the flood wave translation effect, only the Danube without bypass channel is considered.
- Between Drencova (Serbia) and Gruia (Romania) no 1D model is available, since the large weirs of Iron Gate I and II are located here. The upstream and downstream flow conditions are mainly influenced by those weirs and are considered as a hydraulic border. Thus, the 1D model chain ends in Drencova and starts with observed values from the Gruia gauge for the same time periods.
- In the Bistret potential floodplain area, a dike breach occurred during the flood event 2006. To achieve comparability, the Romanian project partners simulated three different situations for the entire Romanian Danube section:
    - CS scenario with dike breach (the real circumstances)
    - CS scenario without a dike breach (hypothetical)
    - RS scenario with three potential floodplains

5.1. Results of Danube flood event 2006

The simulated maximum peak discharge of the 2006 flood event in the CS and RS scenario, as well as the difference (ΔQ) between the two scenarios in m³/s and % are listed in Table 13. In addition, the translation of the flood wave in hours (Δt) is given in the table after each potential floodplain and at the gauges, where the model results are forwarded to the next downstream partner.

The simulation shows, that effect of the restoration of potential floodplains is consistently positive for the reduction of the 2006 flood peak (Table 13). The largest relative reduction (-4.49%) is achieved after the floodplain AT_DU_PFP02 (Nationalpark Donau-Auen) in Austria. Here the HQ in 2006 was assigned a return period of 10 years. Along the Danube an average discharge reduction of -1.12% (median -0.76%) is simulated. Larger relative reductions are modelled for floodplains along the investigated upstream and middle section of the Danube (where the flood event corresponds to a magnitude of HQ_2 to HQ_{10}). Lower relative reductions are found in the Serbian, Bulgarian and Romanian stretch. However, the magnitude of the implemented flood event of 2006 is an HQ_{100} in this section. Thus, a smaller percentage change leads to a higher absolute change for higher initial values (up to 124 m³/s). A slight increase of maximum discharge of 0.01% is simulated after DU_PFP_BG01 (Silvata). Between RS_DU_PFP03 (the furthers downstream potential floodplain in Serbia) and DU_PFP_BG01 (the next downstream potential floodplain)

several tributaries discharge into the Donau and no further potential floodplain is implemented to buffer the additional discharge. Thus, a slight increase can be explained by the superposition of several flood waves.
Again, analyzing the effects subjected to the area of the floodplains, one would assume that a higher peak reduction is obtained for larger floodplain areas. However, as demonstrated for the comparably large floodplain AT_DU_PFP01 (Tullnerfeld) resulting in rather small effects on ΔQ, the size of the floodplain is not the only important parameter in terms of evaluating the effectiveness. The Austrian floodplain is not activated for smaller HQs and only slightly activated for an HQ with a return period of 100 years. Thus, it is also crucial to consider the magnitude from which on a floodplain is activated to achieve the largest possible effectiveness.

The translation of the flood wave in the RS compared to the hypothetical CS (without dike breach) is increasing, i.e. a later approach of the flood wave, as the wave proceeds downstream. In the upper Danube, a peak delay of max. 1 hour is simulated with the RS scenario, in the middle and lower Danube the delay reaches up to 40 hours (not including the dike breach scenario). As mentioned, the magnitude of the flood wave in the Upper Danube is lower than HQ_2. Thus, an activation of the floodplain and a resulting retention of the flood wave is likely to be minor, compared to a larger HQ, as the water is transported mostly in the river channel itself for smaller HQs.

Comparing the real CS scenario (with dike breach) in Bistret with the RS scenario (including no dike breach), the flood peaks are reduced downstream of the PFPs after the dike breach, whereas the implementation of the potential floodplain scenario would lead to higher peak flow values. The attenuation caused by the dike breach is forwarded until the Calarasi gauge. However, the dike breach was not considered in the RS scenario and thus a comparison between the hypothetical 2006 event without dike breach and the RS scenario is more reasonable. In this case, a slight decrease in the flood peak and a translation between 12 to 39 hours later of the arrival of the flood peak is simulated when including the potential floodplain. In contrast, the time shift of the flood peak would be 98 hours earlier downstream of Silvata potential floodplain when comparing it to the real event with the dike breach, due to its special shaped hydrograph (Figure 21). Yet, even in comparison with the real event (with dike breach), further downstream the remaining potential floodplains caused again a comparably high Δt value. Therefore, even in this special case, the extension of the floodplains by the potential floodplains (RS) has a positive effect on the flood mitigation.

Table 13: Simulation results for the 2006 flood event in the Danube for the maximum discharge (Q_{max}) of the current state (CS) and the restoration state (RS) scenario. ΔQ (Q_{maxRS} – Q_{maxCS}) and Δt (t_{maxRS} – t_{maxCS}) are given downstream of each potential floodplain and at the hand-over-gauges

Danube						**2006**				
	# PFP	**DFGIS_ID**	**Name / Location**	**River-km**	**PFP size [ha]**	**Q_{max} CS 2006 [m³/s]**	**Q_{max} RS 2006 [m³/s]**	**ΔQ 2006 [m³/s]**	**ΔQ 2006 [%]**	**Δt 2006 [h]**
DE	1	DE_DU_PFP01	Oberelchingen - Lech	2491	16698	930	902	-28	-3.00	1
	2	DE_DU_PFP02	Lech - Neuburg	2478	3736	889	874	-15	-1.70	2
	3	DE_DU_PFP03	Grossmehring	2451	493	890	870	-20	-2.24	2
	4	DE_DU_PFP04	Katzau	2437	309	917	898	-19	-2.05	3
	5	DE_DU_PFP05	Geisling / Gmuend	2337	2503	1557	1530	-27	-1.71	1
		Engelhartszell		2201		4497	4494	-3	-0.07	0
AT	6	AT_DU_PFP01	Tullnerfeld	1938	16066	7030	7029	0	0.00	0
	7	AT_DU_PFP02	Nationalpark Donau-Auen	1880	12139	6981	6668	-313	-4.49	0
		Thebnerstrassl		1879		7736	7664	-72	-0.93	0
SK		Cunovo		1851		7711	7641	-70	-0.91	1
HU	8	HU_DU_PFP01	Szigetköz	1797	15711	7185	6994	-191	-2.65	9
	9	HU_DU_PFP02	Paks	1521	2214	7692	7602	-91	-1.18	5
	10	HU_DU_PFP03	Veránka-sziget	1463	16172	7366	7286	-80	-1.09	5
	11	HU_DU_PFP04	Béda-Karapnacsa	1426	5471	7213	7129	-84	-1.17	6
		Bezdan		1426		8339	8307	-32	-0.38	9
RS	12	RS_DU_PFP01	Siga - Kazuk	1409	6059	8263	8212	-51	-0.62	12
	13	RS_DU_PFP02	Vajska	1362	5988	8830	8801	-29	-0.33	18
	14	RS_DU_PFP03	Kamariste	1324	10072	8805	8680	-124	-1.41	30
		Drencova		1016		16854	16771	-83	-0.49	10

RO/ BG	15	BG_DU_PFP01	Slivata	753	2024	15575	15577	1	0.01	2
	16	BG_RO_DU_PFP02	Bistret	698	17300	15959	15923	-36	-0.23	13
	17	BG_RO_DU_PFP03	Dabuleni-Potelu-Corabia	634	12425	16354	16286	-68	-0.41	12
	18	BG_DU_PFP_04	Belene	576	5448	16934	16843	-92	-0.54	35
	19	RO_DU_PFP05	Suhaia-Zimnicea	554	6476	16914	16821	-93	-0.55	39
	20	BG_DU_PFP06	Vardim	537	1839	16942	16843	-99	-0.58	40
		Calarasi		375		17105	17021	-84	-0.49	27
RO/ BG	15	BG_DU_PFP01	Slivata	753	2024	15811	15577	-234	-1.48	-98
	16	BG_RO_DU_PFP02	Bistret-Dolni Tibar	698	18477	15842	15923	80	0.51	-17
	17	BG_RO_DU_PFP03	Dabuleni-Potelu-Corabia-Zagrajden	634	14306	16035	16286	252	1.57	2
	18	BG_DU_PFP_04	Belene	576	5448	16592	16843	251	1.51	16
	19	RO_DU_PFP05	Suhaia-Zimnicea	554	6478	16568	16821	253	1.53	28
	20	BG_DU_PFP06	Vardim	537	1839	16592	16843	251	1.51	31
		Calarasi		375		16476	17021	545	3.31	55

without dike breach (hypothetical)	peak reduction	ter peak
	no change	o change
with dike breach	peak increase	arlier peak

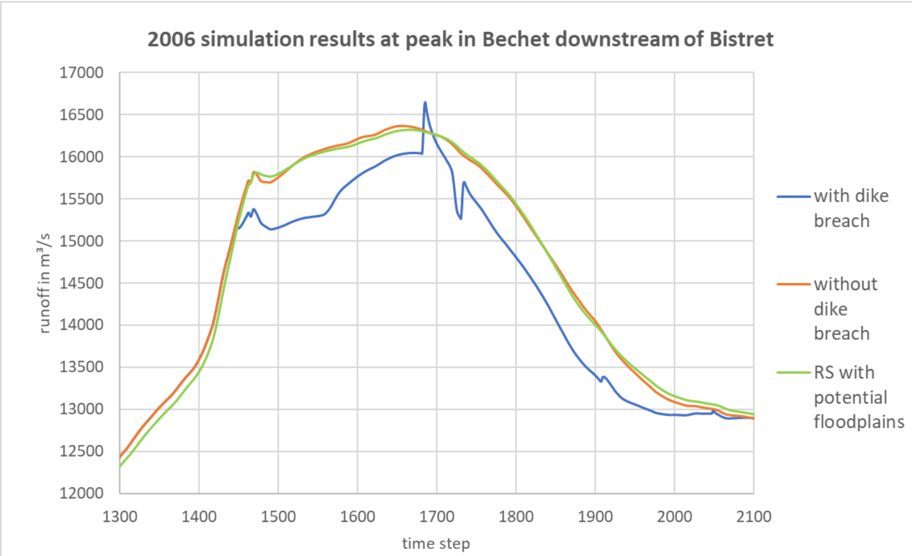

Figure 21: 2006 simulation results (with dike breach, without dike breach and RS) at the peak in Bechet downstream of the Bistret potential floodplain

Figure 22 and Figure 23 show the Q_{max} values downstream of each potential floodplain in a hydrological longitudinal section and also the size of the floodplain in ha for the hypothetical 2006 event (without dike breach) and the real event (with dike breach). The major tributaries (Inn, Morava, Drava, Tisza and Sava) are shown. The proceeding of the peak flow reduction is influenced by the tributaries, e.g. in Engelhartszell the effect of the upstream potential floodplains is superposed by the confluence with the River Inn. Here the reduction of the flood peak of 1.71% to 3% is diminished to 0.07%. Again the importance to consider tributary conditions while assessing the effects of additional floodplains for flood mitigation is emphasized.

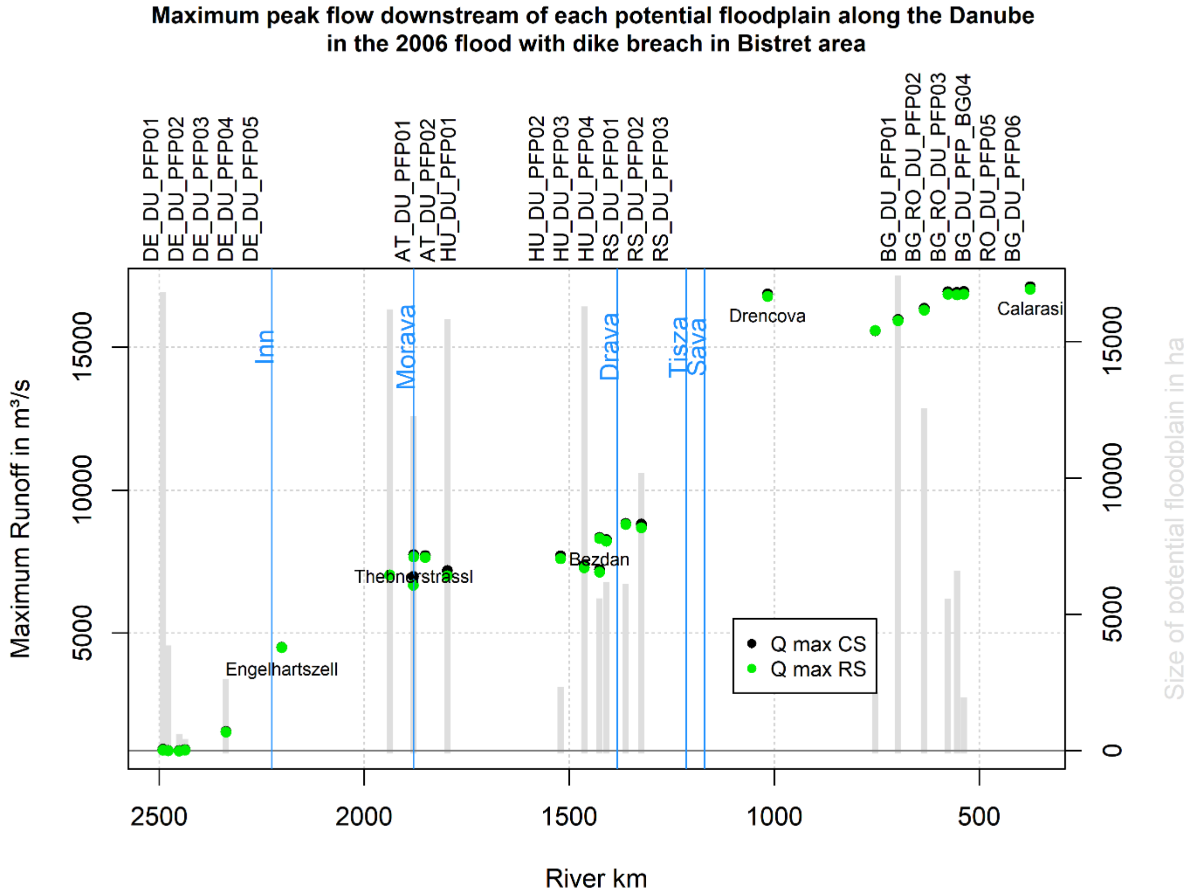

Figure 22: Peak flow of CS and RS simulations in the 2006 flood event downstream of the Danube potential floodplains and at hand over gauges showing the dike breach which occured in the 2006 flood event

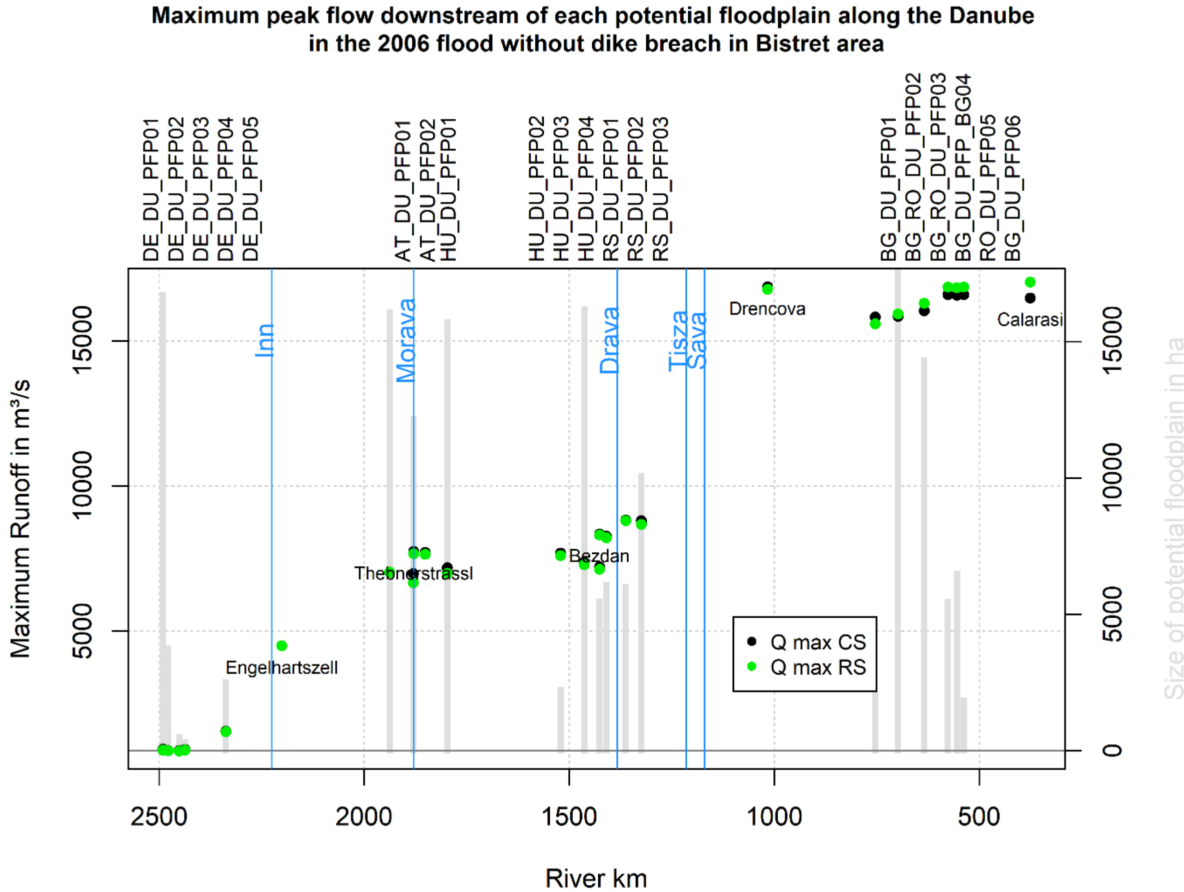

Figure 23: Peak flow of CS and RS simulations in the 2006 flood event downstream of the Danube potential floodplains and at hand over gauges showing a hypothetical situation without the dike breach in the 2006 flood event

5.2. Results of Danube flood event 2010

The simulated maximum peak runoff of the 2010 flood event in the CS and RS scenario, as well as the difference (ΔQ) between the two scenarios in m³/s and % are listed in Table 14. In addition, the temporal shift of the flood peak in hours (Δt) is given in the table after each potential floodplain and at the hand-over-gauges.

Regarding the ΔQ in %, positive values up to 1 % peak increase are observed at locations just downstream of tributary inflows (e.g. Lech downstream of DE_DU_PFP01 or in Drencova downstream of the tributaries Tisza and Sava). Further, the translation of the flood wave is, in cases of close tributaries, negative, i.e. an earlier approach of the flood wave. However, this can be explained by the superposition of the tributaries and the Danube's flood wave. In case of the Lech which discharges into the Donau just downstream of DE_DU_PFP01, an earlier approach of the flood wave of 10 hours is simulated.

Besides, a reduction of the flood peak and a positive translation of the flood wave is simulated, confirming the effectiveness of additional floodplains. Again, the highest flood peak reduction (-5.33%) is achieved after the floodplain AT_DU_PFP02 (Nationalpark Donau-Auen) in Austria. AT_DU_PFP02 covers 12139 ha, with no significant lateral inflow (Table 14). Yet, the larger floodplain AT_DU_PFP01 (Tullnerfeld) is again not activated and not resulting in a reduction of peak discharge.

Like in the 2006 flood event, the time shift of the peak is increasing from the Upper to the Lower Danube. The highest values of Δt are achieved in the RO_DU_PFP02 potential floodplain, where a positive translation of 77 hours is simulated. The exception of the earlier approach by 2 hours and the peak increase of 0.17% at the gauge Drencova is again explained by the confluence of the Danube and the tributary Sava (Figure 24) and is still observable at the next downstream floodplain (BG_DU_PFP01, Silvata).

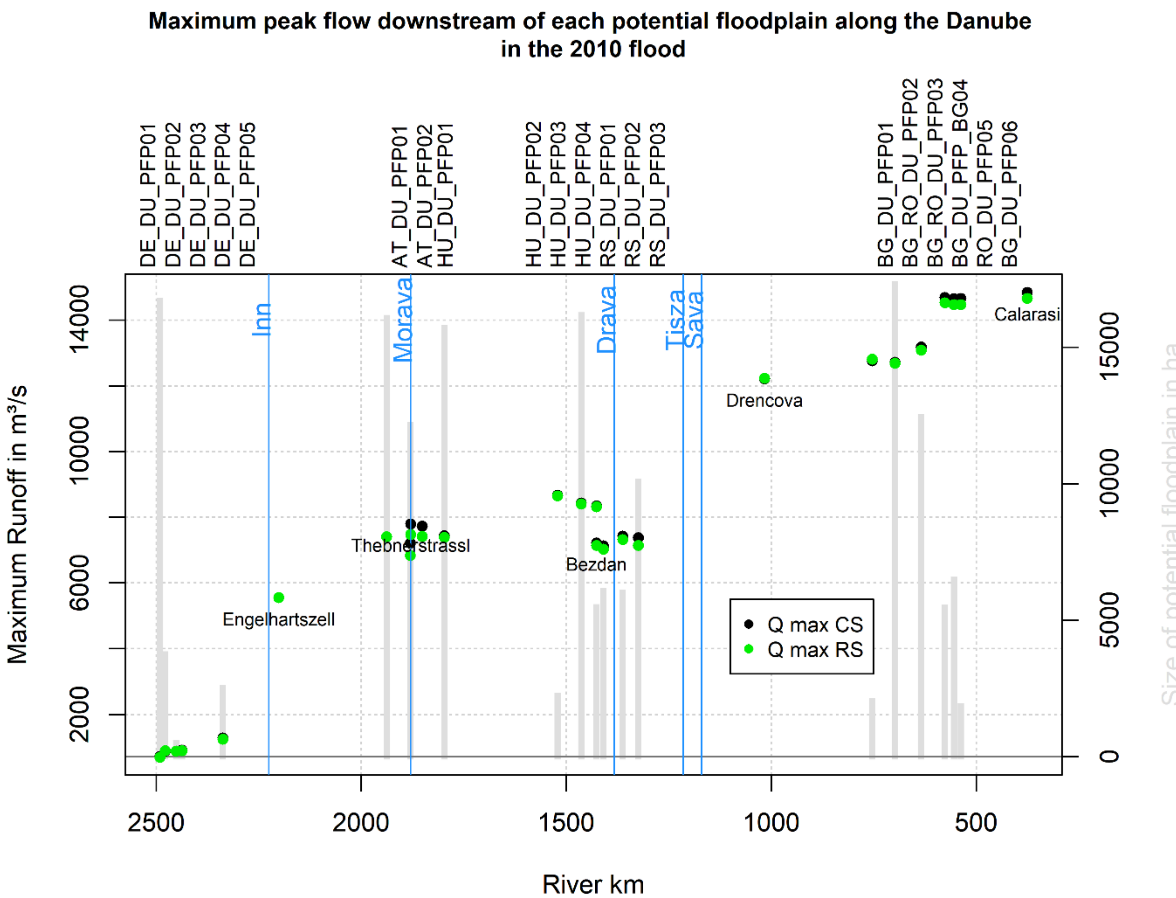

Figure 24: Peak flow of CS and RS simulations in the 2010 flood event downstream of the Danube potential floodplains and at hand over gauges

Table 14: Simulation results for the 20010 flood event in the Danube for the maximum discharge (Q_{max}) of the current state (CS) and the restoration state (RS) scenario. ΔQ (Q_{maxRS} – Q_{maxCS}) and Δt (t_{maxRS} – t_{maxCS}) are given downstream of each potential floodplain and at the handover gauges

Danube						**2010**				
	# PFP	**DFGIS_ID**	**Name / Location**	**River-km**	**PFP size [ha]**	**Q_{max} CS 2010 [m³/s]**	**Q_{max} RS 2010 [m³/s]**	**ΔQ 2010 [m³/s]**	**ΔQ 2010 [%]**	**Δt 2010 [h]**
DE	1	DE_DU_PFP01	Oberelchingen - Lech	2491	16698	713	687	-25	-3.55	-1
DE	2	DE_DU_PFP02	Lech - Neuburg	2478	3736	879	887	8	0.96	0
DE	3	DE_DU_PFP03	Grossmehring	2451	493	876	871	-5	-0.54	-10
DE	4	DE_DU_PFP04	Katzau	2437	309	906	887	-19	-2.06	1
DE	5	DE_DU_PFP05	Geisling / Gmuend	2337	2503	1272	1234	-38	-2.98	3
DE		Engelhartszell		2201		5545	5547	3	0.05	0
AT	6	AT_DU_PFP01	Tullnerfeld	1938	16066	7396	7398	2	0.02	0
AT	7	AT_DU_PFP02	Nationalpark Donau-Auen	1880	12139	7210	6826	-385	-5.33	2
AT		Thebnerstrassl		1879		7792	7463	-329	-4.22	4
SK		Cunovo		1851		7719	7412	-307	-3.98	4
HU	8	HU_DU_PFP01	Szigetköz	1797	15711	7432	7379	-53	-0.71	4
HU	9	HU_DU_PFP02	Paks	1521	2214	8662	8645	-18	-0.21	4
HU	10	HU_DU_PFP03	Veránka-sziget	1463	16172	8426	8397	-29	-0.34	2
HU	11	HU_DU_PFP04	Béda-Karapnacsa	1426	5471	8339	8307	-32	-0.38	9
HU		Bezdan		1426		7213	7129	-84	-1.17	6
RS	12	RS_DU_PFP01	Siga - Kazuk	1409	6059	7121	7022	-100	-1.40	11
RS	13	RS_DU_PFP02	Vajska	1362	5988	7421	7318	-103	-1.39	21
RS	14	RS_DU_PFP03	Kamariste	1324	10072	7369	7136	-233	-3.17	23
RS		Drencova		1016		12205	12226	21	0.17	-2

RO/ BG	15	BG_DU_PFP01	Slivata	753	2024	12759	12803	44	0.35	1
	16	BG_RO_DU_PFP02	Bistret	698	17300	12711	12680	-31	-0.24	35
	17	BG_RO_DU_PFP03	Dabuleni-Potelu-Corabia	634	12425	13172	13082	-91	-0.69	77
	18	BG_DU_PFP04	Belene	576	5448	14682	14523	-159	-1.08	19
	19	RO_DU_PFP05	Suhaia-Zimnicea	554	6476	14644	14462	-182	-1.24	14
	20	BG_DU_PFP06	Vardim	537	1839	14654	14464	-190	-1.30	13
		Calarasi		375		14832	14654	-178	-1.20	15

peak reduction — later peak
no change — no change
peak increase — earlier peak

5.3. Results of Danube flood event 2013

The simulated maximum peak runoff of the 2013 flood event in the CS and RS scenario, as well as the difference (ΔQ) between the two scenarios in m³/s and % are listed in Table 15. In addition, the temporal shift of the flood peak in hours (Δt) is given in the table after each potential floodplain and at the hand-over-gauges.

For the 2013 event a reduction of the flood peak is obtained in all cases (i.e. negative ΔQ values). The highest peak flow reduction (up to 14.32 %) in the RS simulation is achieved in potential floodplains in the German Danube section where the investigated event is of a magnitude larger than a HQ_{100}. An average reduction of 1.99% (median reduction 1.72%) is simulated by implementing additional floodplains, with a minimum reduction of 0.08% after BG_DU_PFP01 (Silvata) and the highest in Germany after DE_DU_PFP03 (Grossmehring). Δt values are also constantly positive, indicating a later approach of the flood wave generated by the additional potential floodplains of up to 11 hours. In the Romanian stretch, the potential floodplains show the highest retention of the flood wave of more than 3 days (77 hours).

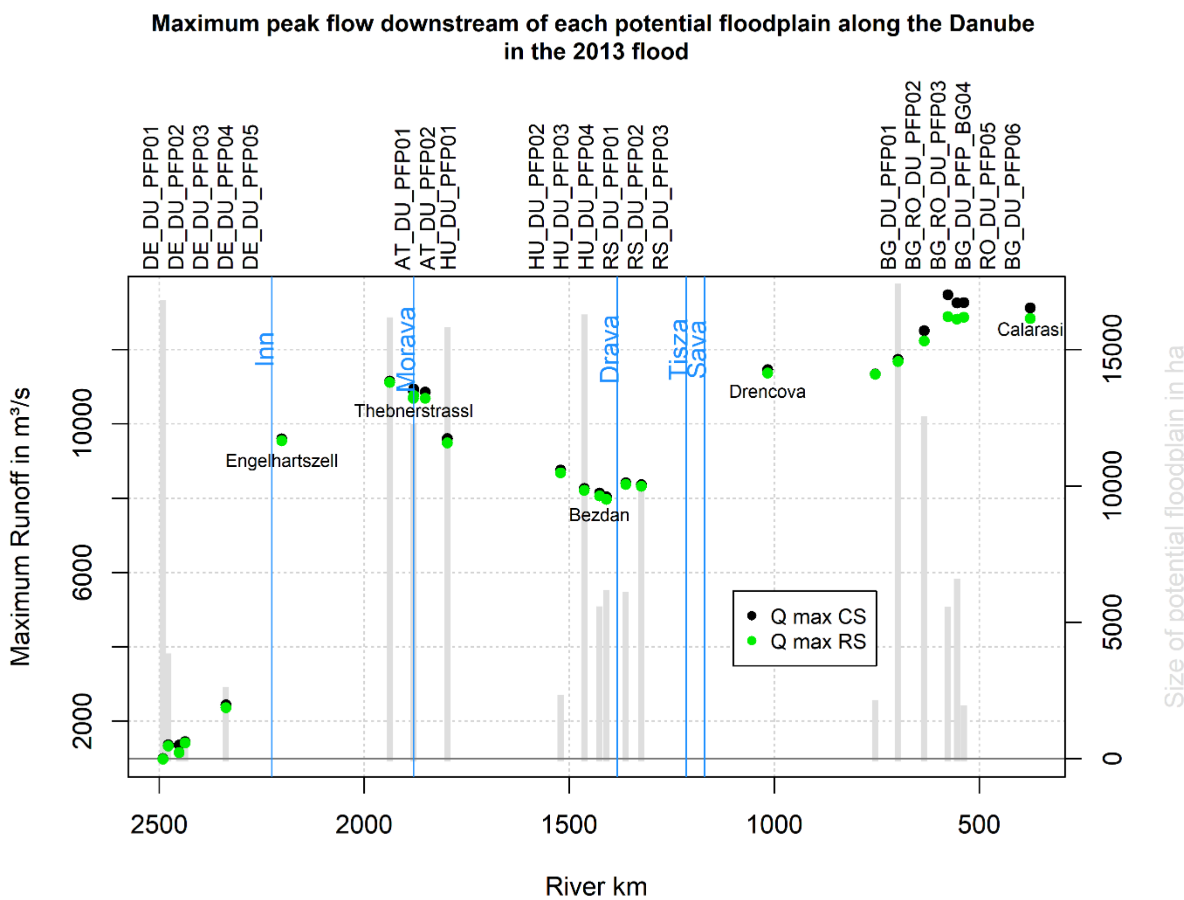

Figure 25: Peak flow of CS and RS simulations in the 2013 flood event downstream of the Danube potential floodplains and at hand over gauges

Table 15: Simulation results for the 2013 flood event in the Danube for the maximum discharge (Q_{max}) of the current state (CS) and the restoration state (RS) scenario. ΔQ ($Q_{maxRS} - Q_{maxCS}$) and Δt ($t_{maxRS} - t_{maxCS}$) are given downstream of each potential floodplain and at the hand-over-gauges

Danube						**2013**				
	# PFP	**DFGIS_ID**	**Name / Location**	**River-km**	**PFP size [ha]**	**Q_{max} CS 2013 [m³/s]**	**Q_{max} RS 2013 [m³/s]**	**ΔQ 2013 [m³/s]**	**ΔQ 2013 [%]**	**Δt 2013 [h]**
DE	1	DE_DU_PFP01	Oberelchingen - Lech	2491	16698	994	980	-14	-1.44	1
DE	2	DE_DU_PFP02	Lech - Neuburg	2478	3736	1362	1331	-31	-2.28	3
DE	3	DE_DU_PFP03	Grossmehring	2451	493	1351	1157	-193	-14.32	4
DE	4	DE_DU_PFP04	Katzau	2437	309	1444	1414	-31	-2.12	6
DE	5	DE_DU_PFP05	Geisling / Gmuend	2337	2503	2436	2362	-74	-3.05	7
DE		Engelhartszell		2201		9589	9541	-48	-0.50	0
AT	6	AT_DU_PFP01	Tullnerfeld	1938	16066	11140	11109	-31	-0.28	1
AT	7	AT_DU_PFP02	Nationalpark Donau-Auen	1880	12139	10875	10682	-193	-1.77	3
AT		Thebnerstrassl		1879		10929	10758	-170	-1.56	3
SK		Cunovo		1851		10851	10682	-170	-1.56	5
HU	8	HU_DU_PFP01	Szigetköz	1797	15711	9603	9478	-125	-1.30	6
HU	9	HU_DU_PFP02	Paks	1521	2214	8750	8673	-77	-0.88	7
HU	10	HU_DU_PFP03	Veránka-sziget	1463	16172	8261	8206	-55	-0.66	1
HU	11	HU_DU_PFP04	Béda-Karapnacsa	1426	5471	8129	8057	-72	-0.89	9
HU		Bezdan		1426		8129	8057	-72	-0.89	9
RS	12	RS_DU_PFP01	Siga - Kazuk	1409	6059	8028	7963	-65	-0.81	9
RS	13	RS_DU_PFP02	Vajska	1362	5988	8409	8364	-45	-0.53	8
RS	14	RS_DU_PFP03	Kamariste	1324	10072	8360	8317	-43	-0.51	8
RS		Drencova		1016		11450	11362	-88	-0.77	11

RO/ BG	15	BG_DU_PFP01	Slivata	753	2024	11338	11328	-9	-0.08	3
	16	BG_RO_DU_PFP02	Bistret	698	17300	11727	11672	-55	-0.47	1
	17	BG_RO_DU_PFP03	Dabuleni-Potelu-Corabia	634	12425	12501	12225	-276	-2.21	4
	18	BG_DU_PFP_04	Belene	576	5448	13462	12880	-582	-4.32	74
	19	RO_DU_PFP05	Suhaia-Zimnicea	554	6476	13246	12808	-437	-3.30	75
	20	BG_DU_PFP06	Vardim	537	1839	13259	12861	-397	-3.00	77
		Calarasi		375		13117	12826	-292	-2.22	32

peak reduction — later peak
no change — no change
peak increase — earlier peak

6. Summary and conclusions

After the comparative analysis of all investigated scenarios at the tributaries Morava, Tisza and Sava as well as along the Danube from Neu-Ulm (DE) to Calarasi (RO) the following conclusions can be drawn:

- Overall the simulations with implemented additional floodplains show a reduction of the flood peak (up to 14.32 % for a larger than HQ_{100} event) and longer travel times of the flood wave; only in some simulations the simulated peak runoff is higher and the wave approaches earlier in the restoration scenario (RS), including the potential floodplains, compared to the current state scenario (CS), including only the currently active floodplains.
- The unexpected increase of the peak after a potential floodplain, the surprising negative translation of the flood wave or generally, the decrease of the effects can be explained by local conditions. Thus, for the determination and evaluation of the effects resulting from floodplain restoration, it is important to consider multiple factors.
- Factors which influence the effects of floodplain restoration are:
    - The magnitude of flood events (HQ) from which on a floodplain is activated (e.g. the potential floodplain AT_DU_PFP_01 Tullnerfeld in Chapter 5.1, 5.2 and 5.3)
    - The shape of the hydrographs and thus, the characteristics of the flood event (e.g. simulations for the Sava tributary (Chapter 4.3))
    - The tributary conditions upstream and downstream of the additional floodplains, as well as the respective flood magnitude in the tributaries, resulting in wave superposition (Chapter 4.2))
    - Special local conditions like dikes, polders, etc. (e.g. dike breach in the 2006 event (Chapter 5.1))
    - The land use in the additional floodplains
- Thus, not only the size of the floodplain has to be considered, but also those above-mentioned factors.
- Additionally, a combination of various restoration measures might result in a different effectiveness, depending on the local conditions.
- In the simulations, the effects on the maximum discharge (ΔQ) and translation of the flood wave (Δt) are only visible when the floodplain is activated. In river sections, where the flood is e.g. only a HQ_2, the river banks are not flooded and thus the floodplain is not inundated.
- In many cases, a higher flood magnitude (HQ) produces higher Δt values (i.e. later approach of the flood wave) in the restoration scenario (RS).

- The translation of the flood wave (Δt) after potential floodplains increases with decreasing river kilometers, that means the further downstream the larger is the temporal displacement of the flood wave in hours.
- It was shown that the combined effect of floodplains can be significant. Thus, it is important to follow a rather integrated approach to efficiently achieve the largest possible effects.
- The demonstrated 1D model chain is a well applicable tool to investigate the trans-regional effects of floodplain restoration on a large scale. The 1D models have a short running time and thus several scenarios can be simulated and compared. Nevertheless, for a detailed floodplain investigation 2D models should be used. The heterogeneity of floodplains can cause flow situations (e.g. flow recirculation), which can be satisfactory modelled only with 2D models.
- For a more detailed analysis of the flood wave propagation and long-reaching effect, it is suggested to extract values for the maximum discharge (ΔQ) and temporal displacement of the flood wave (Δt) at more locations, to create continuous longitudinal sections. Also, the input hydrographs of tributaries to the investigated river stretch should be analyzed to quantitatively compare the effects of both, the additional potential floodplains, and the tributary influence.

7. Responsible Persons for the 1D-Modelling

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