2D flood modelling in the Danube Floodplain pilot areas

Deliverable D 4.1.1

Report on the technical realization scenarios taken into consideration for modelling, the implementation in a 2D model and assessment of the impact as input for D 4.4.1 and part of output 4.1.

WP	WP4: Flood prevention pilots
Activity	Activity 4.1
Deliverable	D 4.1.1 Report on the technical realization scenarios taken into consideration for modelling, the implementation in a 2D model and assessment of the impact as input for D 4.4.1 and part of output 4.1.
Activity-leader	TUM
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Involved partners	All partners from countries with pre-selected pilot areas, CUEI, TUM
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Place and date	Munich, August 2020

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1. Abstract

In this deliverable (D 4.1.1) of work package 4 (flood prevention measures tested in pilot areas) of the Danube Floodplain project, the effect of floodplain restoration measures in different flood events is assessed. The national partners apply hydrodynamic 2D models in five pre-selected pilot areas to investigate the hydraulic efficiency of restoration measures. The pilot areas *Begečka Jama* in Serbia and *Bistret* in Romania are located at the Danube River. The other three pilot areas are situated at tributaries to the Danube: *Krka* in Slovenia at the Krka River, *Middle Tisza* in Hungary at the Tisza River, and at the *Morava* River at the border between Slovakia and the Czech Republic. A homogenous approach with the current state scenario (CS) and two different restoration scenarios (R1 – realistic and R2 – optimistic) for three hydrological events (HQ2-5, HQ10-30 and HQ100) is implemented in each pilot area. Restoration measures include e.g. dike relocation to reactivate floodplains, land use change and topographical variations in the river bed and floodplain expansion (e.g. by reactivating old oxbows). The measures are selected by the national partners.

Spatial results of the applied 2D hydraulic models in raster format of the maximum water depth and flow velocity of each scenario are available for each pilot area showing different effects depending on the restoration measures and maximum discharge of the simulated flood event. Difference maps are created depicting the deviation of the RS scenarios to the CS scenario. All investigated scenarios reveal an alteration of water depth and flow velocity values in different magnitudes. The increase of the flooded area due to dike relocations enhances the stored volume and causes a lower water level and flow velocity in most cases.

Furthermore, the results of the simulated streamflow time series at the downstream model border are compared. The reduction of the flood peak discharge and the translation of the flood wave (time shift of maximum discharge) are analyzed quantitatively. Besides the Begečka Jama pilot area, all pilot areas show a notable effect of these parameters in different magnitudes. The effects are mainly visible in the R2 scenario. The maximum peak reduction can be achieved with the R2 scenario (HQ100) simulation in the Morava pilot area. However some scenarios also reveal a slight increase of the peak value of the flood wave. The flood wave translation is considerable in the Middle Tisza or Bistret pilot area in R2 where the peak approaches 11 to 16 hours later. Yet, an earlier peak is simulated in Morava, which can be explained by an superposition with peak discharges of tributaries.

In general, the 2D hydrodynamic models are very well applicable for this type of study and can be used to analyze the effect of restoration measures on flood wave alterations in the pilot areas. Moreover, the high-resolution (1 - 15m) water depth and velocity results enable a spatially detailed analysis of the restoration effects in the whole floodplain, which is an important input for the ecosystem service (activity 4.2) and the flood risk (activity 4.3) assessment.

2. Introduction

On a basin wide level, the improvement of the current situation to prevent and reduce damage to human health, the environment, cultural heritage and economic activity along the Danube River is intended. Therefore, the ICPDR (2015) recommends with particular importance restoration measures which allow flood retention in previously natural flooded areas. Several measures, such as the relocation of dikes, the removal of weirs, the afforestation of river banks and floodplains as well as the restoration of the natural river beds and meanders are suggested in the Flood Risk Management Plan for the Danube River Basin District (ICPDR 2015).

Analyzing the effects of diverse measures for different hydrological conditions is the main focus of work package four (WP4) of the Danube Floodplain project. In WP4, flood prevention and floodplain restoration measures are investigated in five preselected pilot areas. Within activity 4.1, hydraulic efficiencies with respect to flood protection of particular pilot restoration projects are evaluated. Existing or, if necessary, new hydrodynamic 2D models in the pilot areas are applied to quantitatively assess the effects of restoration measures on flood protection.

Harmonized restoration settings and hydrological scenarios are applied to ensure comparability between the five pilot areas. A current state scenario model (CS) is developed and two different restoration scenarios, one realistic (implementation planned, R1) and one optimistic restoration scenario (R2) based on local circumstances. The three different models are run with three hydrological scenarios to capture the different impacts.

The results of the hydraulic simulations in activity 4.1 (water depth, flow velocity, hydrographs of model output, etc.) are quantitatively analyzed and processed for a further assessment of the floodplains regarding its habitats and ecosystem services (activity 4.2) but also for a standard and extended cost benefit analysis (CBA) (activity 4.3). Furthermore, they are used for the (pre-)feasibility study in preparation of the national approval process which is part of activity 4.4. Figure 1 depicts the interactions of the procedures and results within WP4.

These results are, on the one hand, part of the realization process in the pilot area countries, on the other hand, they deliver experience and recommendations for similar restoration projects in the floodplains of the Danube Basin.

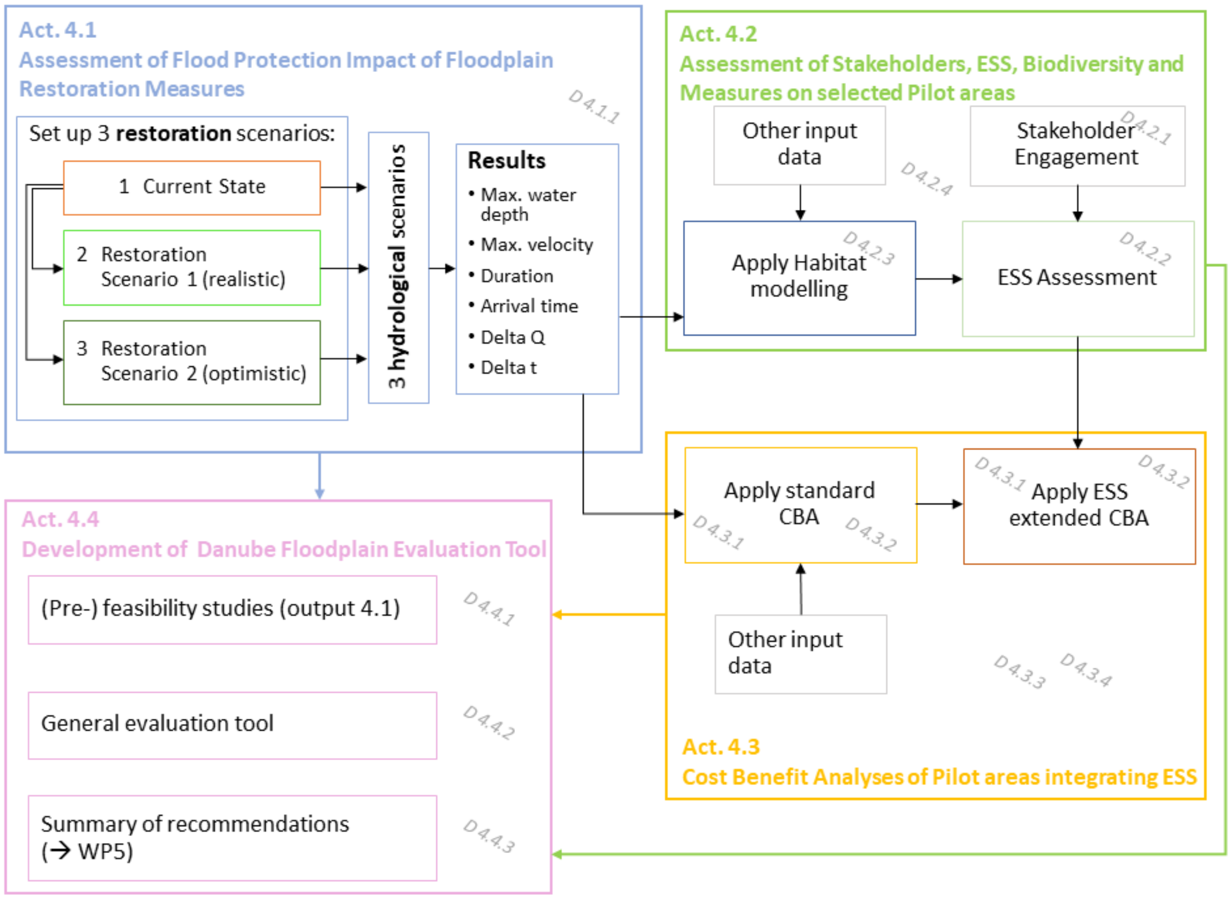


Figure 1: Flow chart of the tasks in WP4 in the pilot areas including activities and deliverables

3. Pilot areas

3.1 Location of the pilot areas

There are five pre-selected pilot areas chosen for the Danube Floodplain project in the Danube basin. Two are situated directly along the Danube River and three at tributaries to the Danube. Figure 2 shows the location of all the pilot areas in the Danube Basin. Figures 3 to 7 show the topographic and aerial maps of the individual pilot areas. The geographical and hydrological characteristics of the five pilot areas as well as the investigated restoration measures are summarized in chapter 3.2.

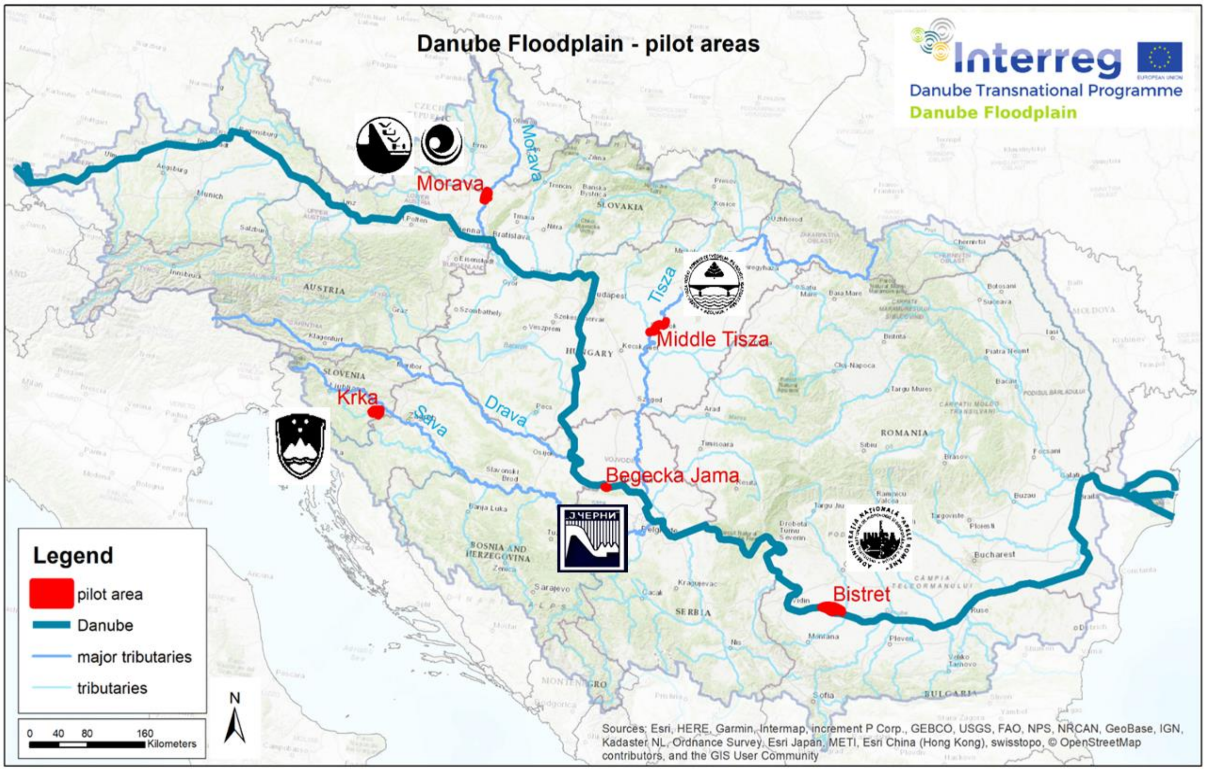


Figure 2: Location of the five pilot areas in the Danube Basin with the responsible partners

1) **Begečka Jama** at the Danube in Serbia, investigated by the Jaroslav Cerni Water Institute (JCI);

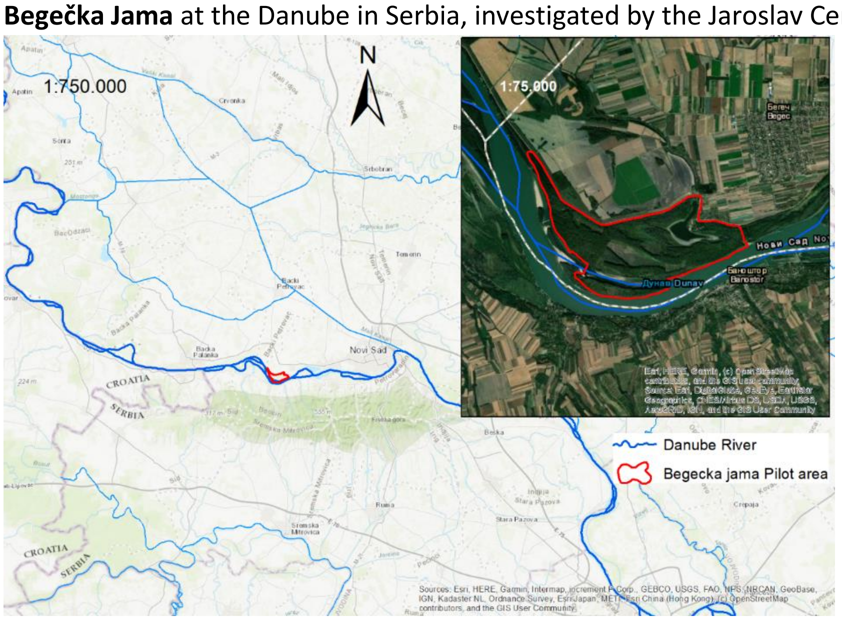


Figure 3: Topographic and aerial map of the Begečka Jama pilot area

2) **Bistret** at the Danube in Romania, investigated by the National Administration "Romanian Waters" (NARW) and the National Institute for Hydrology and Water Management of Romania (NIHWM);

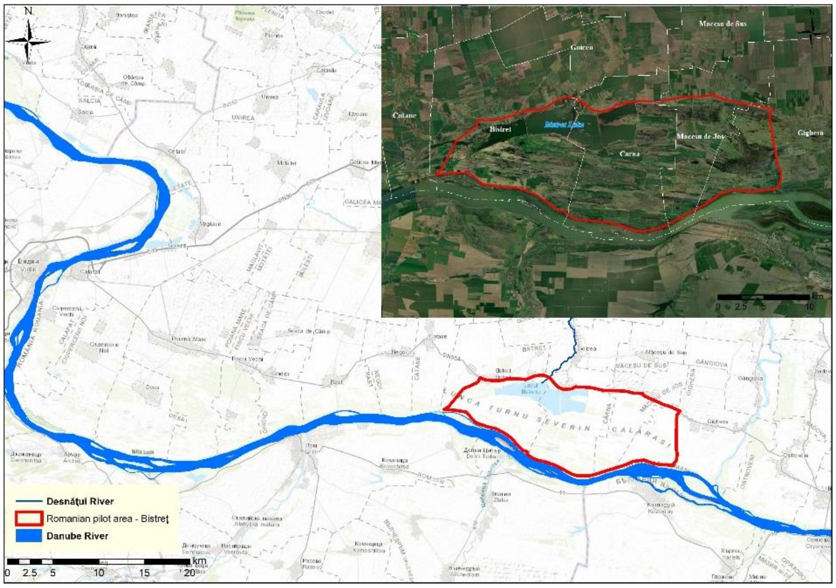


Figure 4: Topographic and aerial map of the Bistret pilot area

3) **Kostanjevica na Krki (Krka)** at the Krka River in Slovenia, investigated by the Slovenian Water Agency (DRSV);

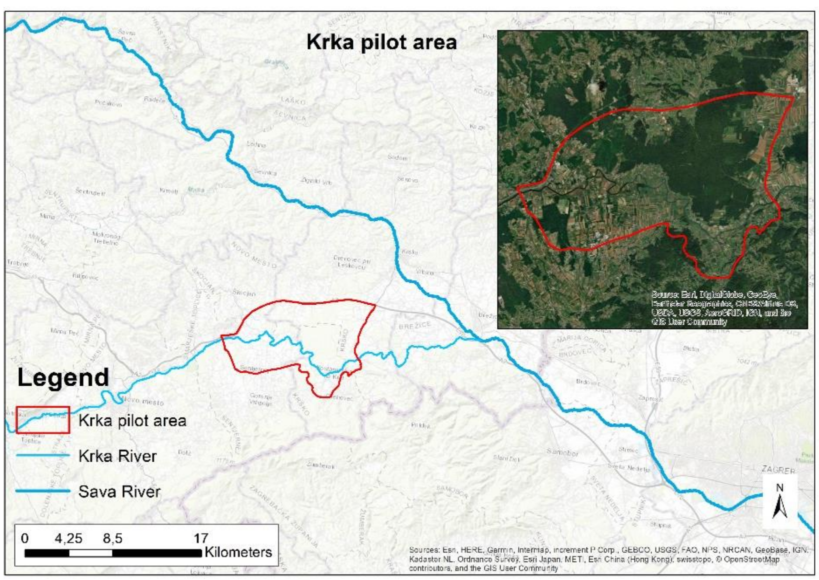


Figure 5: Topographic and aerial map of the Krka pilot area

4) **Middle Tisza** at the Tisza River in Hungary, investigated by the Hungarian Middle Tisza District Water Directorate (KOTIVIZIG) and

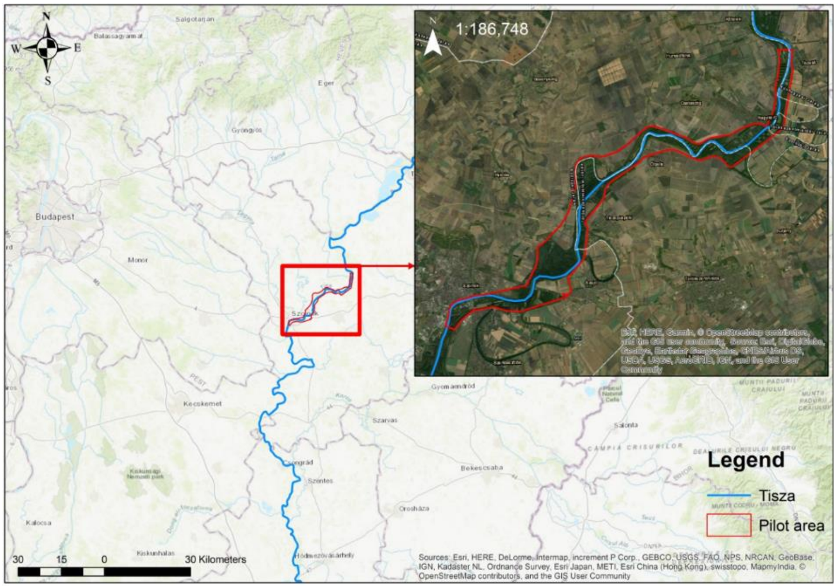


Figure 6: Topographic and aerial map of the Middle Tisza pilot area

5) **Morava** at the Morava River at the border between the Czech Republic and Slovakia, investigated by the Czech Morava River Basin Authority (MRBA) and the Water Research Institute of Slovakia (VUVH);

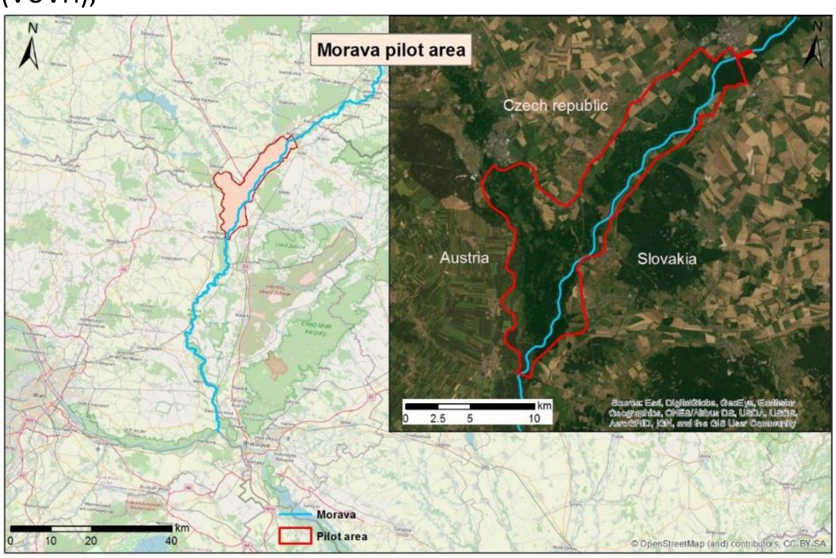


Figure 7: Topographic and aerial map of the Morava pilot area

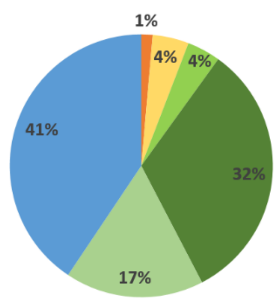
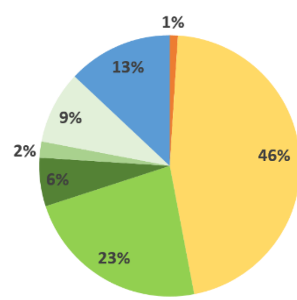
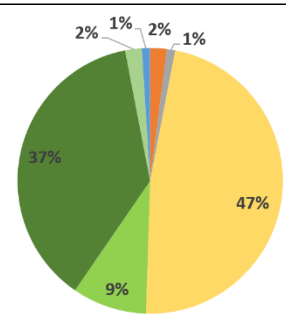
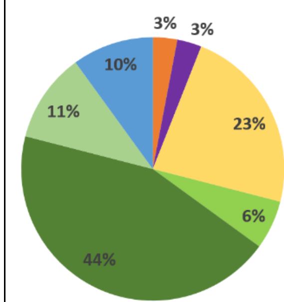
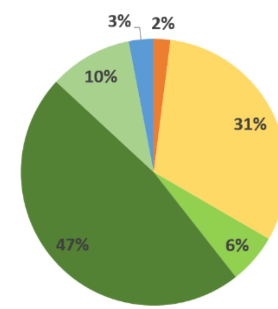
3.2 Characteristics of the pilot areas

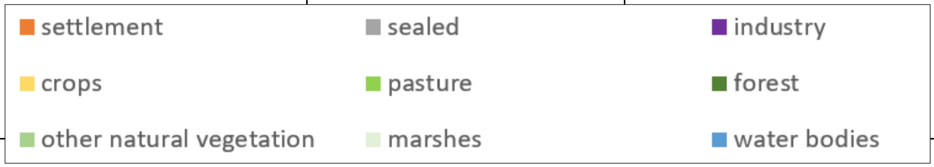
The five pre-selected pilot areas show different properties in size, from 10km² in the Begečka Jama area to 177 km² at the Romanian Danube in Bistret, but also in geographical characteristics and land use. Further, the purpose of restoration follows different motivations, e.g. flood risk management, reconnecting old oxbows and reactivating the floodplain, enhancing the ecological conditions to improve habitats for plant and fish species, or promoting sustainable development and ecotourism. The planned restoration measures also differ. Mainly dike relocation, land use change or excavation and reactivation of old oxbows are implemented by topographical adjustments of the 2D model. Table 1 comprehensively summarizes the characteristics of each pilot area in detail.

Table 1: Characteristics of the five pilot areas in the Danube Floodplain Project

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
River	Danube	Danube	Krka	Tisza	Morava
Country	Serbia	Romania	Slovenia	Hungary	Slovakia, Czech Republic
Responsible PP	JCI	NIHWM/HARW	DRSV	KOTIVIZIG	VUVH/MRBA
Pilot area size [km²]	10.13	176.98	85.56	49.51	147.37
Geographical / morphological characteristics	Begečka Jama Nature Park (BJNatP) is located on the active floodplain on the left bank of the Danube River, upstream from the City of Novi Sad. The length of the area is approx. 7,8 km (rkm 1.276+200-1.284), while the central point is 45° 13' 23“N, 19° 36' 23“E. Formerly, it was part of a larger floodplain, that was reduced to the current extent due to agricultural development and flood protection measures	The **Bistret** pilot area is located on the left bank of the Danube river, just upstream of the confluence with Jiu river. It has an average length of approx. 24 km and an average width of about 7 km. The average altitude of the land in the Bistret enclosure is 27.50 mdMN, and the average slope is approx. 0.00833%. The Bistret area also includes the Bistret lake in	The Kostanjevica na Krki pilot area is combined from the Kostanjevica na Krki town, Krakovski forest, and Šentjernej field. It is situated in the SE part of Slovenia, at (45°50'46'' N 15°25'29'' E, altitude 155m). The pilot area is influenced by moderate continental climates. The whole area has natural water retention function. The main watercourse is the Krka river (94 km, 2,315	The **Middle Tisza** region is a meandering river section. Flood risk and vulnerability are of particular importance in the area. After the river regulation in the 19th - 20th centuries both riverside are there dyke construction. These dyke sections protect the settlements, industrial zones and the arable lands from flood event. The Middle Tisza section is the lower section of the river, so in	The **Morava River** is a lowland river, in the past strongly meandering, extensive river training works were done (channel straightening, cut-off meanders, uniform channel with bank protection, reduction of floodplain areas, interruption of longitudinal continuity by weirs and sills); confluence of Morava and Thaya on CZ side with large retention

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
	implemented in the early 18th century. Several geomorphologic types of fluvial erosion of different ages - islands, natural levees (ridges), oxbow lakes and backwaters, created mutually by fluvial erosion and reclamation- enabled the development of a mosaic of wetland habitats at different stages of succession of floodplain vegetation, which represent a refuge for many animal and plant species. BJNatP is an important reproduction area for many fish, amphibians and bird species. The status of the wetland habitats (oxbows, backwaters, wet meadows, marshes) and the hydrological regime have significantly deteriorated over the past 30 years due to siltation and aggradation caused by both natural processes and anthropogenic activities (forestry, pollution from the surrounding arable land, flood protection). Intensive land use caused habitat degradation and fragmentation.	which the Desnatui tributary flows. The area is delimited in the south by the defense dikes from the Danube, in the west by the compartmentalization dike between the Rast enclosure and the Bistret enclosure, in the north by the Bistret lake and the terrace, and in the east by the magistral irrigation channel Macesu-Nedeia. In the northern terrace area are the localities Bistret, Plosca, Dunareni, Sapata, Macesu de Jos. The average altitude of the terrace is about 31 mdMN. In the pilot area, drying and irrigation systems and pumping stations are executed. The main pumping stations that ensure the drying of the area are SP-Malaians in the upstream end which also ensures the gravitational discharge of Lake Bistret when flows on the Danube are less than aprox. 8000 m^3/s, SP-Stejaru, and SP-Nedeia located in the downstream end of pilot area.	km^2). In the upper part, where the river is in a gorge, there are many karstic underground springs. The surface tributaries appear in the lower part of the Krka river where the valley widens. Some of them (Radulja, Sajovec, Lokavec, Senuša) discharge into the Krka river near the pilot area. The lower part of the river is characterized by slow river flow and extensive flood plains – one of them is Krakovski forest, which represents the largest remnant of lowland floodplain forest in the country (consisting of Pseudostellario–Quercetum and Pseudostellario europaeae-Carpinetum (tree species such as Quercus robur, Carpinus betulus, Alnus glutinosa are characteristic here). Beside the Krka river itself, it is the Krakovski forest which is important on the European level by its habitat and species diversity (protected under the Habitat	this area can accumulated more sediment on the floodplain area and lose the conveyance capacity between the dykes. In the floodplain the main land use type is the forest, the second is crops and we can find some other less land use type (e.g. pasture).	area to release flood discharges; several villages along the area but outside the floodplain area; modelling area delineated by present flood dykes and the retention area on the confluence with Thaya river.

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
	River training and flood protection measures disrupted the dynamics of flood events. The planting and management of poplar plantations enabled the spreading of invasive plant species, whilst the backwaters, oxbows and wet meadows are being filled up due to forestry activities and needs. The area became less attractive for visitors due to the loss of aesthetic and recreational values.		and Bird Directives, and Natura2000). Šentjernej field is covered mostly by meadows, farmland, and scattered settlements. Kostanjevica na Krki is an important cultural and historical site. Geologically and geomorphologically about it is largely a tectonic lowland depression on the carbonate geological basis, filled with clay-gravel sediments.		
land cover (CORINE 2020) of 2D model area					



Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
Current ecological status and deficits	The pilot area belongs to the Danube River Water Body RSD8: Danube between Novi Sad and HR-RS State border. The status assessment below is taken from the Danube RBMP update 2015, ICPDR (DanubeGIS): - The water body is provisionally HMWB, - The chemical status is poor (assessed with low confidence), - The ecological potential is moderate (assessed with medium confidence).	3 Surface Water Bodies has been identitified for the active floodplain - RORW14-1-27_B172 Desnatui -Ac. Fantanele - Ac. Bistret in moderate ecological status status (river continuity and morphological conditions in moderate status). Moderate status for fishfauna (caused by upstream river dam Fantanele) - RORW14-1-27-8_B176 Buzat - izvor - cf. Desnatu;RORW14-1-27-7_B175 Baldal (Jivan) - izvor - cf. Desnatui in good ecological status - Good chemical status with a small increasing for CCOCr for all WB	General information on the Krka (section Otočec – Brežice) Water body, according to the RBMP for Danube basin district: - Overall ecological status: GOOD - Significant diffuse pressures: Agriculture - Significant point pressures: Communal waste waters, Industrial waste waters - Significant hydromorphological pressures: Land use in the riparian area - Other significant anthropogenic pressures: No Protected areas: - The entire area is characterized by high biodiversity. More than 50 species from the Natura2000 protected species list can be found in the river and on its floodplains. Some of them are on the International Union for the Conservation of Nature and Natural Resources red list.	The Middle Tisza River is a natural category with heavily modified sections. This section of the river, based on physico-chemical data supporting biology, has excellent potential and the concentrations of the hazardous substances we studied did not exceed the environmental quality limit. The narrow strip of floodplains between the dams of the Tisza active floodplain, plays an important role in the migration and spreading of aquatic and aquatic habitats as ecological or green corridors. The floodplain of the Middle Tisza, due to its function as a core area and as an ecological corridor, is of great natural value and is of great ecological importance. Unfortunately, nowadays floodplains are the most important routes and channels for the invasion of invasive plant species. This process could significantly reduce biodiversity in the future. In	Heavily modified water body (HMWB) - Ecological status: 3 - moderate; Hydromophological quality: 4 - poor

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
				addition, floodplain management is in many cases not consistent with the requirements of natural floodplain habitats. The area is also part of the Middle Tisza (HUHN10004) Special Protection Area and the Middle Tisza (HUHN20015) Special Area of Conservation.	
Major restoration purposes	• Adequate water supply throughout the year in the Begečka Jama lake, oxbows and channel system and improving habitats for aquatic species • Increase in the water surface area and depth of the oxbows and existing channels • Increase in biodiversity and spawning areas as a result of habitat restoration • Increasing the types of ecosystem services, as well as improvement of the quality and quantity of existing ecosystem services of the area	• Flood protection for population (major damages during 2006 flood) • Sustainable development and ecotourism	Improvements for: • Flood risk management • Nature protection • Forestry	• Increasing conveyance capacity/ floodplain area • Decreasing flood hazard	• Improvement of flow conditions in the river floodplains with respect to flood protection and nature protection goals • Optimization of water regime in the floodplains • Enhancement of conditions for diverse biotopes, which can be found in the area of interest • Improvement of conditions for fish migration

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
Restoration measures Scenario 1 - realistic	• Cleaning and widening of the existing connecting channel between Danube River and Begečka Jama lake and weir reconstruction which allow fish migration • Floodplain DEM modification via the deepening of existing oxbows and channels and the excavation of new channels between the deepened oxbows, which would allow for the controlled inflow/outflow from the system • Increase the diversity of the river morphology as a result of the excavation, deepening and cleaning of oxbows, and existing and new channels. • Creation of new fish spawning areas which contribute to the maintenance and increase of biodiversity.	• Construction of a recreational and fishfarming lake (200 ha) in the area of Rast • Relocation of the dikes in the confluent area of Desnaţui River with Bistret Lake • Creation of a large water drainage channel to supply Lake Bistret and to facilitate the natural flow of Desnatui River back in the Danube	SC1 - Scenario 1 is a combination of a corridor enabling floodplain activation, and measures to increase water conductivity in the river bed through Kostanjevica, thus lowering water levels within the settlement. It comprises 2 measures: K1- river bed deepening of the northern stream of the Krka river through Kostanjevica, and an inundation at the bifurcation, and K3- a corridor to the floodplain, length 650 m, width 45 m.	• Increase floodplain area: Dike relocation • Land use change: Arable land to pasture • Create fish spawning area	• removal of weirs • Removal or adjustment of selected barriers (weirs, sills) • removal of levees • relocation of flood dykes (to include the cut off sidearms in the floodplain area)

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
Restoration measures Scenario 2 - optimistic	• Cleaning and widening of the existing connecting channel between Danube River and Begečka Jama lake and weir reconstruction which allow fish migration • Floodplain DEM modification via the deepening of existing oxbows and channels and the excavation of new channels between the deepened oxbows, which would allow for the controlled inflow/outflow from the system • Increase the diversity of the river morphology and diversity of cross profiles of the river as a result of the excavation, deepening and cleaning of oxbows, and existing and new channels as well as the widening of the existing river channel. • Creation of new fish spawning areas which contribute to the maintenance and increase of biodiversity.	• Additional dike relocation from the Danube close to the villages along the alluvial terraces	SC2 - Scenario 2 is a combination of 4 measures, being three corridors enabling floodplain activation, and additional measures within the river bed in Kostanjevica: K1– river bed deepening of the northern stream of the Krka river through Kostanjevica, and an inundation at the bifurcation; K2– a corridor to the floodplain, length 950 m, width 30 m; K3– a corridor to the floodplain, length 650 m, width 45 m; K4– a corridor to the floodplain, length 280 m, width 60 m.	• Increase floodplain area: Dike relocation and Controlled dike overtopping • Land use change: Plough (cultivated) land to pasture • Vegetation regulation: Controlled afforestation • Create wetland habitats (eg. lake)	• R1 + relocation of flood dykes (further than in R1) • Renewal of river pattern Reconnection of oxbows with the main Morava channel (at present state they are behind the dyke) Deepening of existing oxbows
Major recent floods	2006: HQ100	2006: >HQ100 (ICPDR 2008)	2010: HQ100	2000: ~HQ100	2010: >HQ100 (ICPDR 2012)

Pilot Area	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
	2010: HQ10-20 (HIDMET 2014)	2010: >HQ20 (ICPDR 2012)			
HQs investi-gated	HQ2-5	HQ2	HQ2-5	HQ2, HQ5	HQ5
	HQ10-20	HQ10	HQ10	HQ10, HQ30	HQ10
	HQ100	HQ100	HQ100	HQ100	HQ100

3.3 Restoration scenarios in the pilot areas

The responsible project partners develop two restoration scenarios (RS1 and RS2) individually in cooperation with national authorities as well as the identified stakeholders (Table 1 and Table 2). The planned restoration measures are discussed on two stakeholder workshops in each of the pilot areas with relevant stakeholders – fishery, agriculture, shipping, municipal authorities, nature protection, residents etc. The results of these stakeholder meetings are summarized in deliverable D 4.2.1.

In Table 2, as summary of all restoration measures in the pilot areas for both scenarios is given. Different kinds of restoration measures , e.g. in-stream measures which change the roughness and the shape of the river bed, alterations in the floodplain size (through e.g. dike relocation), as well as morphological and / or land cover changes in the floodplain are determined. Of course, the main purpose of the restoration measures is to re-establish as far as possible the natural floodplain conditions and to achieve a win-win situation for both, the environment and for flood protection.

After an agreement on the explicit restoration measures in each scenario with the stakeholders, the project partners set up the **three 2D models** for the pilot areas.

1. **Current State (CS)**
   The first model represents the current state of the area (CS). It is set up based on a recent high resolution DEM and up-to-date ground survey data. It is the base model for the restoration scenarios models.
2. **Realistic restoration scenario 1 (R1)**
   In the second 2D model (realistic restoration scenario 1; R1) all planned measures are implemented, e.g. dike relocation, modification of land cover and river geometry.
3. **Optimistic restoration scenario 2 (R2)**
   Furthermore, an optimistic scenario model (optimistic restoration scenario 2; R2) is developed which includes more extensive measures. With this approach, the maximum capacity of flood protection obtained by restoration measures in the pilot areas without consideration of real limitations is shown.

In order to quantify the effects of the two restoration scenarios, the simulation results of both are compared with the current state scenario.

Table 2: Restoration measures determined and implemented for R1 and R2 for the five pilot areas

Restoration measures to be implemented in the pilot areas										
restoration scenario	RS1	RS2	RS1	RS2	RS1	RS2	RS1	RS2	RS1	RS2
Which measures are implemented in the pilot areas?	**Begecka Jama**		**Bistret**		**Krka**		**Middle Tisza**		**Morava**	
1. constructions										
1.1 dike relocation			X	X			X	X	X	X
1.2 dike removal				X			X	X		
1.3 controlled dike overtopping / gaps in dike			X				X	X		
1.4 removal of weirs									X	X
1.5 change operation mode of weirs	X	X								X
1.6 migration permeability at weirs	X	X								
1.7 removal of culverts										
2. land cover and lateral branches										
2.1 convert land cover towards natural conditions				X			X	X		
2.2 modify floodplain DEM	X	X			X	X	X	X	X	X
2.3 increasing the roughness of floodplain (afforestation)								X		
2.4 create and connect new lateral branches or pools / new water regime	X	X	X	X	X	X				
2.5 create retention areas / flood channels			X		X	X		X		
2.6 connection of lateral branches/owbows	X	X	X							X
2.7 deepening lateral branches/oxbows	X	X								X
2.8 reconnect old oxbow										X
2.9 increase floodplain area				X	X	X	X	X	X	X
3. river channel geometry alteration										
3.1 increasing the roughness in the river channel (according to natural bedrock)										
3.2 widening of river channel		X			X	X				
3.3 increase of the river bed (decrease of water depth)										
3.4 increase the diversity of the river morphology (riffles, pools, potholes, sand or gravel banks, cut banks and slip-off-slope, broader and narrower passages of the river,...); diversity of cross profiles of the river	X	X								
3.5 removing bank stabilizations / embankments							X	X		
3.6 riperian vegetation (increase roughness, stabilizes the riverbank, decreases nutrient inflow)										
3.7 implementing groynes, boulders or dead wood to initiate meandering										
3.8 change course of river (meandering)										X
3.9 removing ground sills, plunges									X	X
3.10 create fish spawning areas	X	X						X		
3.11 Removing sand bars							X	X		

RS1 = realistic implementation scenario
RS2 = optimistic implementation scenario

4. Methodology

4.1 2D modelling for floodplain restoration

To quantify and evaluate the river hydrodynamics, hydraulic 2D modelling is a broadly used tool. Although the data requirements and processing is demanding, the clear advantage are the spatially detailed results which can be used for further planning (Stone et al. 2017). 2D hydrodynamic models reveal detailed patterns of flow conditions with a high spatial resolution during flood events and are therefore applicable for analyses of ecological functions (Gibson und Pasternack 2015). The models can reproduce the dynamic interactions between the river and its floodplain. These interactions are an important indicator for regulating ecosystem services such as the flood regulation, but also for provisioning ESS like wood from floodplain forests or fish since the models provide information for habitats (Stone et al. 2017, see also D 4.2.1). Furthermore, the 2D results deliver important hazard information (e.g. water depth or velocity maps) for detailed damage estimations (Hattermann et al. 2018).

Consequently, the application of 2D hydrodynamic models in the five pilot areas of the Daube Floodplain project, is an ideal base for the further analysis of the flood prevention effect of floodplain restoration measures (activity 4.1), the improvements for habitats and ecosystem services (ESS) (activity 4.2) as well as the ESS extended CBA (activity 4.3) (see Figure 1). It has to be mentioned that the 2D model results do not generate exact real conditions, but with several simulated scenarios an approximation can be yielded on how the floodplains would react in flood events (Stone et al. 2017).

4.2 Modelling procedure in Danube Floodplain

The modelling procedure in the pilot areas was decided on several project meetings as follows. The responsible national project partners (see Table 1) investigate their pilot areas:

- The partners request necessary data from other national authorities (digital elevation model, ground survey data, land use data to derive roughness criteria, hydrological data),
- set up the current state 2D model (CS) including calibration and validation in an adequate spatial resolution based on the obtained input data,
- decide on the measures for two restoration scenarios (R1 and R2) in cooperation with the identified local stakeholders (WP2) and other national partners,
- modify the CS 2D model geometry accordingly to receive the two restoration scenario models R1 and R2,
- perform unsteady simulation runs for all set up models with the three hydrological scenarios (HQ2-5, HQ10-30, HQ100),
- deliver results (spatial data and hydrographs) and provide a detailed report on the work steps in a documentation file to the activity leader TUM.

The results are then consistently visualized and analyzed (see chapter 5 and chapter 6) in cooperation with all partners and conclusions are drawn which serve as input for the upcoming deliverables.

A short overview of the properties of the set up 2D models in the five pilot areas is represented in the following table (Table 3).

Table 3: 2D model properties in all pilot areas

	Begečka Jama	Bistret	Krka	Middle Tisza	Morava
Developed by	JCI	NARW	IZVO-R ltd. (External partner of DRSV)	KÖTIVIZIG	VUVH
2D model type and release	HEC-RAS 5.0.7	HEC-RAS 5.0.7	MIKE FLOOD v. 2012	HEC-RAS 5.0.7	HEC-RAS 5.0.7
2D model size in km²	10.13	176.98	85.56	49.51	147.37
Number of nodes	CS 30855 R1 31412 R2 31997	CS - 115135 R1 - 151914 R2 - 230968	380266	CS 165057 R1 170182 R2 170182	1448241
Nodes per km²	CS 2656 R1 2701 R2 2751	CS - 2265 R1 - 1826 R2 – 1026	4444	CS 1597 R1 1602 R2 1602	10000
DEM base	1x1m Lidar and Bathymetric surveys (2019)	5 x 5m (2007-2008)	1 x 1m Lidar (2015)	1x1m	2x2m (2010)
Ground survey	Feb 2019	Cross section and bathymetry 2007-2017	Cross sections and bathymetry from 2019	From 2018 (100 m distance of cross sections)	-
Major tributaries in model area	-	Desnatui River	Radulja River	Zagyva River	Dyje River Myjava River Many small tributaries
Temporal resolution	1 hour	1 hour	1 hour	1 hour	1 hour

4.3 Hydrological scenarios

To assess the effect of floodplain restoration on different characteristics of flood events, it was decided to apply at least three hydrological scenarios. All scenarios investigated are analyzed with a non-steady input hydrograph, to determine the differences in the flood peak height and the flood wave translation. In previous studies of floodplain assessment, mostly steady-state simulations were applied which are less demanding in terms of computational performance but do not reveal the important procedure of water expansion and retreat during a flood event (Stone et al. 2017).

A frequent flood event (HQ_{2-5}), a medium flood event (HQ_{10-30}) and a 100-year flood event (HQ_{100}) are simulated by the project partners in their pilot area models. The input data for these events is mainly taken from observed past events in the pilot areas at nearby gauging stations or up- or downscaled hydrographs of these events to fit to the selected HQ values. The data is provided by national hydrological authorities. In combination with the three restoration scenarios, nine scenarios are simulated in total in each pilot area.

The transient time series are added as input to the model in hourly time steps at the upper model boundary in the main channel. Major tributaries are implemented with a steady runoff value or unsteady observed runoff time series, if measured data is available from the according event. Lateral inflow of small magnitude is added punctually at several locations.

5. Results

To quantitatively assess the impacts of restoration measures on flood events in all five pilot areas, the simulation results of CS and RS are compared regarding their maximum discharge (Q_{max}), change in flooded area, flood wave volume, average flood depth and velocity as well as the translation of the flood wave (Δt). Analyzing the hydrographs, the temporal and quantitative impact of the modifications on the flood peak are shown, while water depth, where available water level and velocity maps depict the spatial variability and changes after potential restoration projects for the three different flood events.

5.1 Results of pilot area Begečka Jama (RS)

For the Begečka Jama pilot area no visible change in the peak discharges of the flood wave (see Table 4 and Figure 8) is simulated in any of the restoration scenarios. In comparison with the CS scenario, both restoration scenarios only show a negligible effect on the flood wave maximum discharge (Q_{max}). Considering the implemented restoration measures in Begečka Jama , the minor effects can be explained as more measures on the river channel itself (e.g. deepening and widening of the channel, reconnection of former oxbows) than expanding the riparian floodplains are investigated. Thus the discharge is still transported in the channel for R1 and R2, however its capacity is increased.

The change in the flooded area in the restoration scenarios is marginable. Yet, the stored water volume can be amplified by up to 7.2% in the HQ_{2-5} event in R2 due to the excavation of the new oxbows. The effects in R1 are much lower, as, unlike in R2, less additional channels are excavated.

The translation of the flood wave in the R1 scenario during the HQ_{2-5} event is +3 hours (i.e. the flood wave approaches 3 hours later). However, it approaches 1 hour earlier in both restoration scenarios in the HQ_{10} event. This can be explained by the excavation of the additional river channels in R1 and R2, as a faster transportation of the flood wave can be achieved with an increasing HQ magnitude. During larger HQ events, more water will be transported in the new channels. As the new channels have a smaller distance between their outflow and the location where the simulation data is investigated, marginal smaller travel times are observed. Yet, taking a detailed look at the three hydrographs and no change in the shape of the wave is visible among the CS, R1 and R2 scenario.

Table 4: Results and analysis of the 2D simulations in the Begečka Jama pilot area

		HQ_{2-5}	HQ_{10}	HQ_{100}
Q_{max} in m³/s	out CS	5766.9	6475.8	8372.1
	out R1	5764.1	6476.0	8370.0
	out R2	5767.4	6475.5	8370.5
ΔQ_{max} in m³/s	R1-CS	-2.8	0.2	-2.1
	R2-CS	0.5	-0.2	-1.6
ΔQ_{max} in %	R1-CS	-0.1	0.0	0.0
	R2-CS	0.0	0.0	0.0
Δt in hours	R1-CS	3	-1	0
	R2-CS	0	-1	0
Change in flooded area in %	R1-CS	0.0	0.0	0.0
	R2-CS	1.2	0.0	0.0
Change in volume in %	R1-CS	0.3	0.2	0.2
	R2-CS	7.2	5.2	4.7
Average water depth in m	CS	4.44	5.55	6.04
	R1	4.45	5.56	6.05
	R2	4.74	5.83	6.32
Average flow velocity in m/s	CS	0.47	0.63	0.64
	R1	0.47	0.62	0.64
	R2	0.48	0.60	0.61

Analyzing the spatial results of the water depth and water level in the Begečka Jama pilot area the increased capacity of the river channel can be again confirmed. The difference maps of the water depth in Figure 9, Figure 12 and Figure 15, e) and f) respectively, for each hydrological scenario, show the excavated channels of the restoration scenarios (dark orange). In the difference maps of the water level (Figure 10, Figure 13 and Figure 16) the effective change of water height is shown. Here we can see that the increased capacity of the channels has a larger effect on the water level change during lower HQ events (HQ_{2-5}) than during larger HQ events (HQ_{100}). The blue area in the water depth and water level difference maps indicate a reduction of water height. The water depth and water level in the HQ_{2-5} event can be significantly reduced (larger blue area) as the excavated channel has the capacity to transport the flood discharge. However, the effect is negligible as soon as the capacity of the newly excavated channels is exceeded as in the case of the HQ_{100}.

The flow velocity in the floodplain increases in the floodplain due to its reactivation but decreases in the Danube main riverbed Figure 11, Figure 14, Figure 17). This effect is mostly visible in the R2 scenario. In the average velocity over the whole area, no major modification is observable.

The results of the 2D models show that the purposes of restoration in the Begečka Jama pilot area were met. The capacity in the oxbows and existing channels is increased, relieving the main Danube channel. This effect is already observable in the more frequent flood events of magnitude $HQ_{2\text{-}5}$ and is more effectively in the R2 scenario. The subsequent improved water supply in the Begečka Jama Lake is expected to lead to an upgrade of habitat quality and ecosystem services. Those effects are investigated in activity 4.2 of the project.

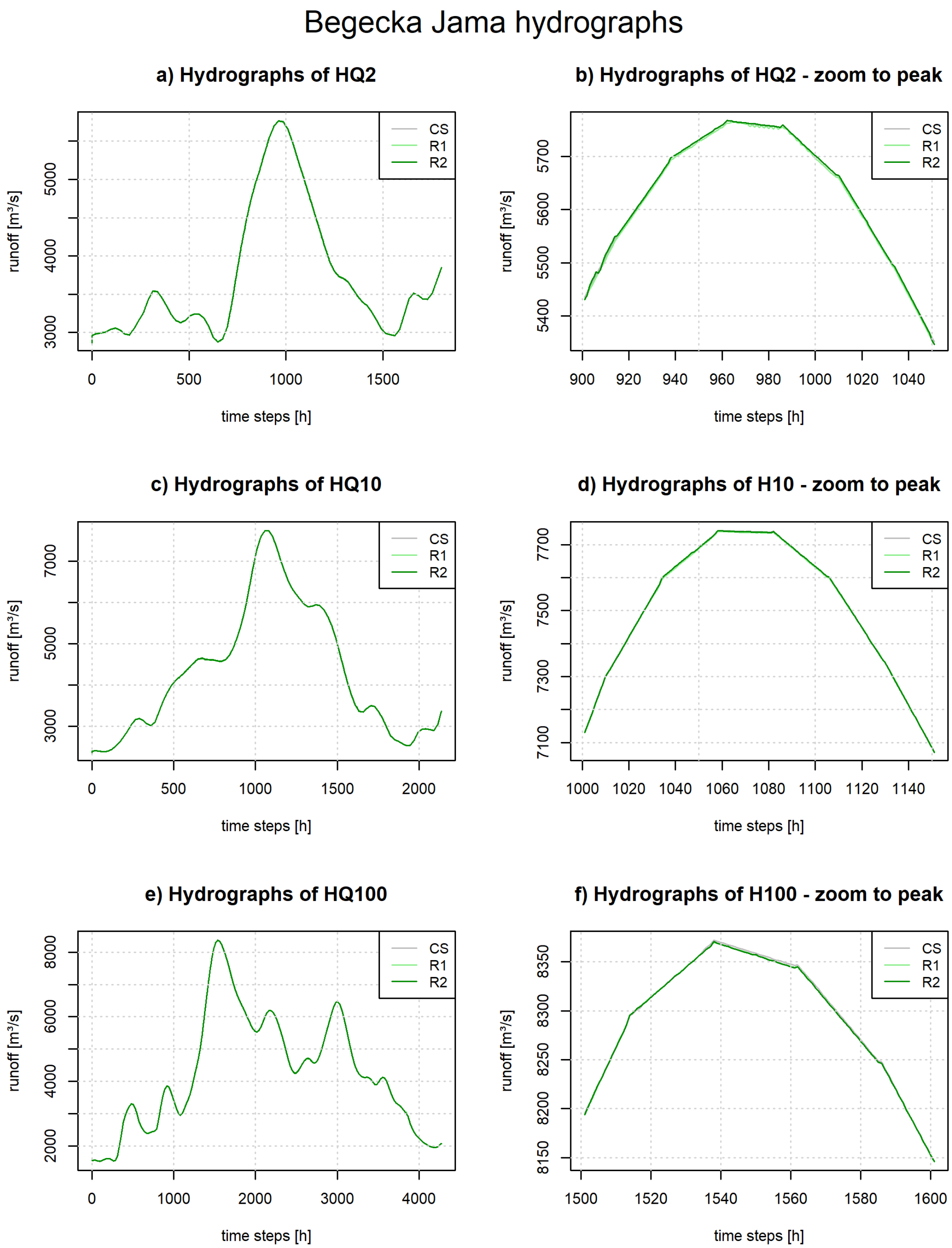


Figure 8: Hydrographs at the downstream model boundary of the Begečka Jama pilot area for HQ$_{2-5}$ (a)+b), HQ$_{10}$ (c) and d) and HQ$_{100}$ (e) and f) for CS, R1 and R2. The figures on the right side show a zoom to the flood peak.

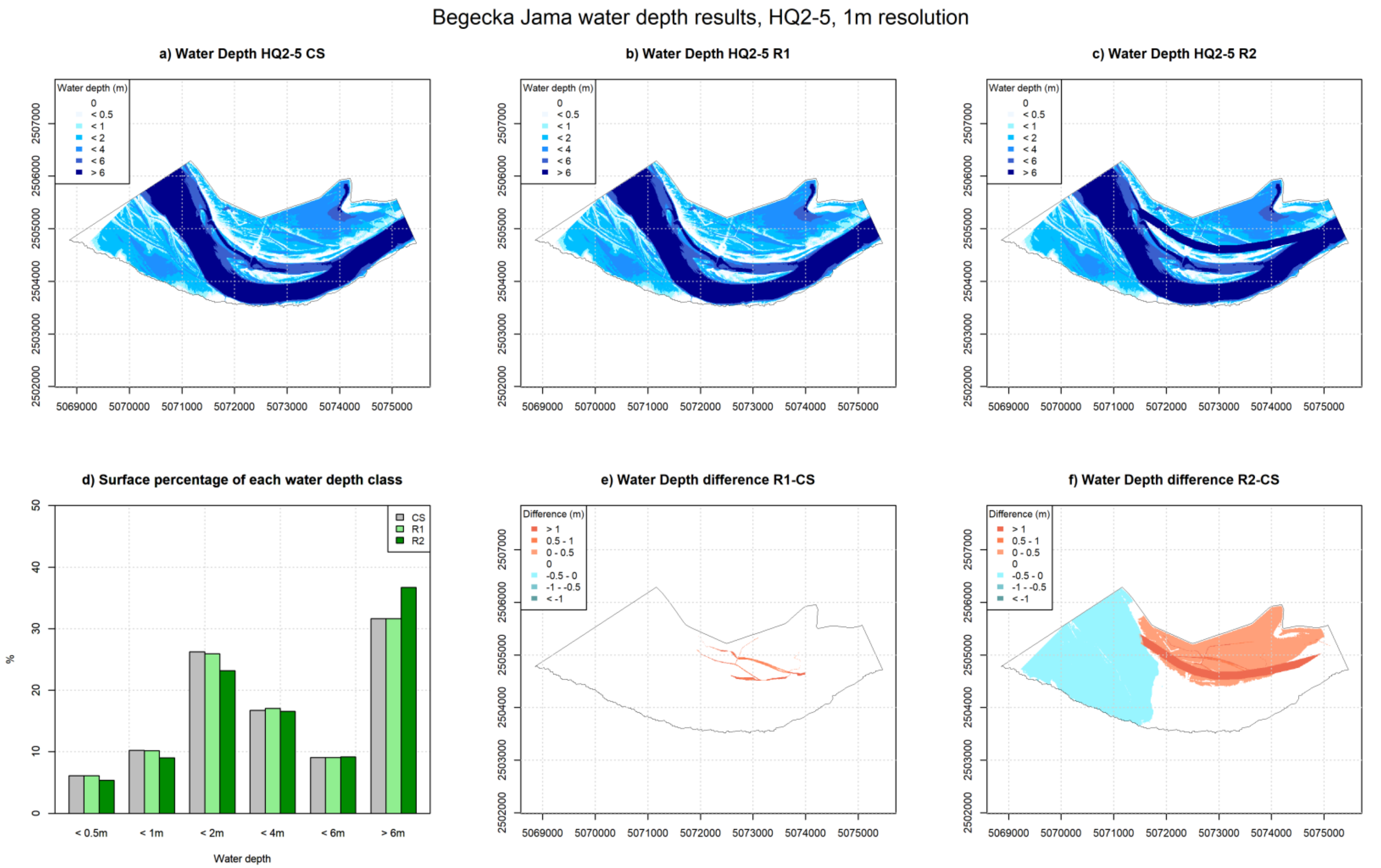


Figure 9: Begečka Jama water depth results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 1m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area

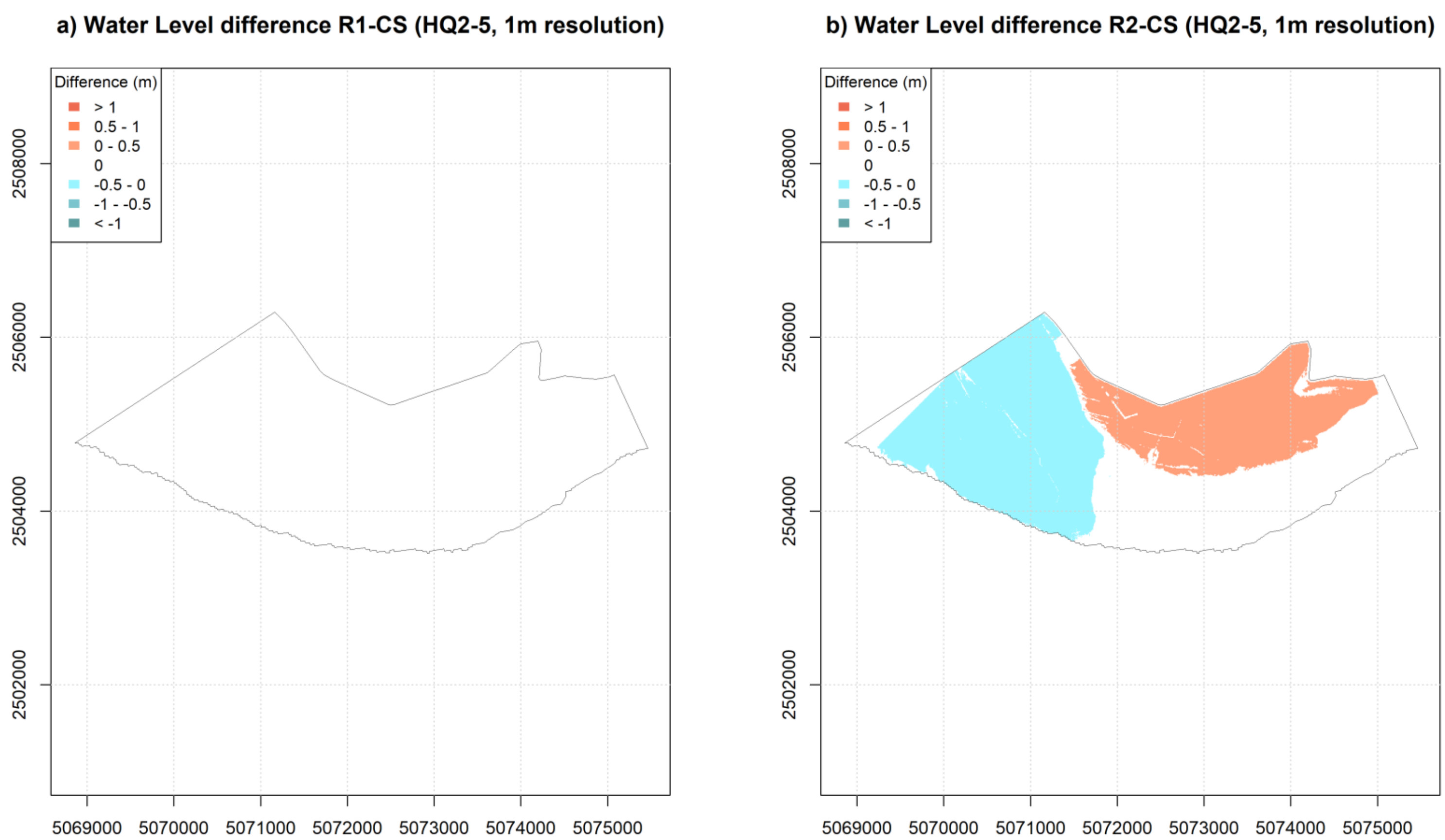


Figure 10: Begečka Jama water level difference maps (left R1-CS and right R2-CS) for HQ_{2-5} in 1m spatial resolution

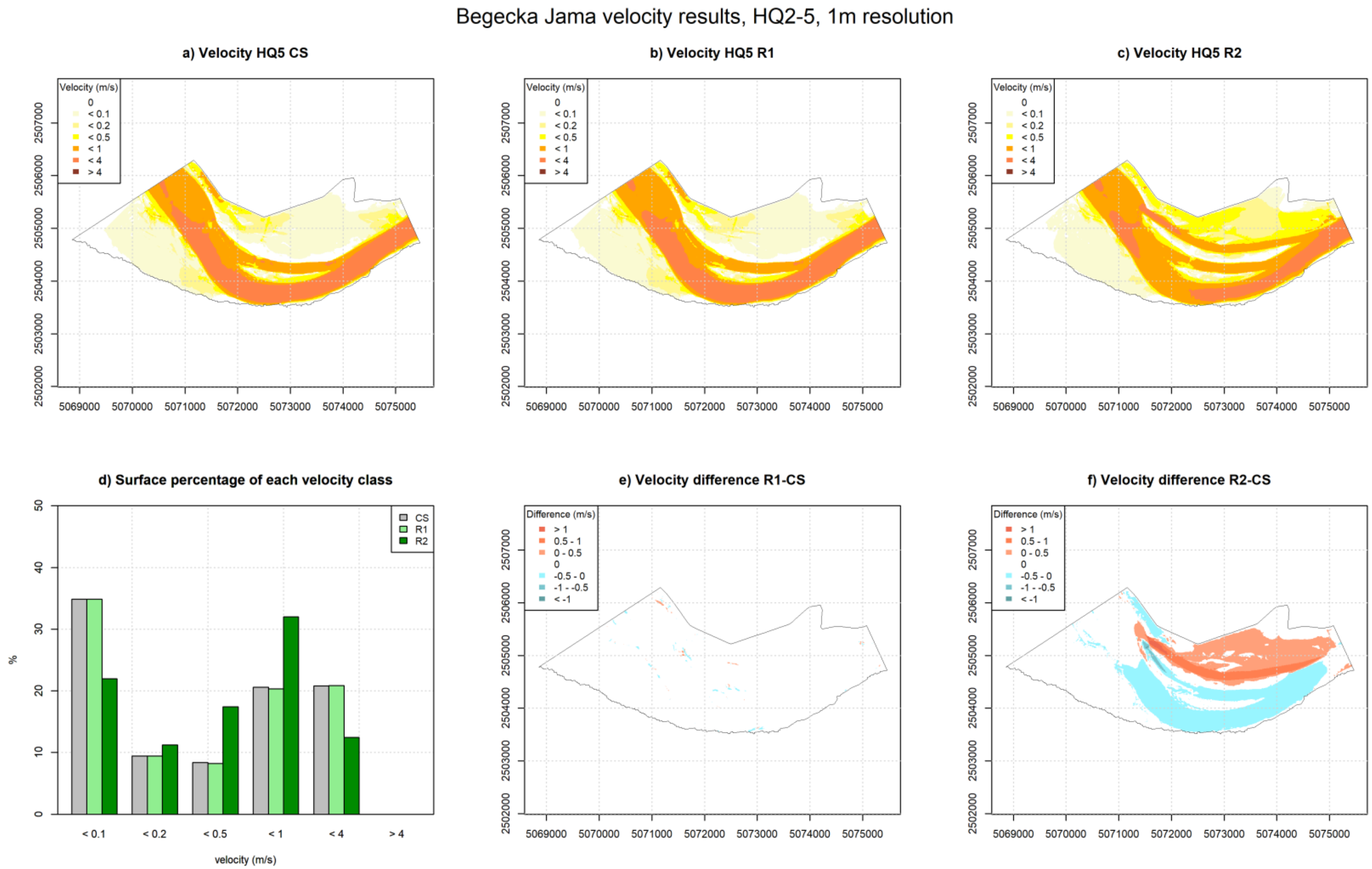


Figure 11: Begečka Jama flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 1m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area

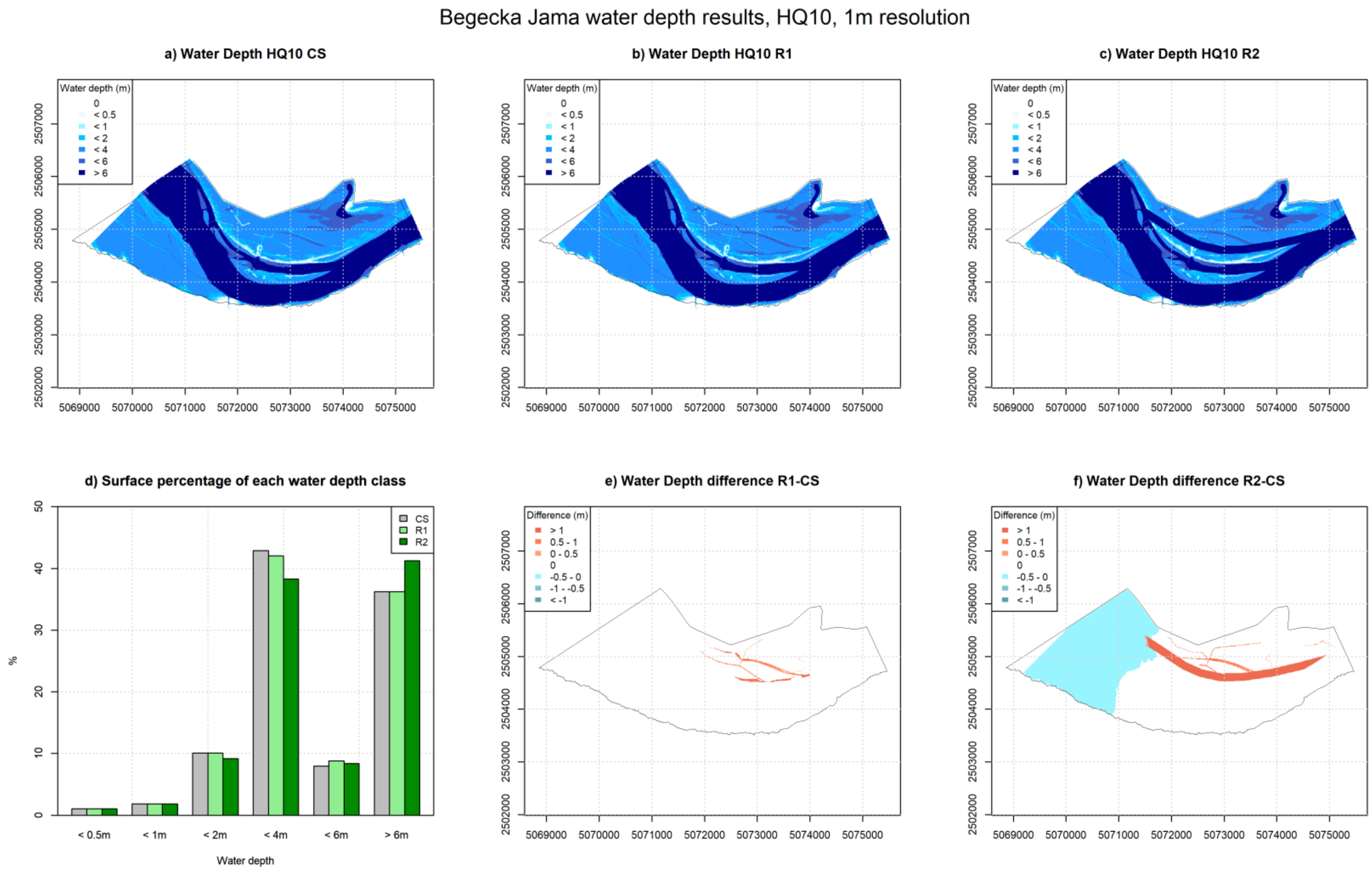


Figure 12: Begečka Jama water depth results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 1m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area

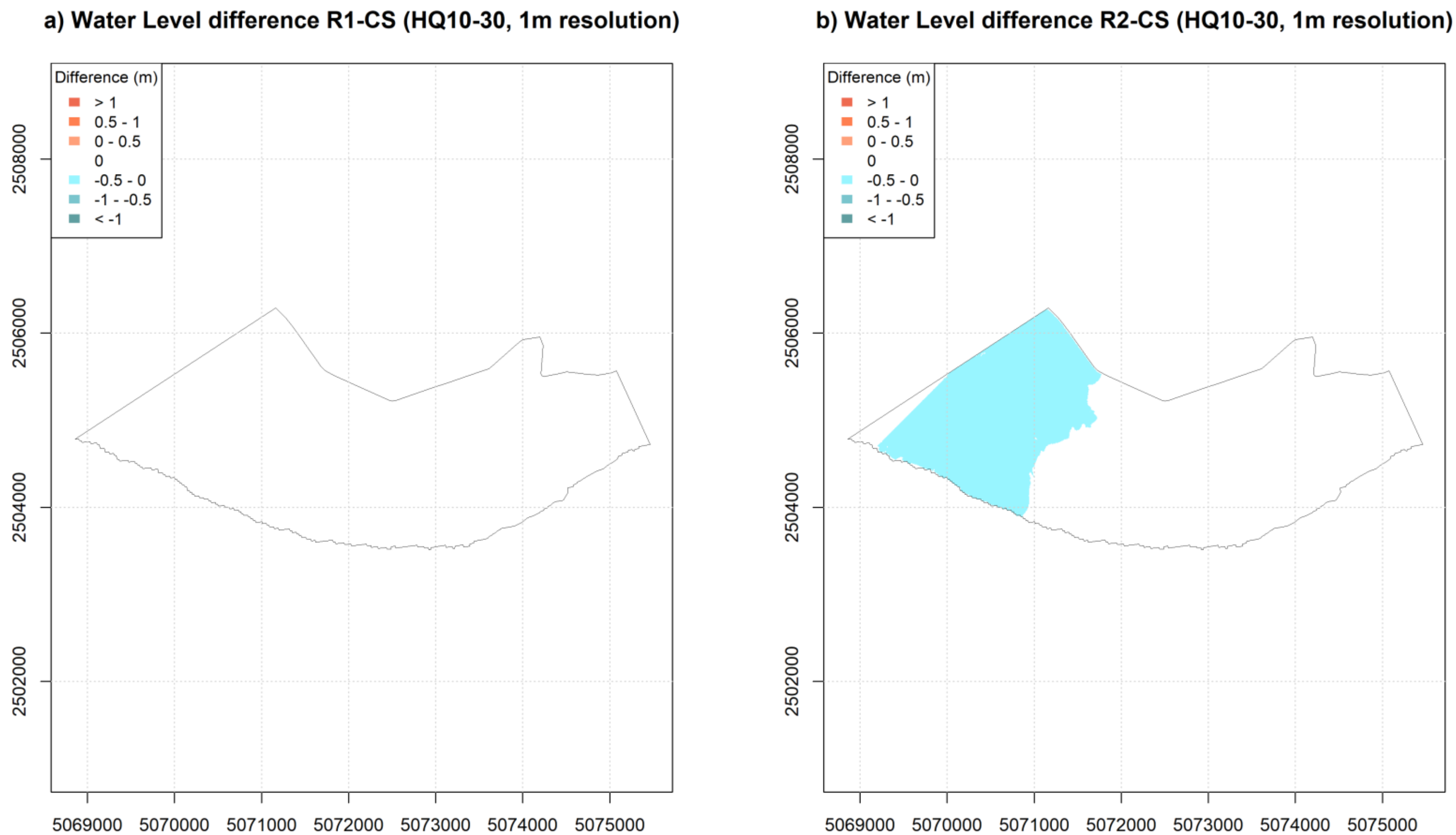


Figure 13: Begečka Jama water level difference maps (left R1-CS and right R2-CS) for HQ_{10} in 1m spatial resolution

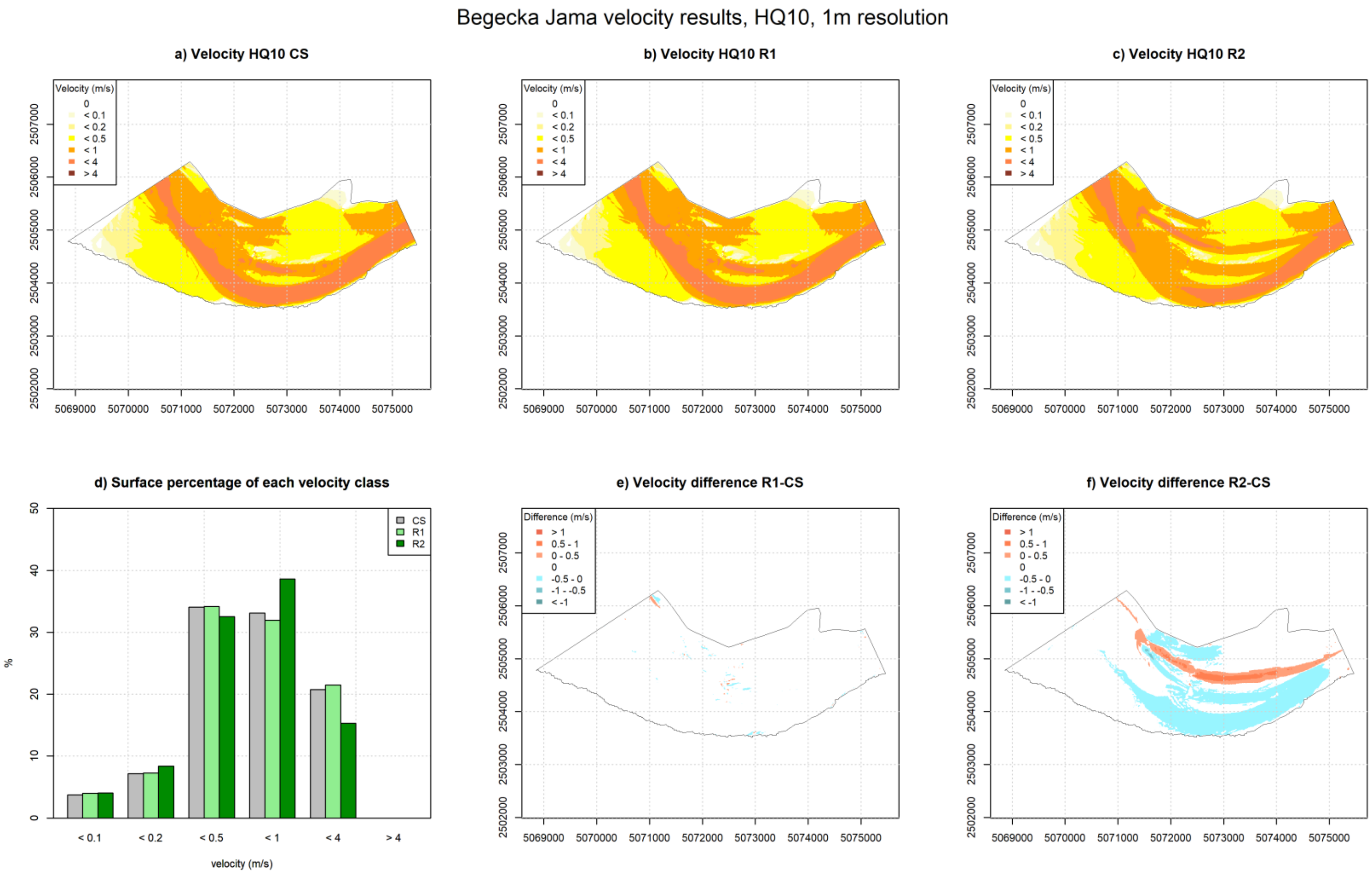


Figure 14: Begečka Jama flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 1m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area

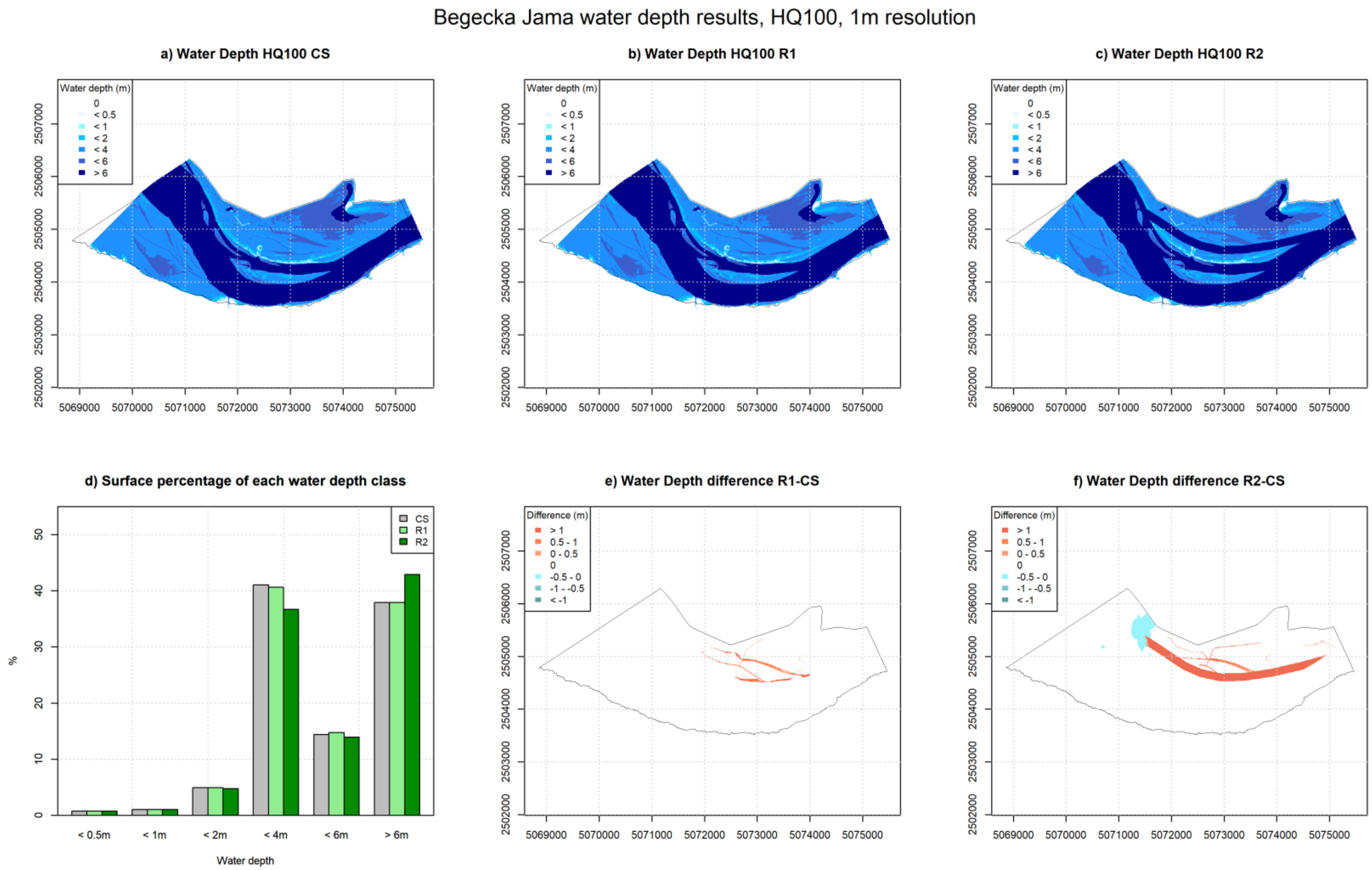


Figure 15: Begečka Jama water depth results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 1m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area

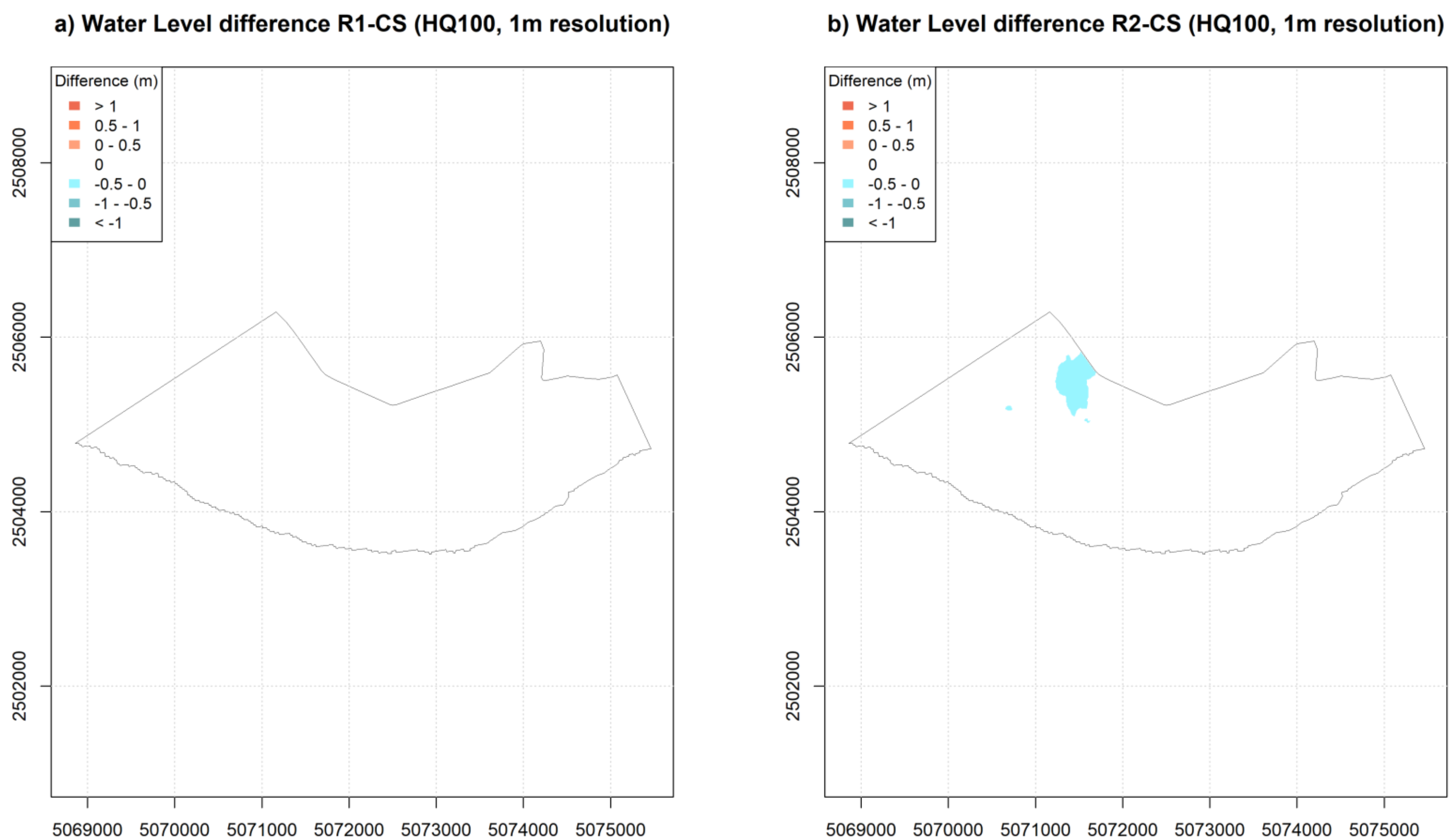


Figure 16: Begečka Jama water level difference maps (left R1-CS and right R2-CS) for HQ_{100} in 1m spatial resolution

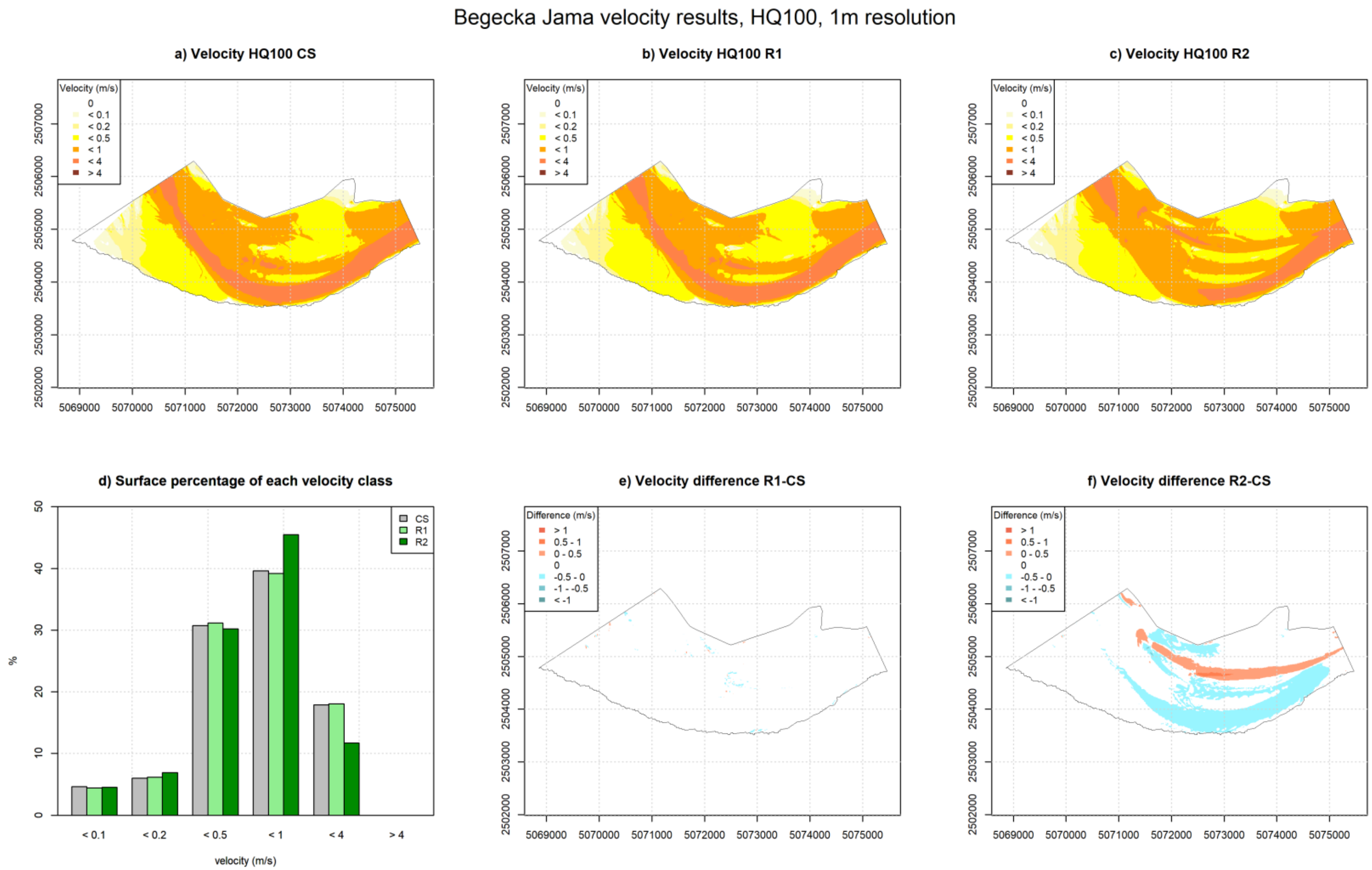


Figure 17: Begečka Jama flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 1m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area

5.2 Results of pilot area Bistret (RO)

The areas analyzed for the two restoration scenarios R1 and R2 in the Bistret area partially overlap, but the flooding mechanisms are different. In the case of R1, the flooding from the Danube is caused by the implementation of a spillway with a length of 150 m, in case of R2 the flooding is caused by overtopping the left banks of the Danube River along the entire length of the pilot area.

The results of the hydraulic modeling in the Bistret pilot area do not show a significant reduction of the maximum flow values (Q_{max}) (Table 5). The largest reduction of the maximum flow values can be obtained in the case of R2 in the hydrological scenario HQ100, of approx. 103 m³/s which represents 0.7% compared to the maximum value of the current state flow (15400 m³/s). For the other restoration and hydrological scenarios, the percentage reduction of the maximum flow values does not exceed 0.2%.

Table 5: Results and analysis of the 2D simulations in the Bistret pilot area

		HQ_2	**HQ_{10}**	**HQ_{100}**
Q_{max} in m³/s	out CS	10568.7	13097.7	15398.4
	out R1	10567.9	13085.7	15295.2
	out R2	10544.8	13083.2	15383.2
ΔQ_{max} in m³/s	R1-CS	-0.8	-12.1	-103.2
	R2-CS	-23.9	-14.5	-15.2
ΔQ_{max} in %	R1-CS	0.0	-0.1	-0.7
	R2-CS	-0.2	-0.1	-0.1
Δt in hours	R1-CS	0	0	0
	R2-CS	16	11	11
Change in flooded area in %	R1-CS	0.4	43.2	66.8
	R2-CS	300.7	329.3	347.0
Change in volume in %	R1-CS	0.3	5.0	31.5
	R2-CS	94.5	128.2	149.3
Average water depth in m	CS	6.65	7.38	8.21
	R1	5.75	5.16	6.47
	R2	3.14	3.81	4.54
Average flow velocity in m/s	CS	4.00	3.92	4.02
	R1	3.45	2.62	2.44
	R2	1.05	1.00	1.06

A significant effect of the restoration scenarios is simulated for the flood wave translation (Δt). For the R2 scenario a delay of the peak of 11 hours is achieved for a HQ_{100} and 16 hours for a HQ_2 (Figure 18). In the R1 scenario, the propagation time does not change compared to the CS. The large effect on the flood wave translation in the R2 scenario can be related to the large effects on the percentage of flooded area (Table 5). Figure 19 and Figure 20, Figure 22 and Figure 23, Figure 25 and Figure 26 show for each HQ scenario ($HQ_{2\text{-}5}$, $HQ_{10\text{-}30}$, HQ_{100}, respectively) the changes in water depth and water level from the CS scenario to the R1 and R2 scenario. The large increase of the water depth is obvious among all hydrological scenarios and especially pronounced in R2 scenario. Relating it to the translation of the flood wave, it can be assumed that the flood discharge is temporarily stored in the floodplains and contributes to the discharge 11 to 16 hours later. This also explains the small effect on Q_{max} as the discharge is still contributing but later. The large percentage change values for flooded area are explained by the initially small flooded area (in CS scenario). The change in flooded area is also reflected in the change in stored volume (increase of up to 150%)

The average water depths and the average velocity (Table 5) for CS are given for the area of the dammed Danube riverbed, while for scenarios R1 and R2 they are given for the area of the floodplains.

The maximum velocity in the Danube riverbed does not change in the two restoration scenarios compared to the current state (Figure 21, Figure 24 and Figure 27). However, the mean maximum flow velocity in the floodplain is increasing, as before no water was discharged through the floodplains. In Figure 21 d), Figure 24 d) and Figure 27 d) the histogram of the percentage of surface area with a certain velocity class can be seen. In the restoration scenarios lower velocity classes are dominant than in the CS scenario, with a more pronounced effect in the R2 scenario. However the velocities increase again under the restoration scenarios with the increase of the HQ magnitude.

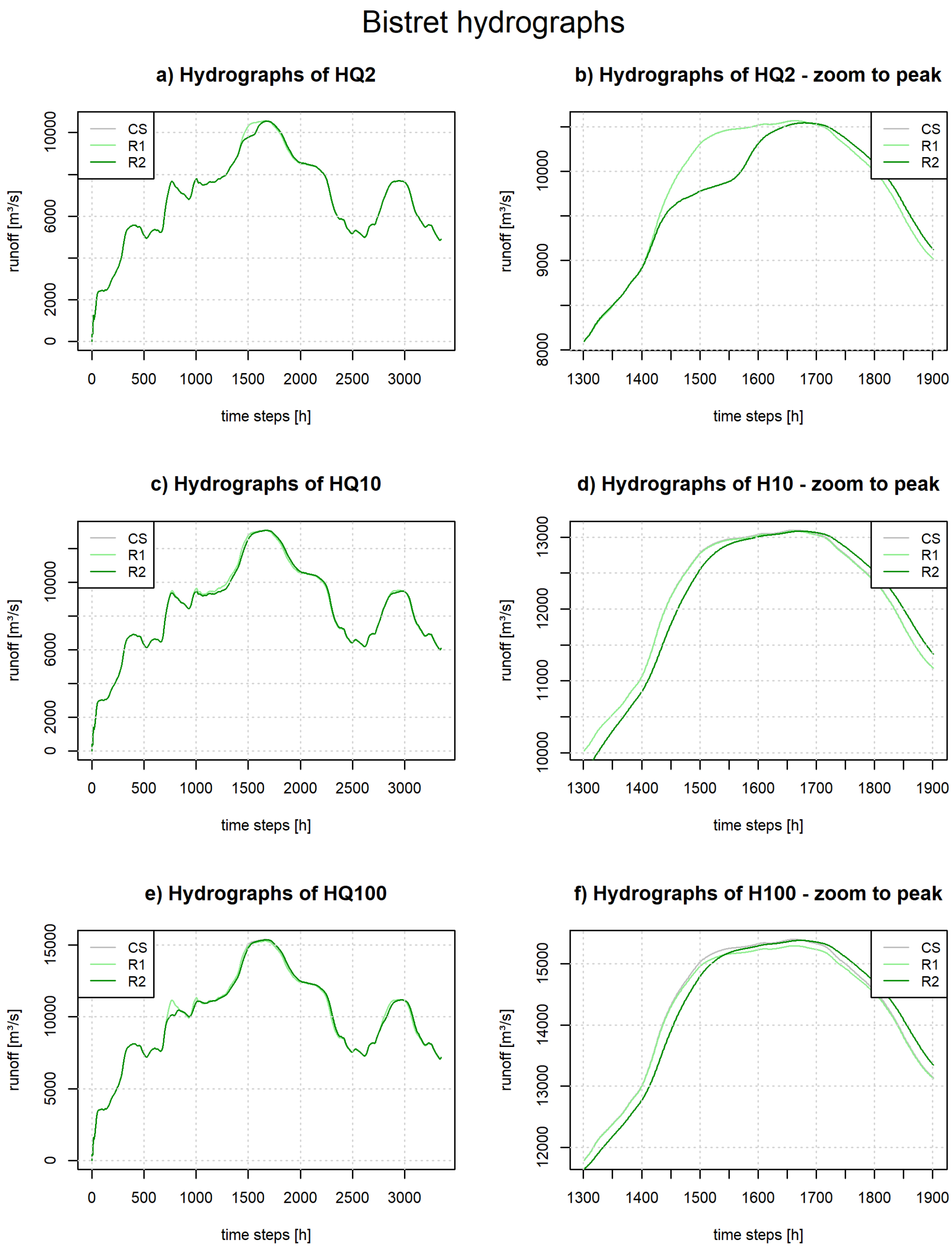


Figure 18: Hydrographs at the downstream model boundary of the Bistret pilot area for $HQ_{2\text{-}5}$ (a)+b), HQ10 (c) and d) and HQ100 (e) and f) for CS, R1 and R2. The figures on the right side show a zoom to the flood peak.

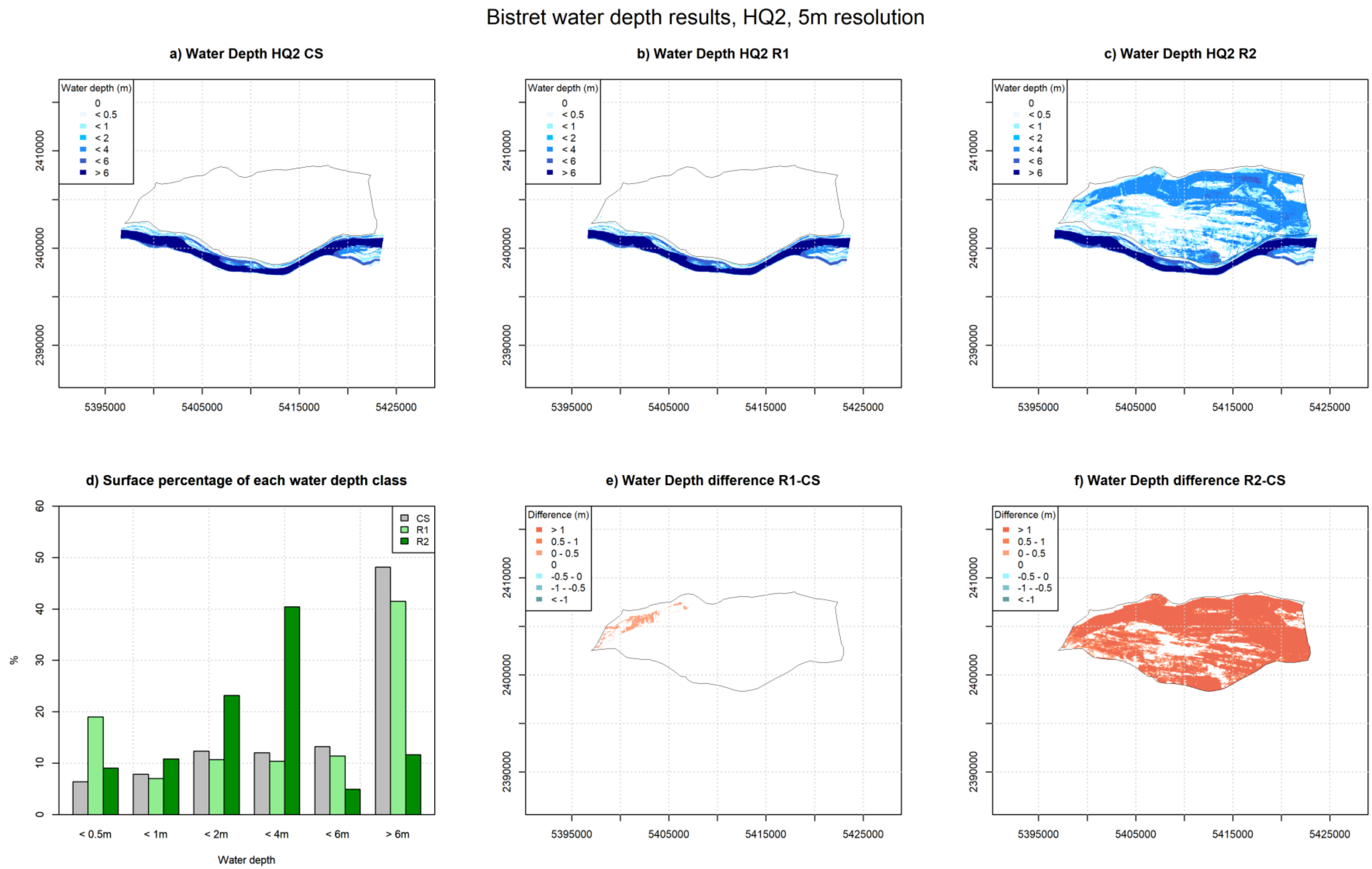


Figure 19: Bistret water depth results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 5m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

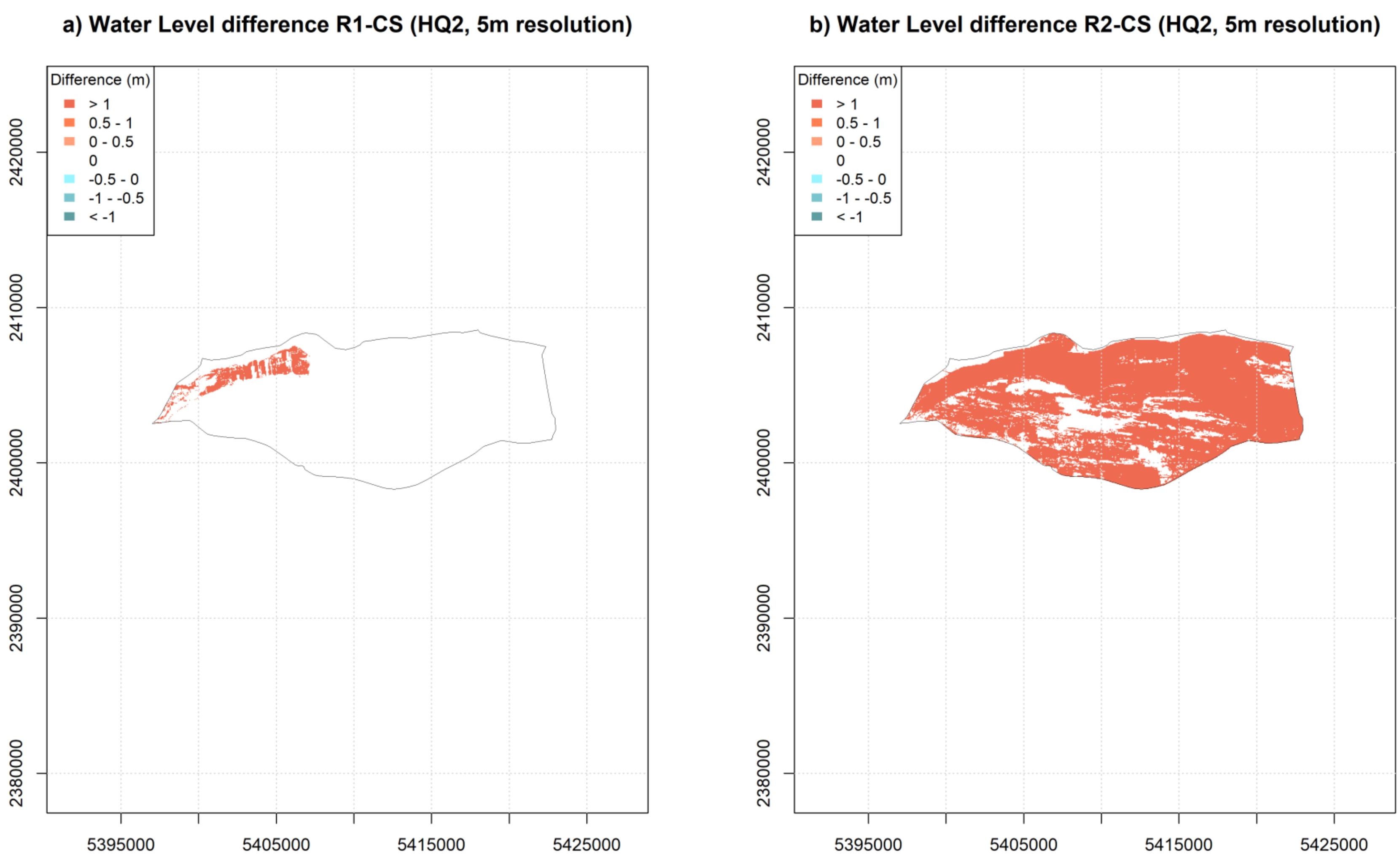


Figure 20: Bistret water level difference maps (R1-CS and R2-CS) for $HQ_{2\text{-}5}$ in 5m spatial resolution

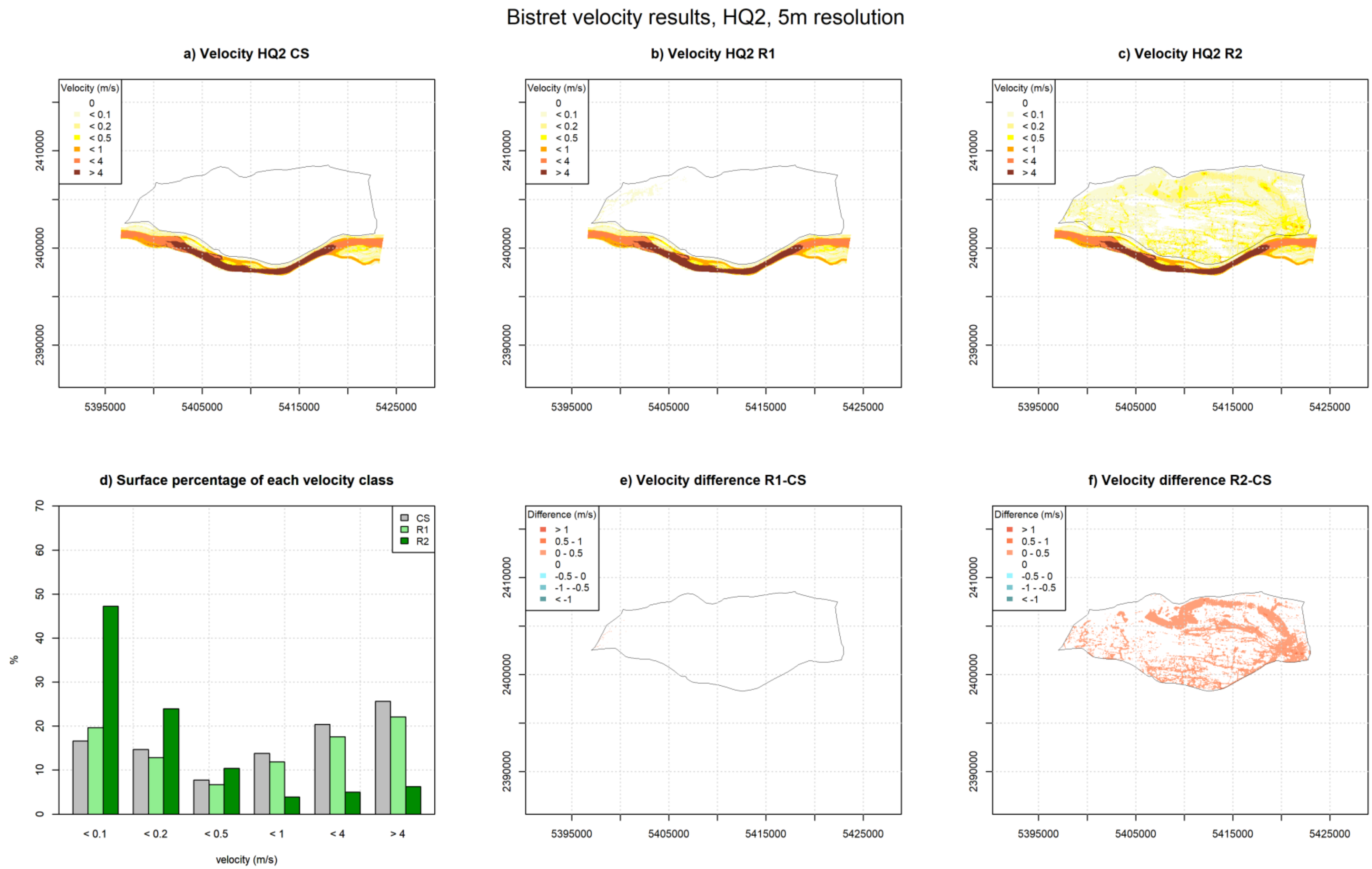


Figure 21: Bistret flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 5m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

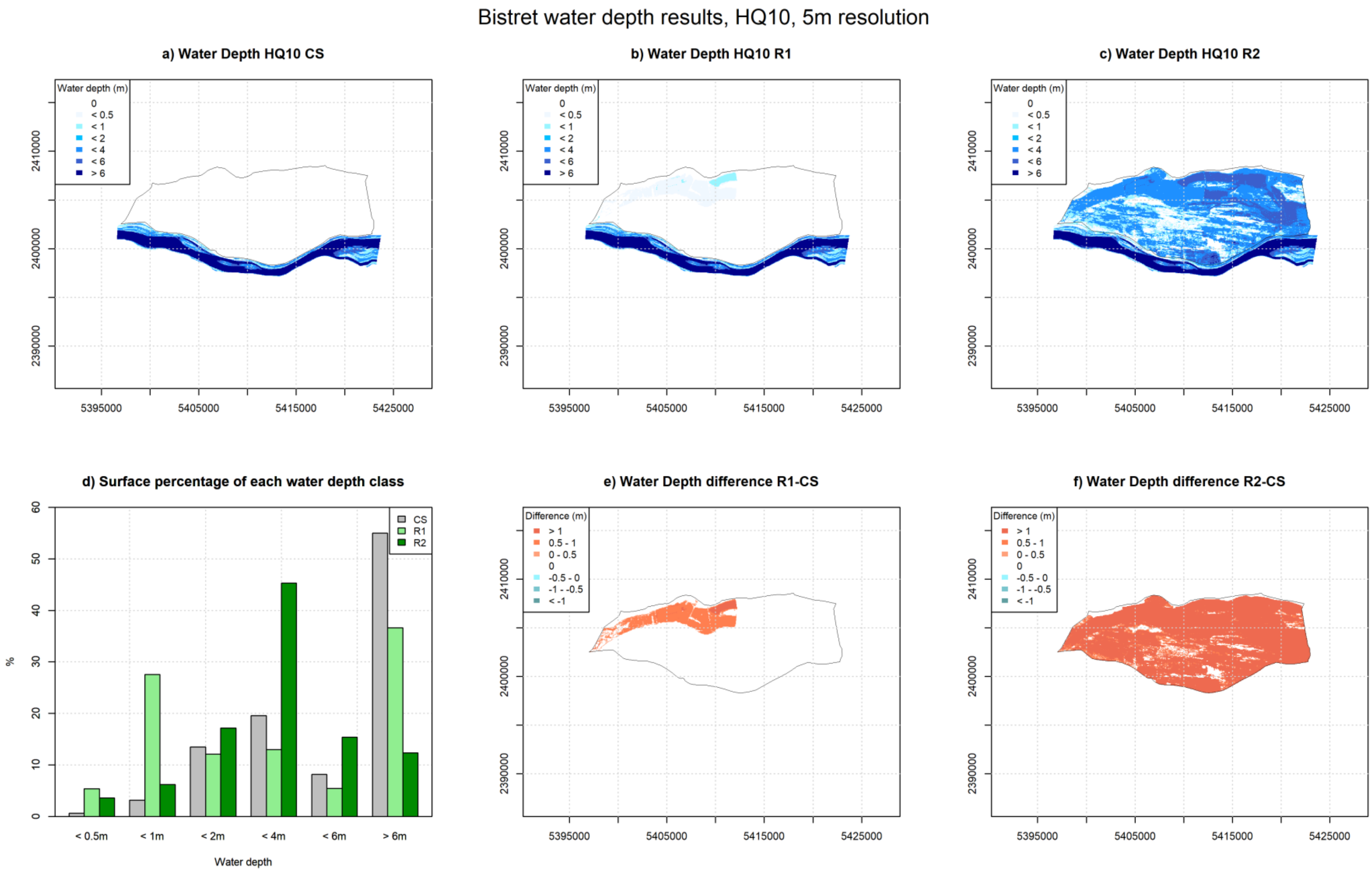


Figure 22: Bistret water depth results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 5m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

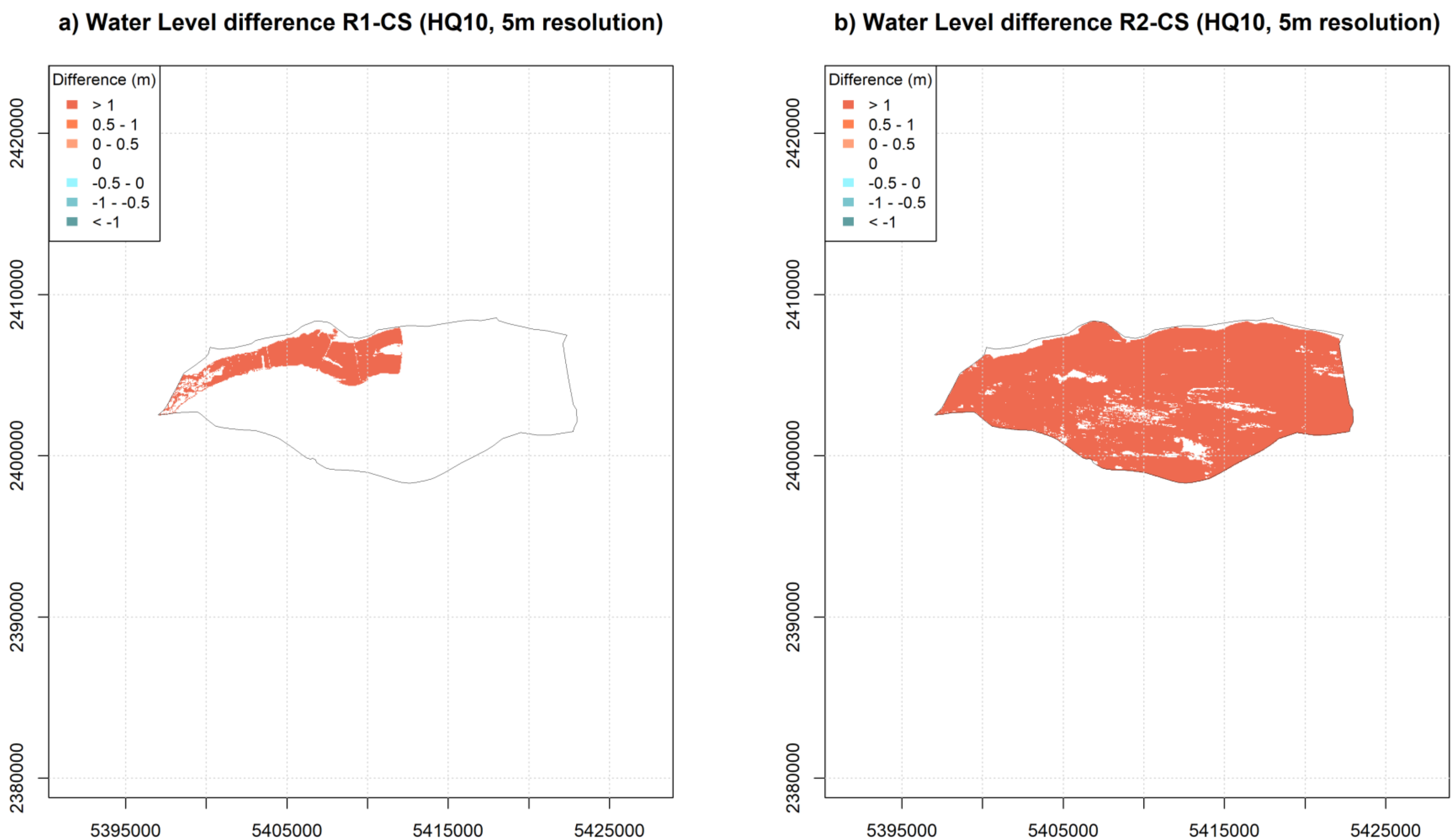


Figure 23: Bistret water level difference maps (R1-CS and R2-CS) for HQ_{10} in 5m spatial resolution

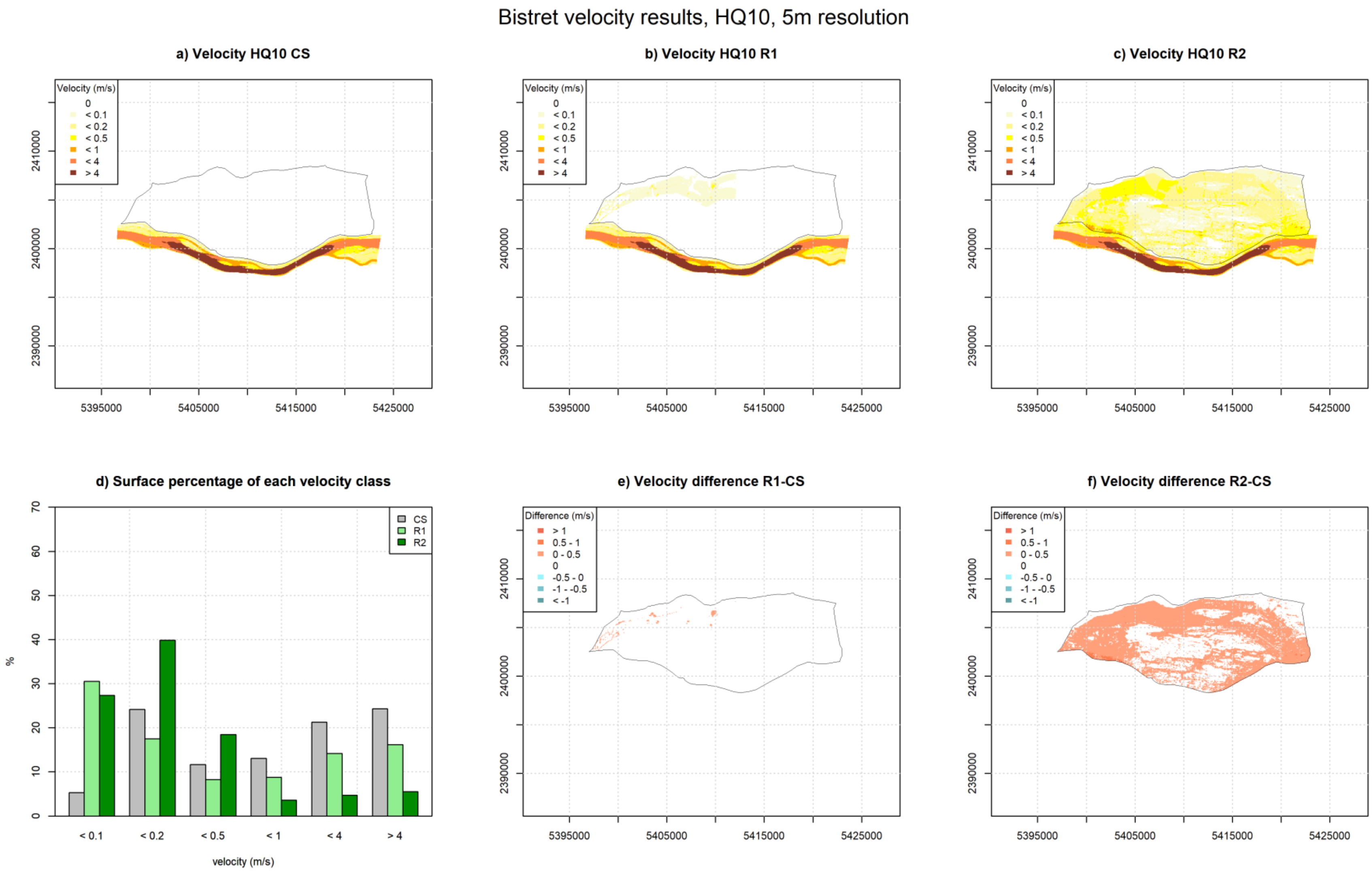


Figure 24: Bistret flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 5m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

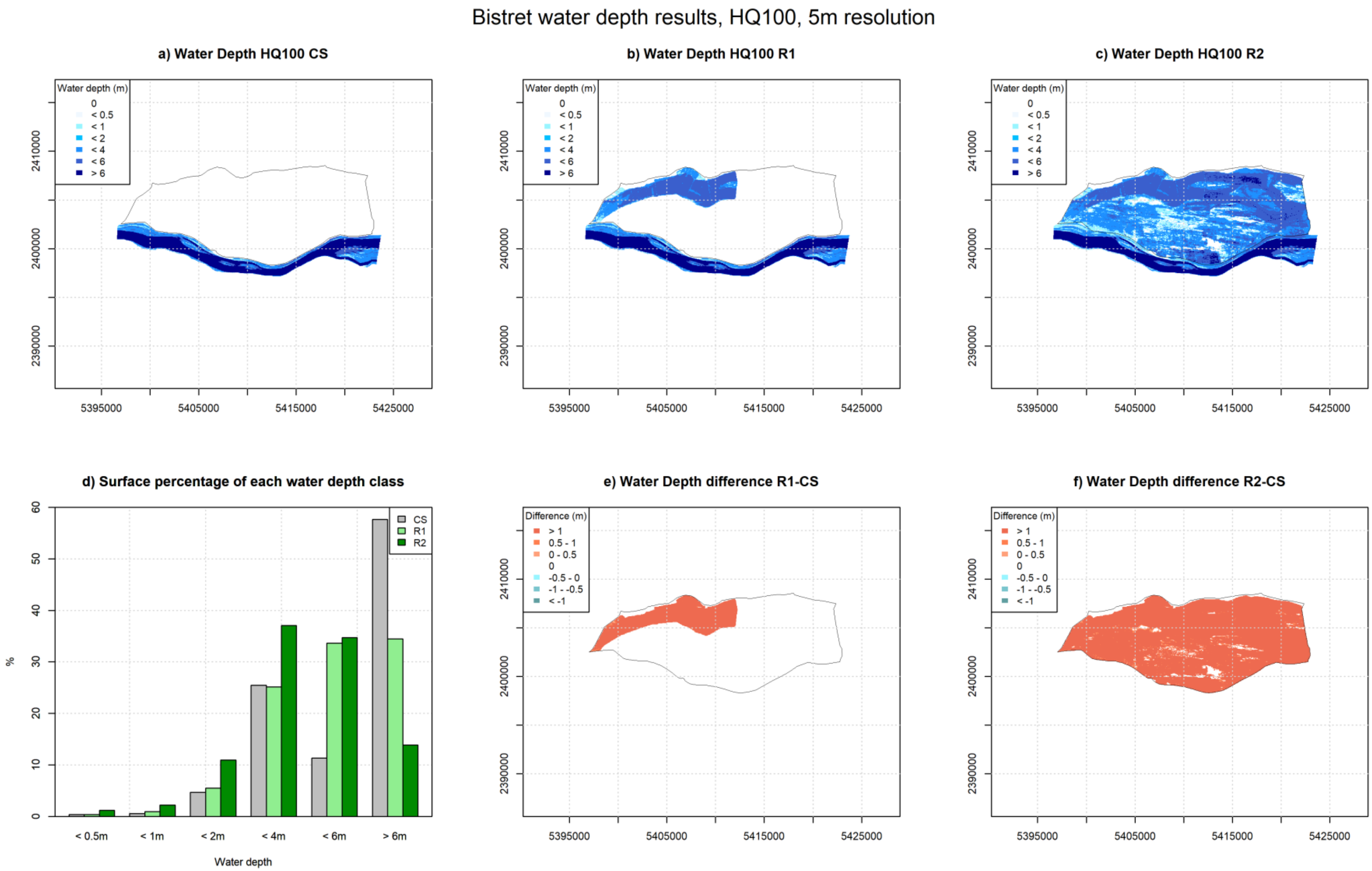


Figure 25: Bistret water depth results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 5m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

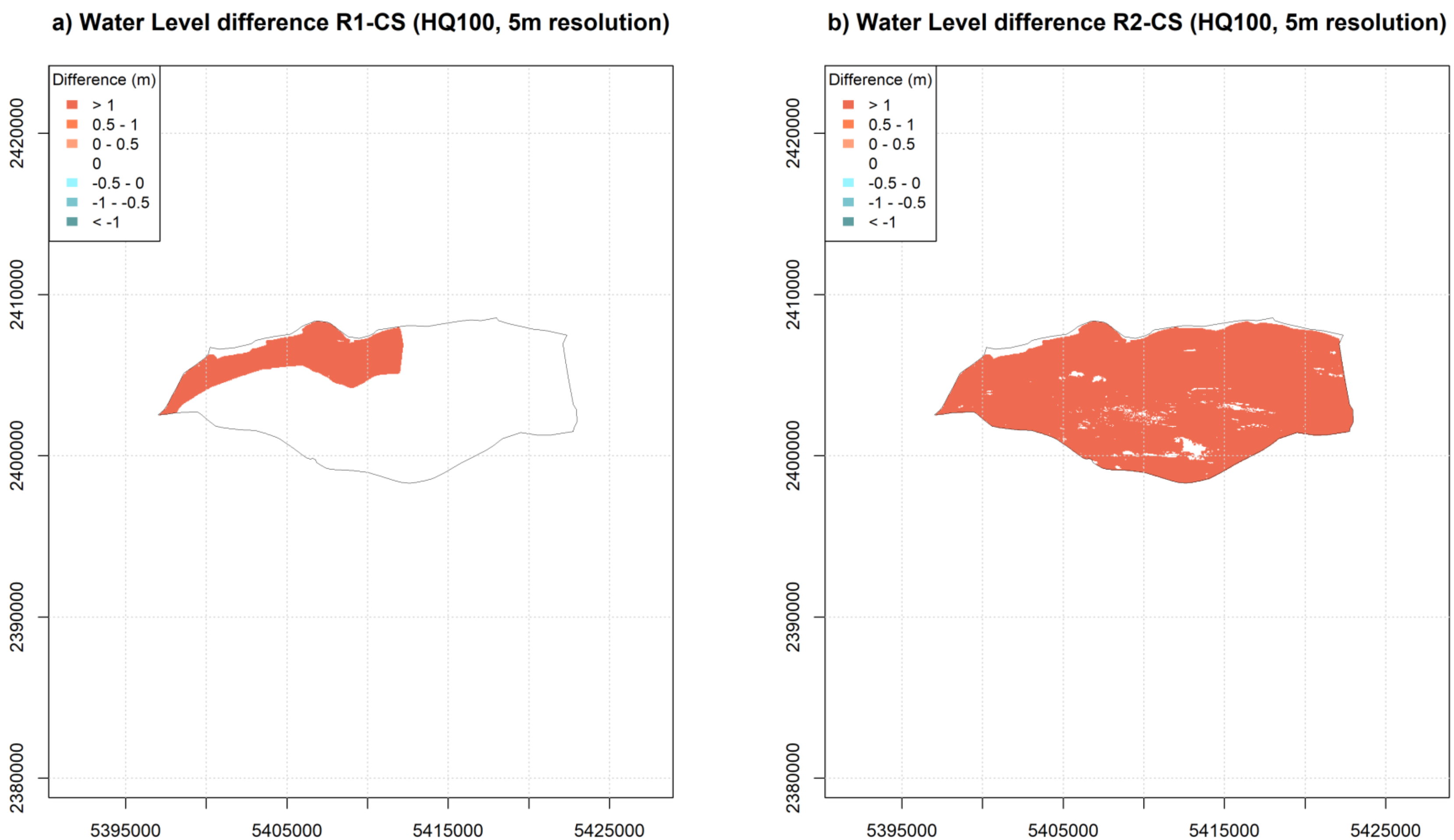


Figure 26: Bistret water level difference maps (R1-CS and R2-CS) for HQ_{100} in 5m spatial resolution

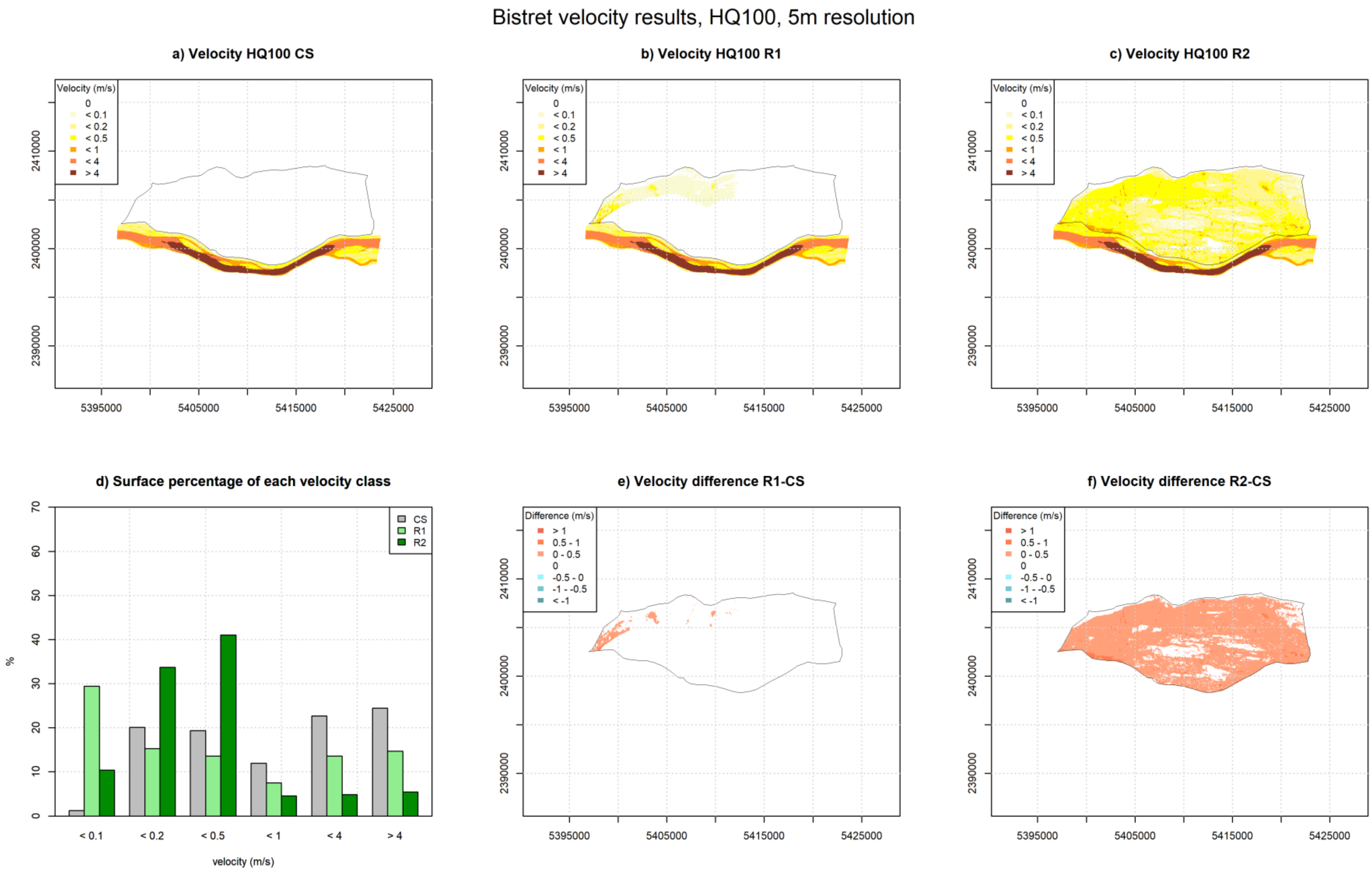


Figure 27: Bistret flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 5m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

5.3 Results of pilot area Krka (SI)

The measures implemented in the Krka 2D models for the restoration scenarios comprise the creation of several corridors and channels to activate the Krakovski forest north of the Krka River and the deepening of the river bed north of the town of Kostanjevica to lower the water depth within the settlement area. The results of the hydraulic simulations in the Krka pilot area reveal a reduction of the maximum discharge values (-0.1% to -3.7%) (Table 6 and Figure 28). None of the designed scenarios has a significant impact on the flood discharge in the town of Kostanjevica. The translation of the flood peak (one hour) is not significant in both scenarios.

Table 6: Results and analysis of the 2D simulations in the Krka pilot area

		$HQ_{2\text{-}5}$	HQ_{10}	HQ_{100}
Q_{max} in m³/s	out CS	319.3	370.3	431.4
	out R1	317.7	363.7	422.3
	out R2	319.1	360.7	415.5
ΔQ_{max} in m³/s	R1-CS	-1.6	-6.6	-9.1
	R2-CS	-0.2	-9.6	-15.9
ΔQ_{max} in %	R1-CS	-0.5	-1.8	-2.1
	R2-CS	-0.1	-2.6	-3.7
Δt in hours	R1-CS	-1	0	-1
	R2-CS	-1	0	0
Change in flooded area in %	R1-CS	6.3	4.1	-0.2
	R2-CS	6.1	4.2	-0.3
Change in volume in %	R1-CS	0.6	0.9	-0.4
	R2-CS	-1.1	0.7	-0.7
Average water depth in m	CS	1.12	1.17	1.20
	R1	1.06	1.13	1.24
	R2	1.05	1.13	1.23
Average flow velocity in m/s	CS	0.11	0.11	0.12
	R1	0.11	0.11	0.12
	R2	0.11	0.11	0.12

The flooded area can be increased in the frequent (HQ_{2-5}) and medium (HQ_{10}) flood event by 4% to 6.3% through the activation of the floodplain forest resulting from the excavation of additional channels. However, no major change can be observed for a HQ_{100} (reduction of flooded area of -0.2% and -0. 3% respectively). The effects of the restoration measures on the stored volume is equivocal (either lower or higher). Yet the magnitude is rather small with around 1%. None of the designed scenarios has a significant impact on the flood discharge in the town of Kostanjevica, with showing only a slight reduction of maximum discharge (ca. 2% to 3.5%).

Analyzing the average water depth and the average flow velocity in the flooded area, no markedly effect is simulated. Further, the riverbed deepening (measure in both restoration scenarios and visualized in Figure 29 e) and f), , Figure 32 e) and f) Figure 35 e) and f) in dark orange) of the northern stream of the Krka river has no perceivable effects on the average water depth. Spatially, (Figure 29 to Figure 37) the measures reveal local changes, e.g. a decrease of water depth within the settlement and an increase in the floodplain. Yet the effects of water depth increase in the floodplain area increases with an increasing HQ magnitude and are larger for R2 scenario (Figure 29 f), Figure 32 f), Figure 35 f)). The water level illustrates the effective change caused by the restoration scenarios (Figure 30, Figure 33 and Figure 36), i.e. without visualizing the deepening of the channels. It is confirmed that in R2 the effect is generally larger than in R1. In the floodplain forest the inundation increases compared to the CS scenario (orange area), which is more pronounced during an HQ_{100} than a HQ_{10}. The effect of the measures on flow velocity outside of the river bed is local and negligible, and is minor within the river bed itself.

The main purposes of the floodplain restoration measures, i.e. improvements for flood risk management, forestry and nature protection, were partly met with the planned restoration measures. The results show that floodplains along the Krka River within the pilot area are already largely active at lower return periods of flood events. The flood mitigation effect can be assessed as minor while the effects on the nature and forestry will be assessed with the ESS analysis in the activity 4.2 and 4.3 deliverables.

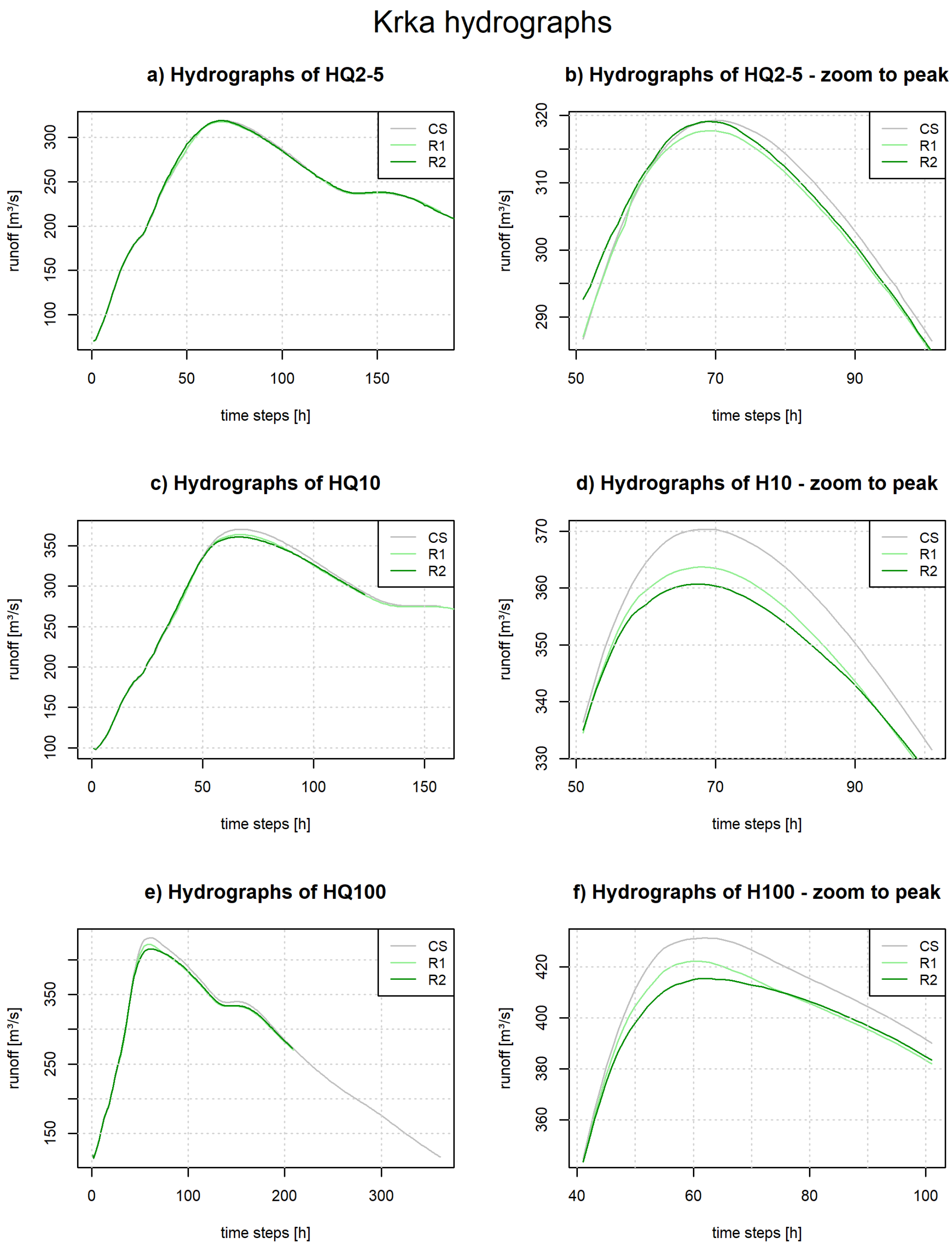


Figure 28: Hydrographs at the downstream model boundary of the Krka pilot area for $HQ_{2\text{-}5}$ (a)+b), HQ10 (c) and d) and HQ100 (e) and f) for CS, R1 and R2. The figures on the right side show a zoom to the flood peak.

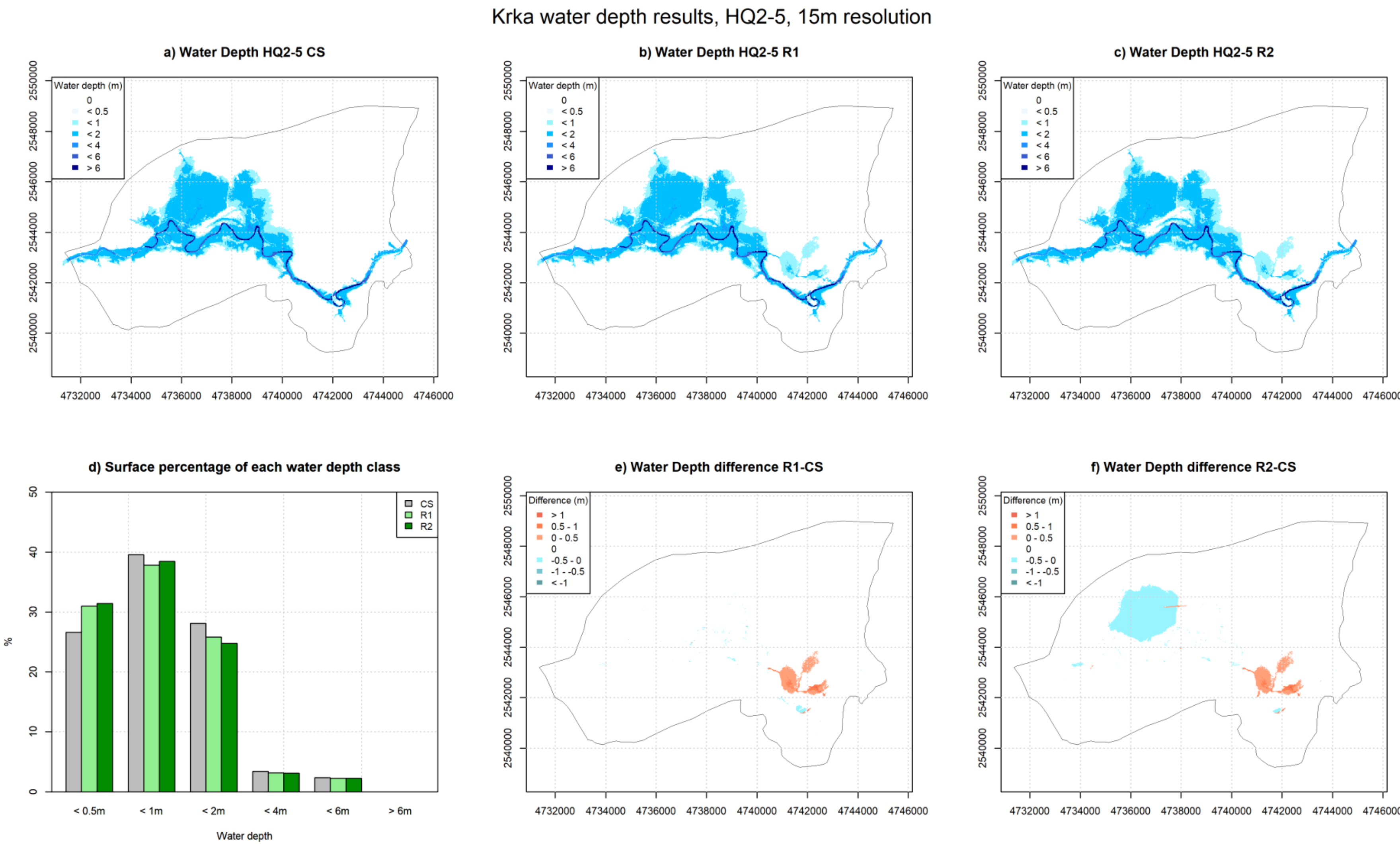


Figure 29: Krka water depth results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 15m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

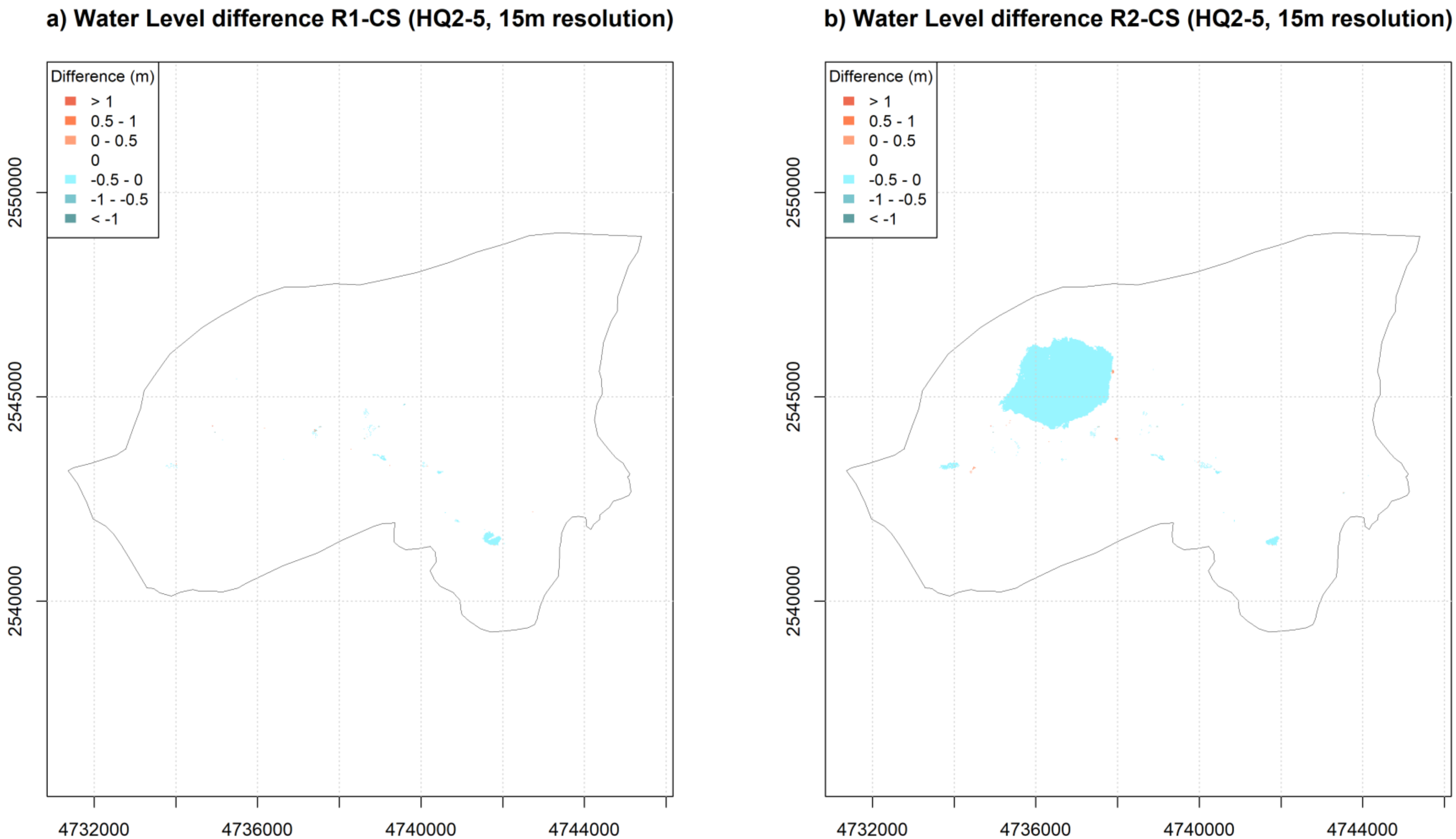


Figure 30: Krka water level difference maps (R1-CS and R2-CS) for HQ_{2-5} in 15m spatial resolution

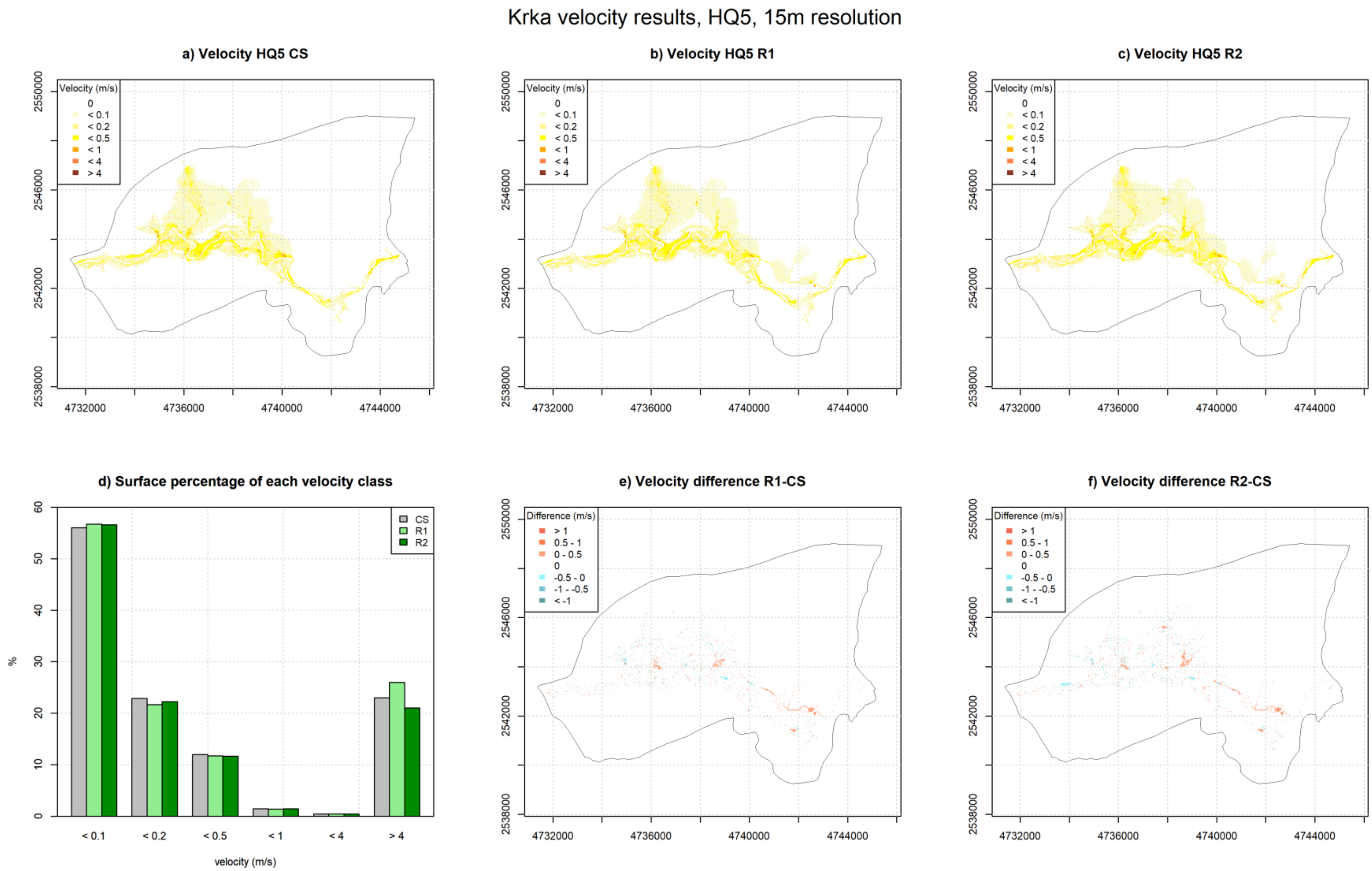


Figure 31: Krka flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 15m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

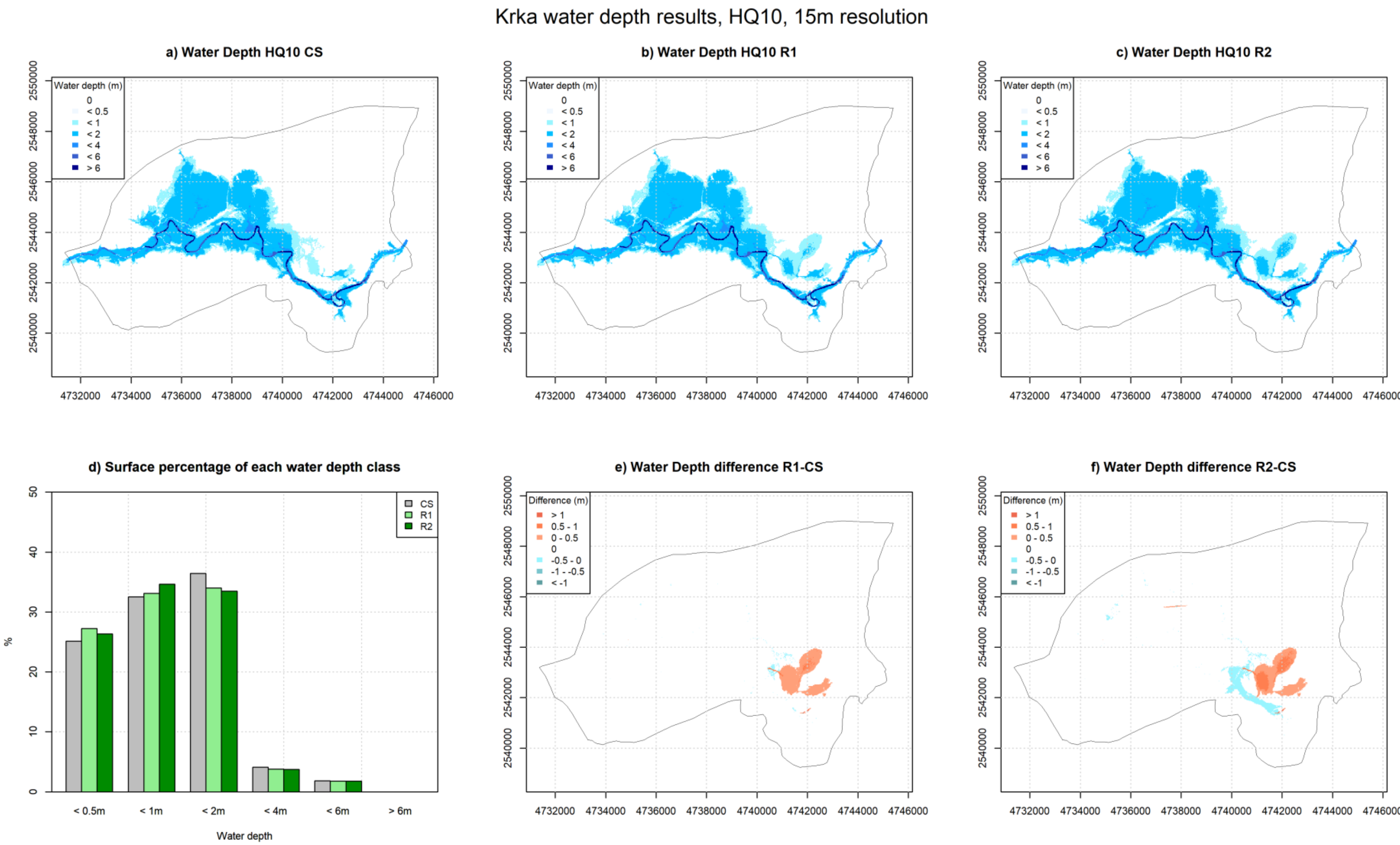


Figure 32: Krka water depth results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 15m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

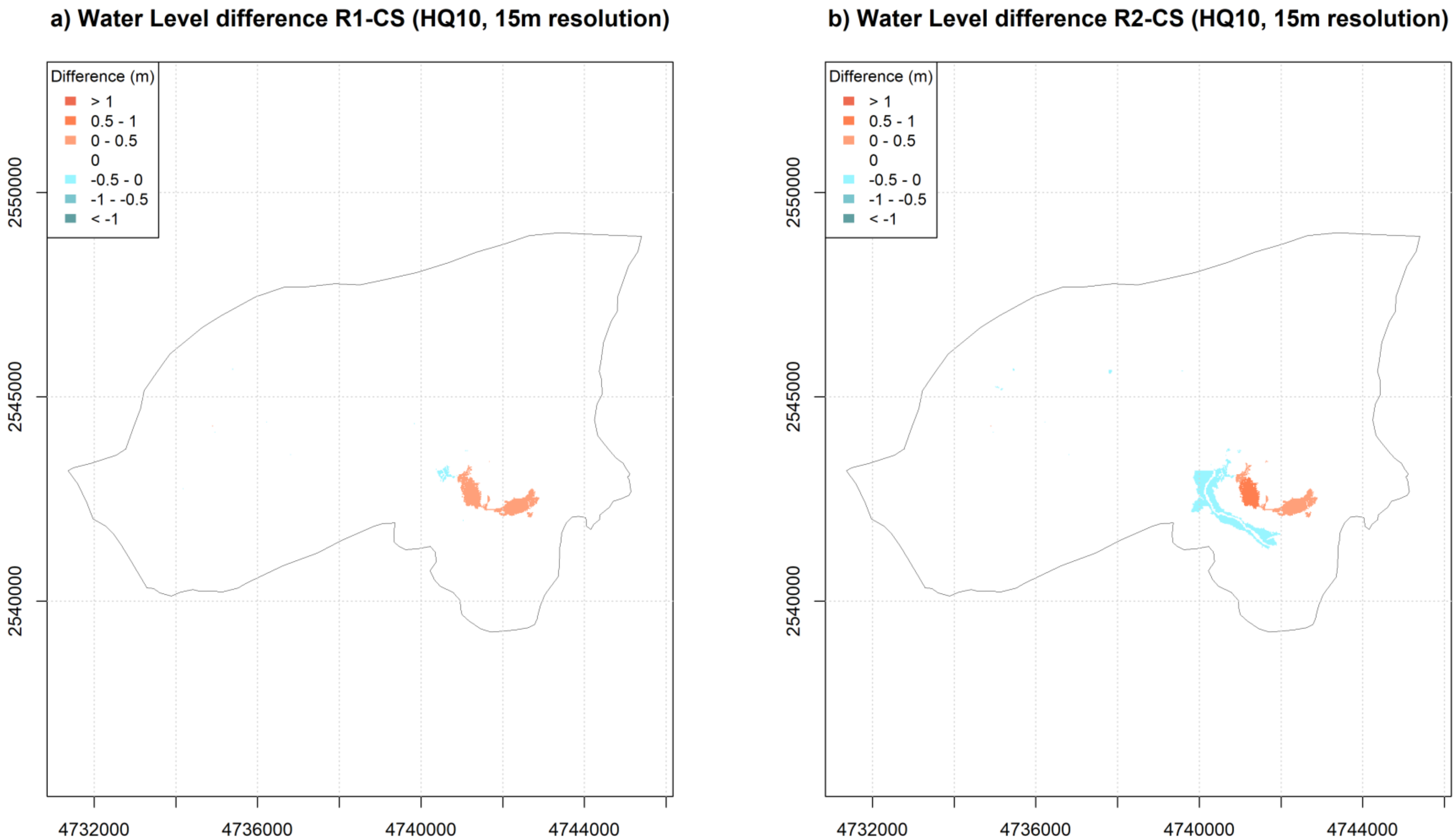


Figure 33: Krka water level difference maps (R1-CS and R2-CS) for HQ_{10} in 15m spatial resolution

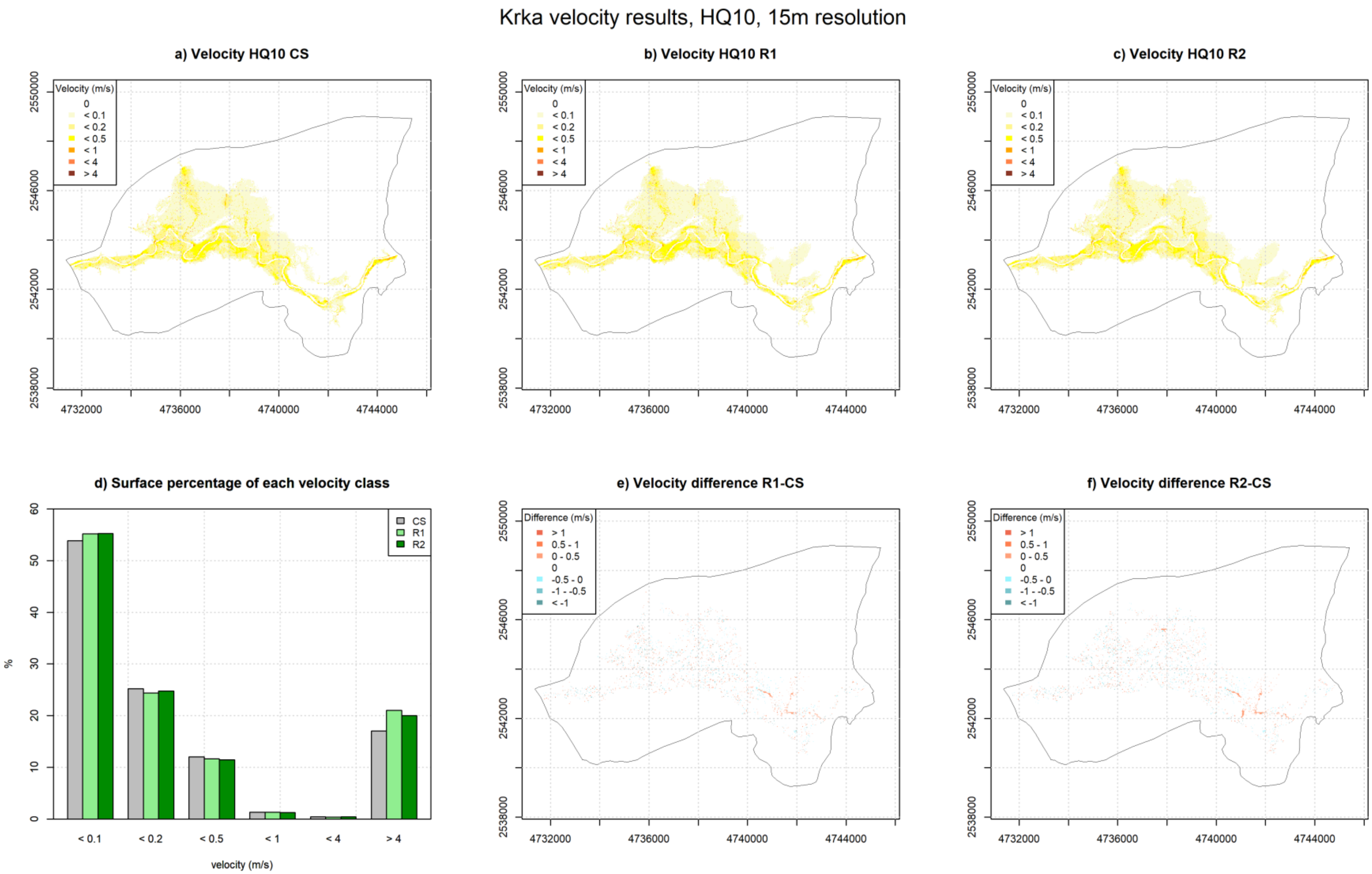


Figure 34: Krka flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 15m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

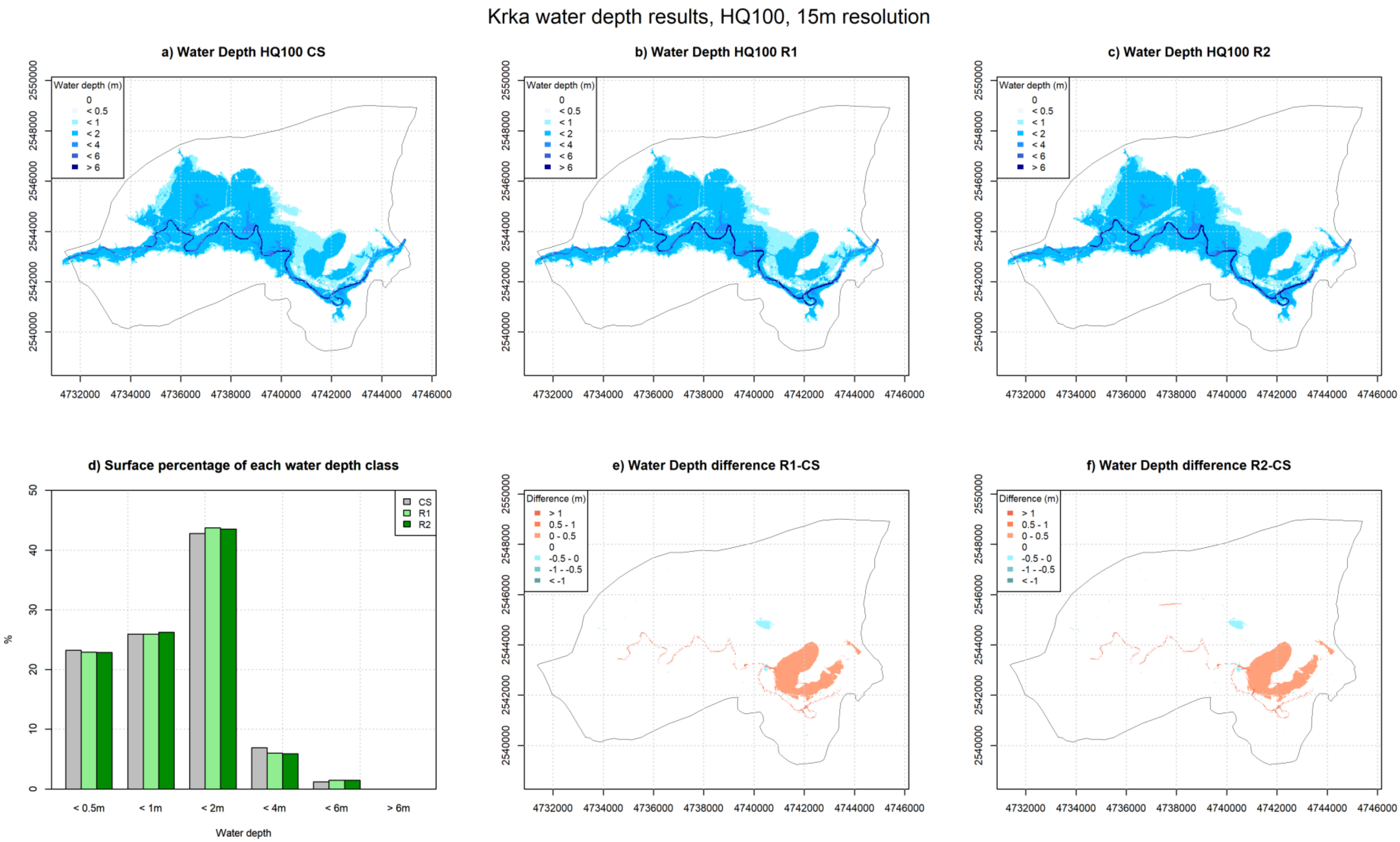


Figure 35: Krka water depth results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 15m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

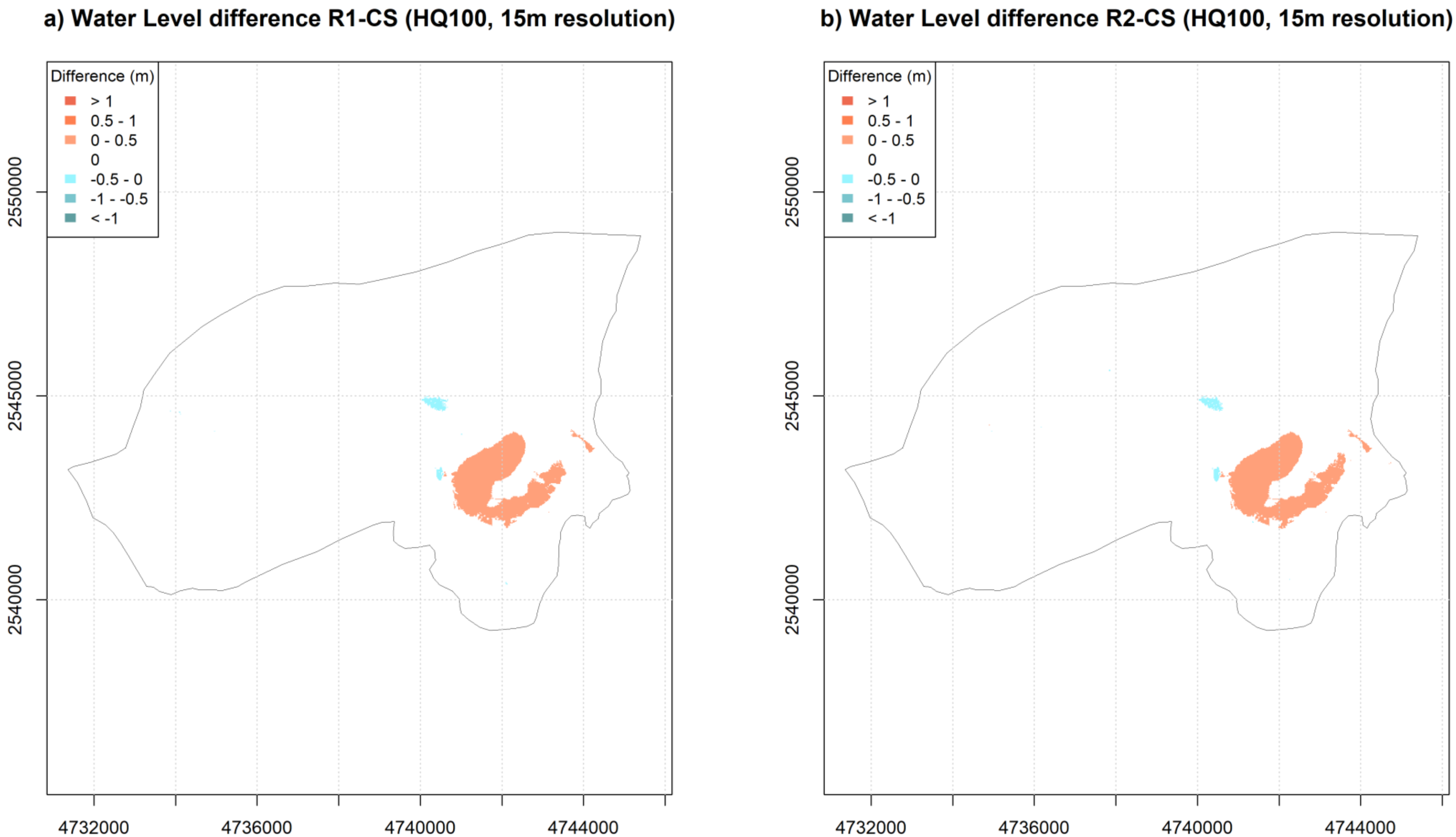


Figure 36: Krka water level difference maps (R1-CS and R2-CS) for HQ_{100} in 15m spatial resolution

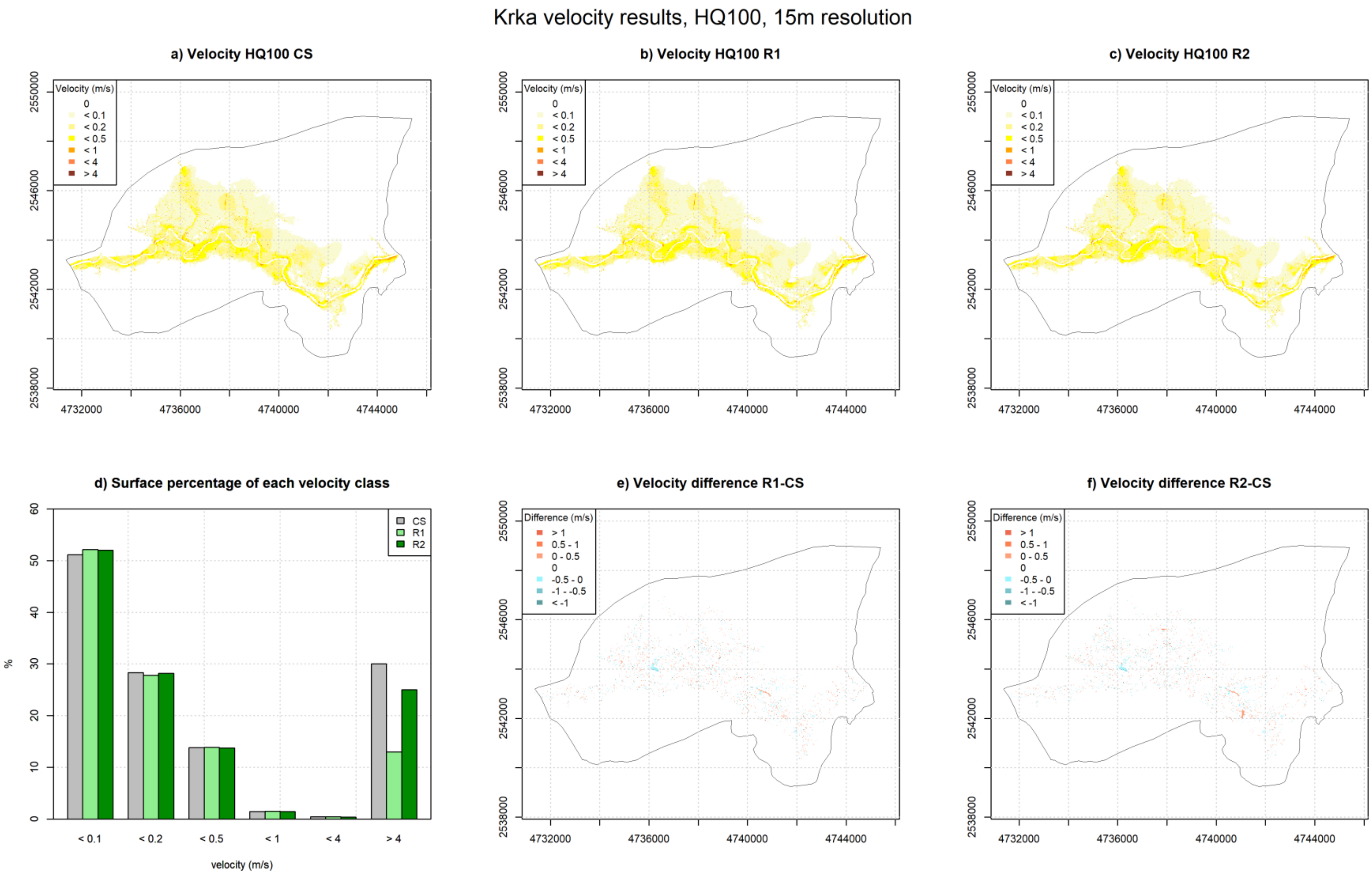


Figure 37: Krka flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 1m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

5.4 Results of pilot area Middle Tisza (HU)

The hydraulic simulation results (Table 7) of the different scenarios in the Middle Tisza pilot area reveal negligible effects in the peak discharge (Q_{max}) of the flood waves of +/- 0.4%. The translation of the flood wave peak is noteable in all events of the R1 scenario with a maximum peak delay of 15 hours in the HQ_{100} scenario. The effects on flood wave translation are lower in the R2 scenario with no change in the HQ_{10} event. The flooded area increases by 4.4% to maximum 6.2% due to the relocation of the dike. The largest effects are simulated for HQs with a return period of 5 years and 100 years without significant differences between R1 and R2. Yet, the increase of flooded area causes an increase in stored volume of 3.9% to 5.0% in all scenarios compared to the CS. The average water depth of the whole flooded area can be decreased through the augmentation of the flooded area by up to 9cm in both restoration scenarios in all investigated events.

The spatial distribution of the effects in water depth is visible in a locally decreased water depth (up to 0.5m) starting upstream of the dike relocation until the upper model boundary (Figure 39, Figure 41 and Figure 43). Downstream of the dike relocation there is no change in water depth. Looking at the velocity (Figure 40, Figure 42 and Figure 44), the flow velocity in the Tisza riverbed is decreased, but this reduction is just visible for around 7 km of the river length.

Overall the effects of the restoration measures are only minor and local by spatial (Figure 39 to Figure 44) and quantitative (Table 7) means.

The initially specified purposes of restoration were partly met. The conveyance capacity and the floodplain area were increased and show the significant effect in flood volume storage. However, the decrease of the flood hazard by implementing the determined restoration scenarios is only notable locally.

Table 7: Results of the 2D simulations in the Middle Tisza pilot area

		HQ_5	HQ_{10}	HQ_{100}
Q_{max} in m³/s	out CS	1928.5	2172.2	2727.1
	out R1	1926.7	2173.4	2728.3
	out R2	1936.9	2162.7	2728.3
ΔQ_{max} in m³/s	R1-CS	-1.8	1.3	1.2
	R2-CS	8.4	-9.5	1.2
ΔQ_{max} in %	R1-CS	-0.1	0.1	0.0
	R2-CS	0.4	-0.4	0.0
Δt in hours	R1-CS	8	4	15
	R2-CS	7	0	6
Change in flooded area in %	R1-CS	6.2	5.0	6.2
	R2-CS	6.1	4.4	6.1
Change in volume in %	R1-CS	4.5	5.0	5.0
	R2-CS	3.9	4.4	5.0
Average water depth in m	CS	3.70	5.20	5.97
	R1	3.63	5.14	5.90
	R2	3.61	5.12	5.90
Average flow velocity in m/s	CS	0.15	0.20	0.22
	R1	0.14	0.18	0.21
	R2	0.15	0.19	0.22

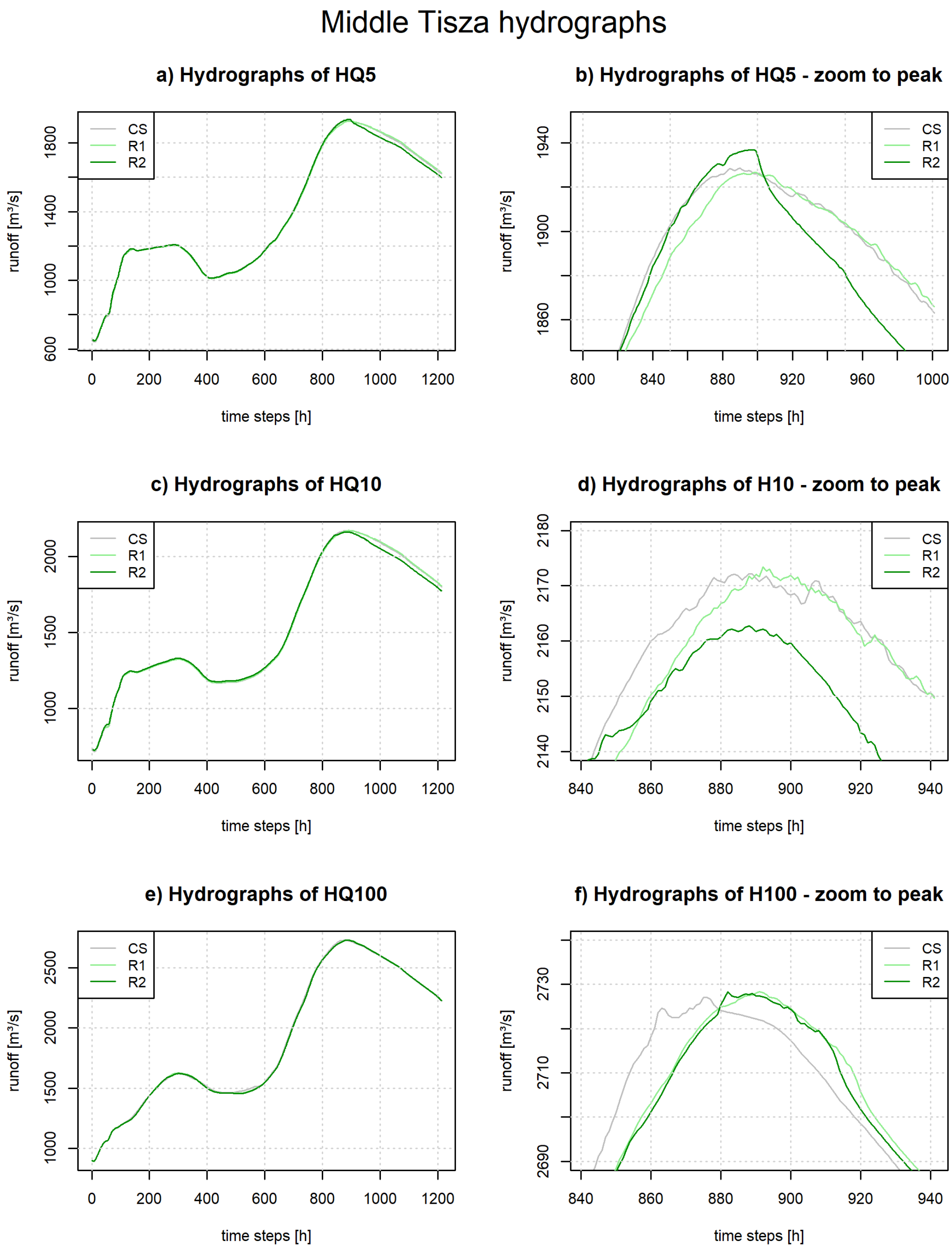


Figure 38: Hydrographs at the downstream model boundary of the Middle Tisza pilot area for $HQ_{2\text{-}5}$ (a)+b), HQ10 (c) and d) and HQ100 (e) and f) for CS, R1 and R2. The figures on the right side show a zoom to the flood peak.

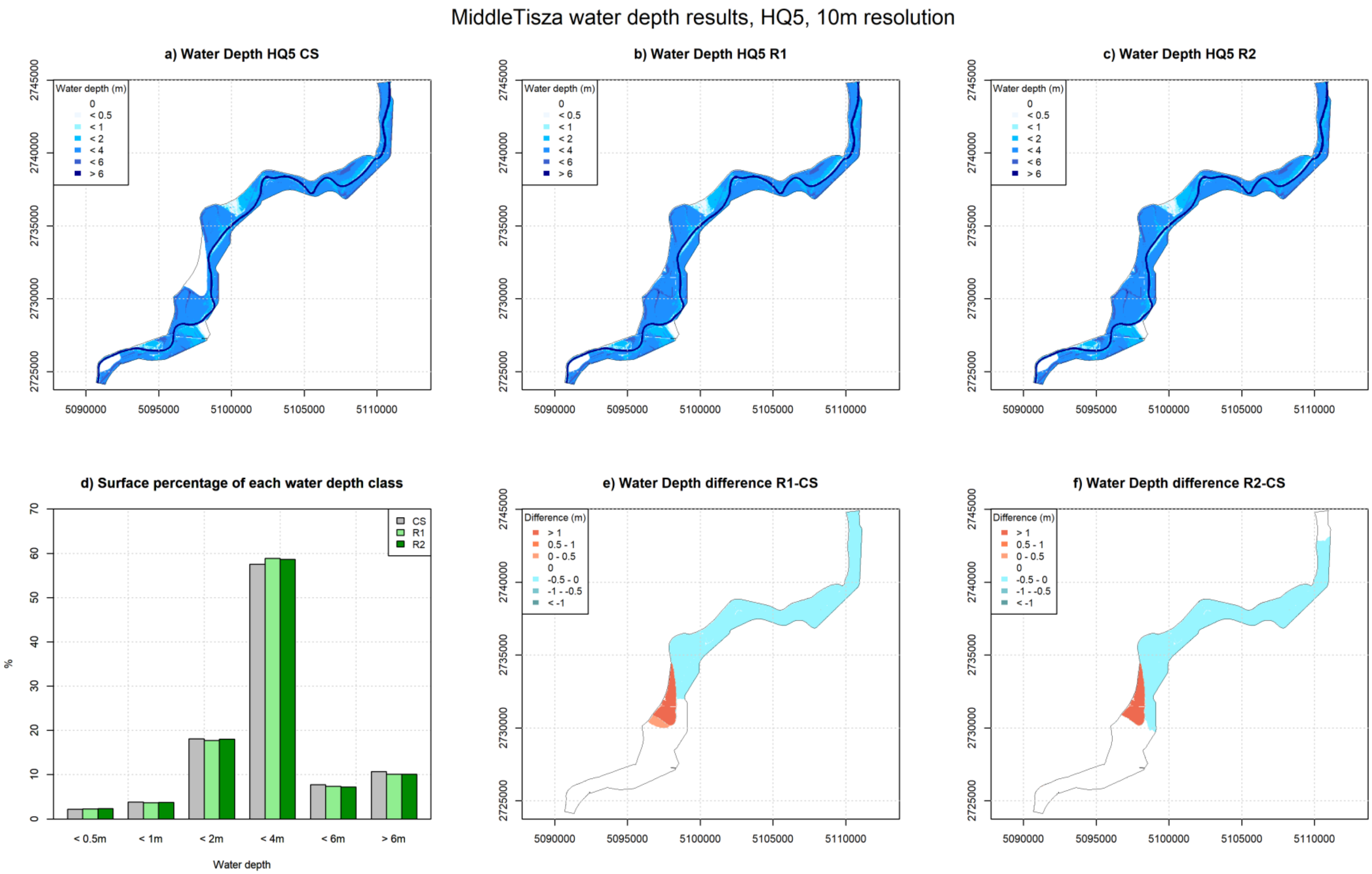


Figure 39: Middle Tisza water depth results, and difference maps (R1-CS and R2-CS) for HQ2-5 in 10m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

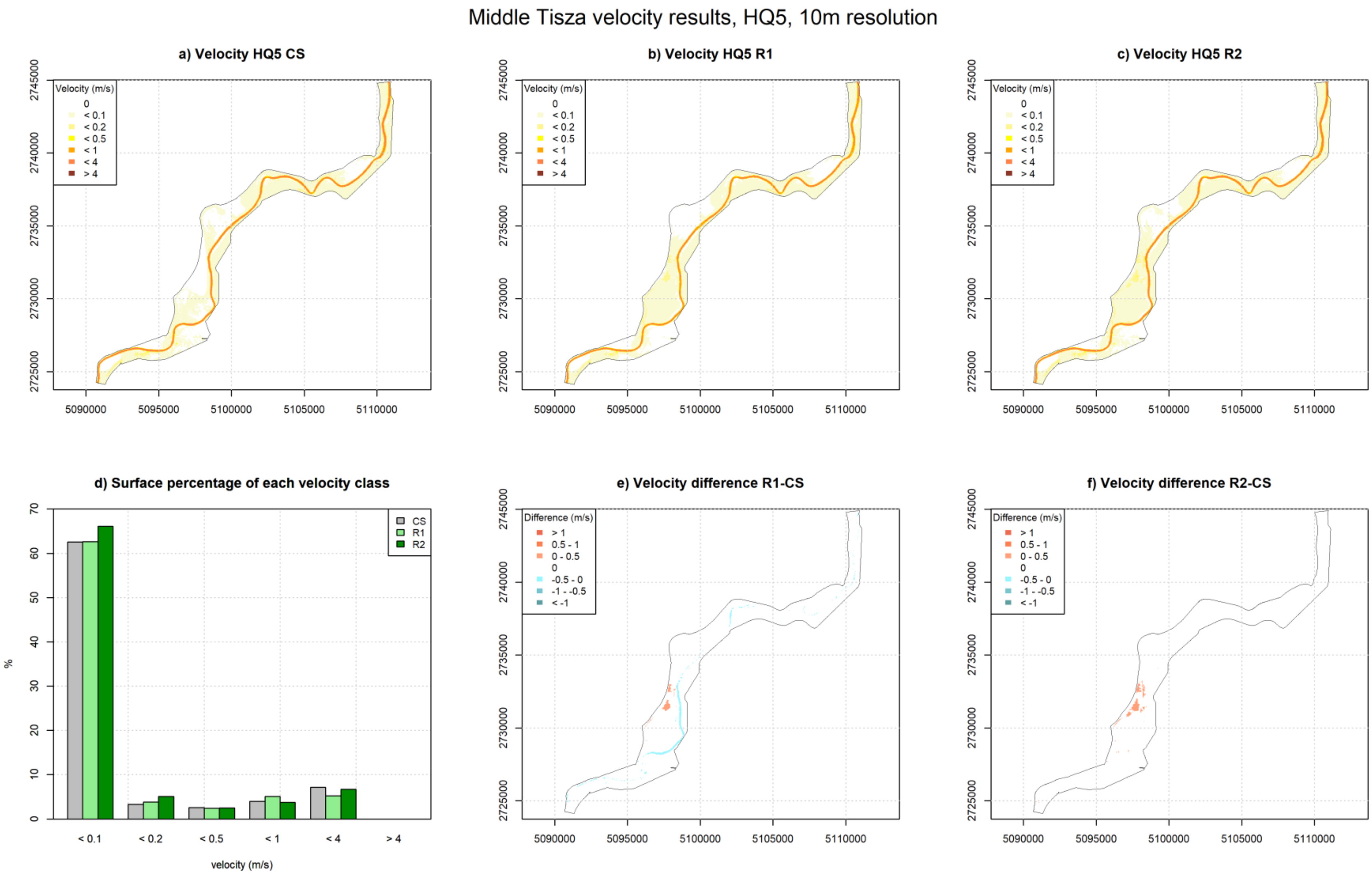


Figure 40: Middle Tisza flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 10m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

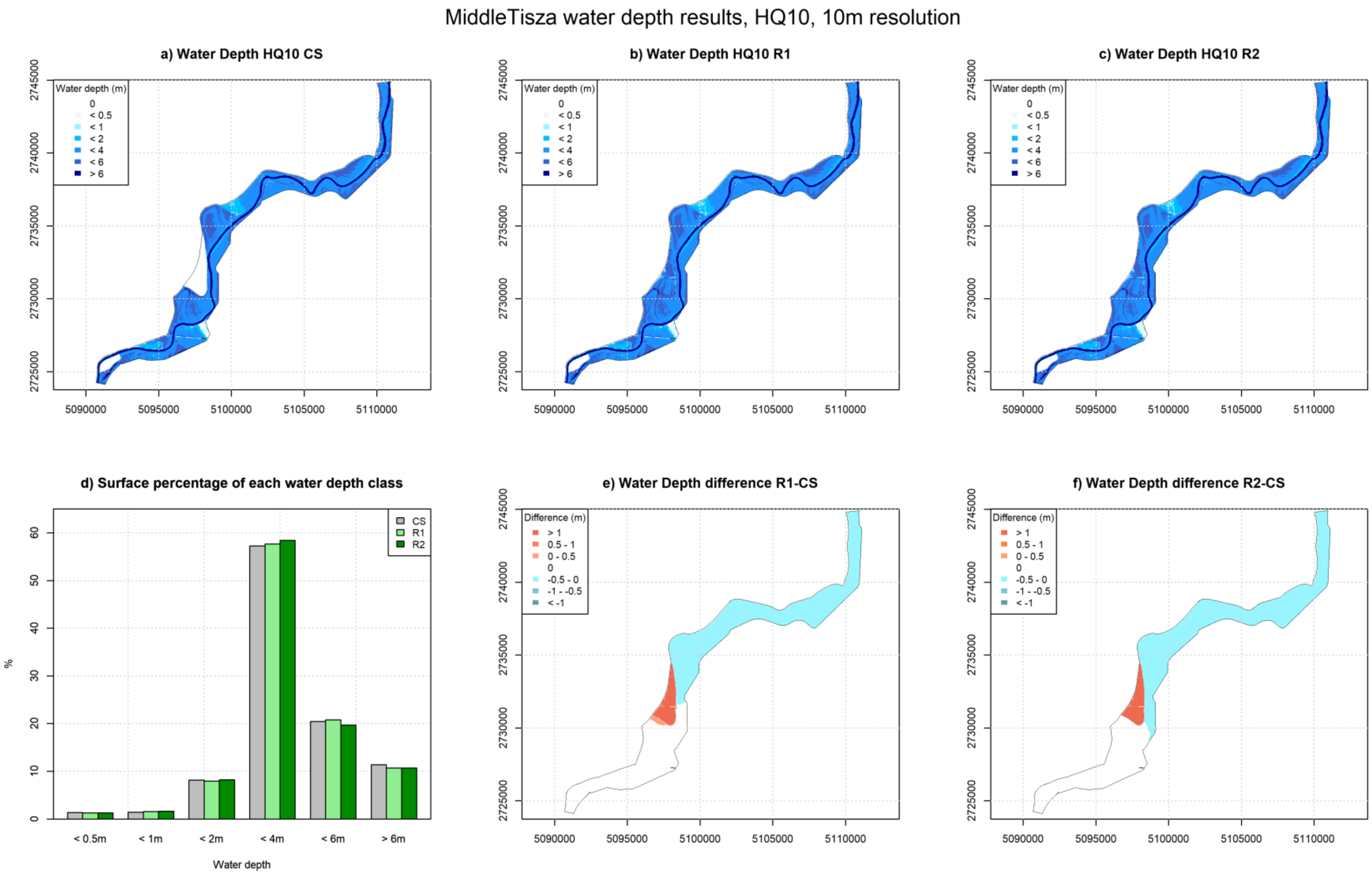


Figure 41: Middle Tisza water depth results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 10m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

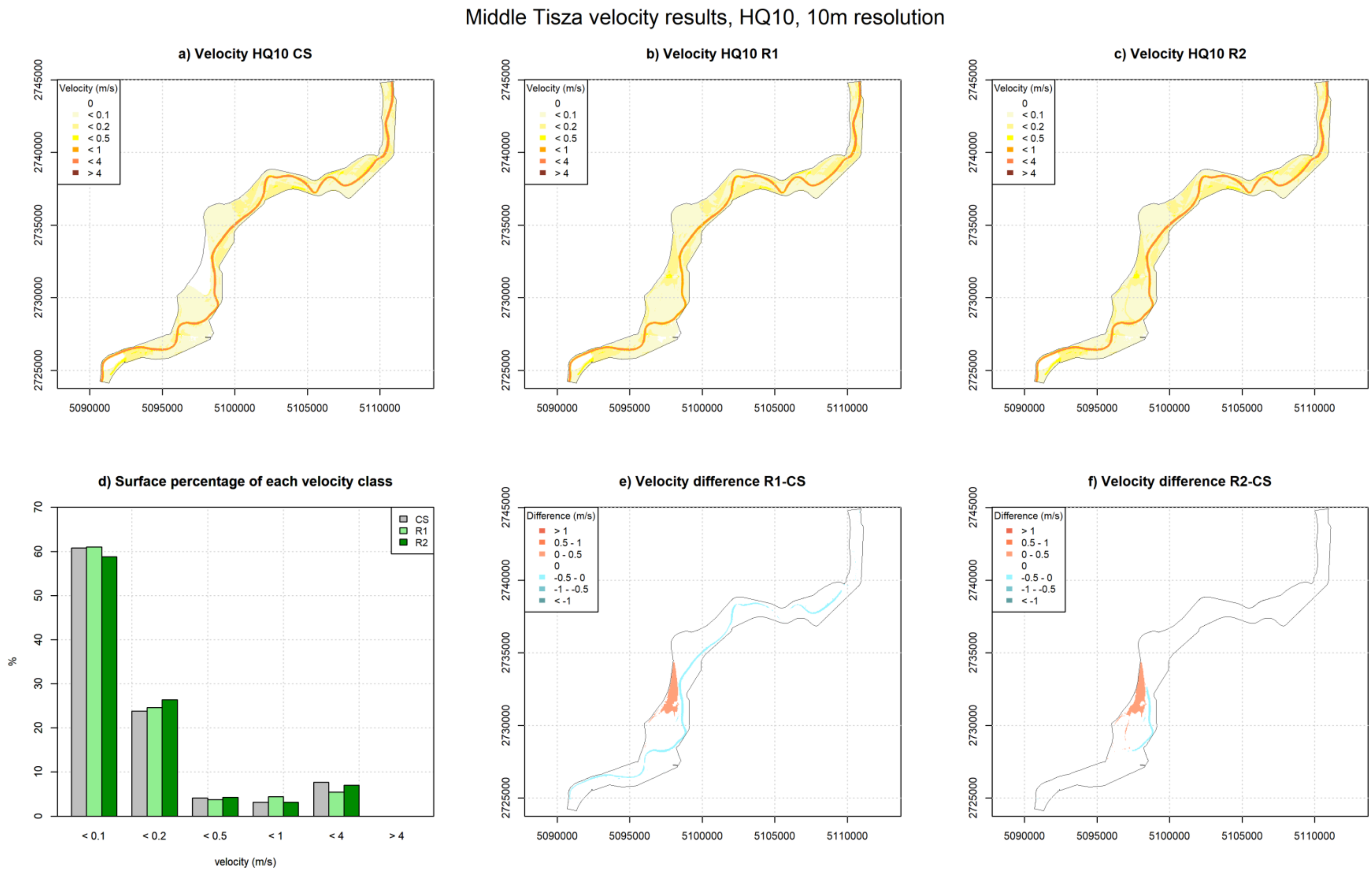


Figure 42: Middle Tisza flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{10} in 10m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

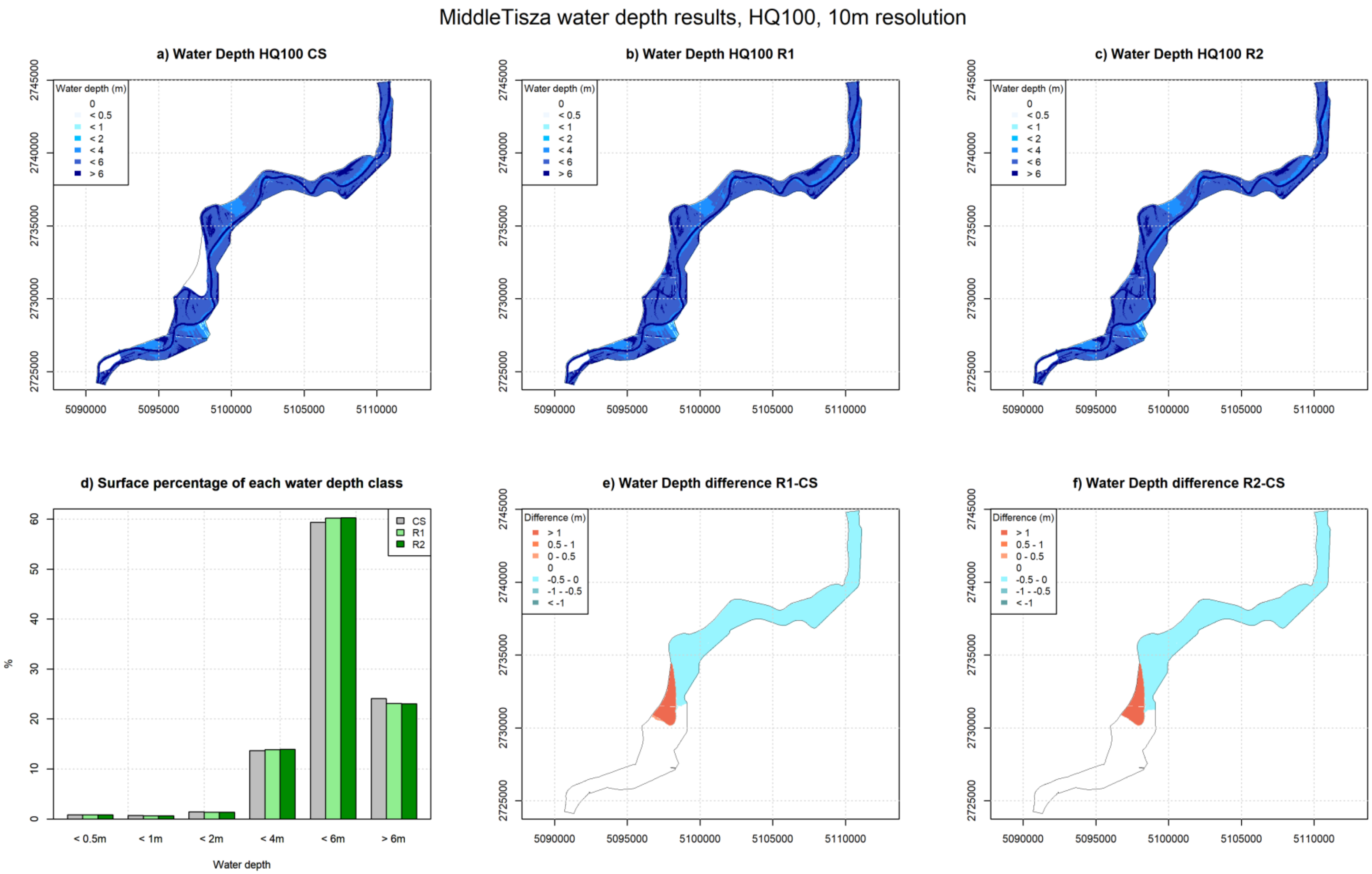


Figure 43: Middle Tisza water depth results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 10m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

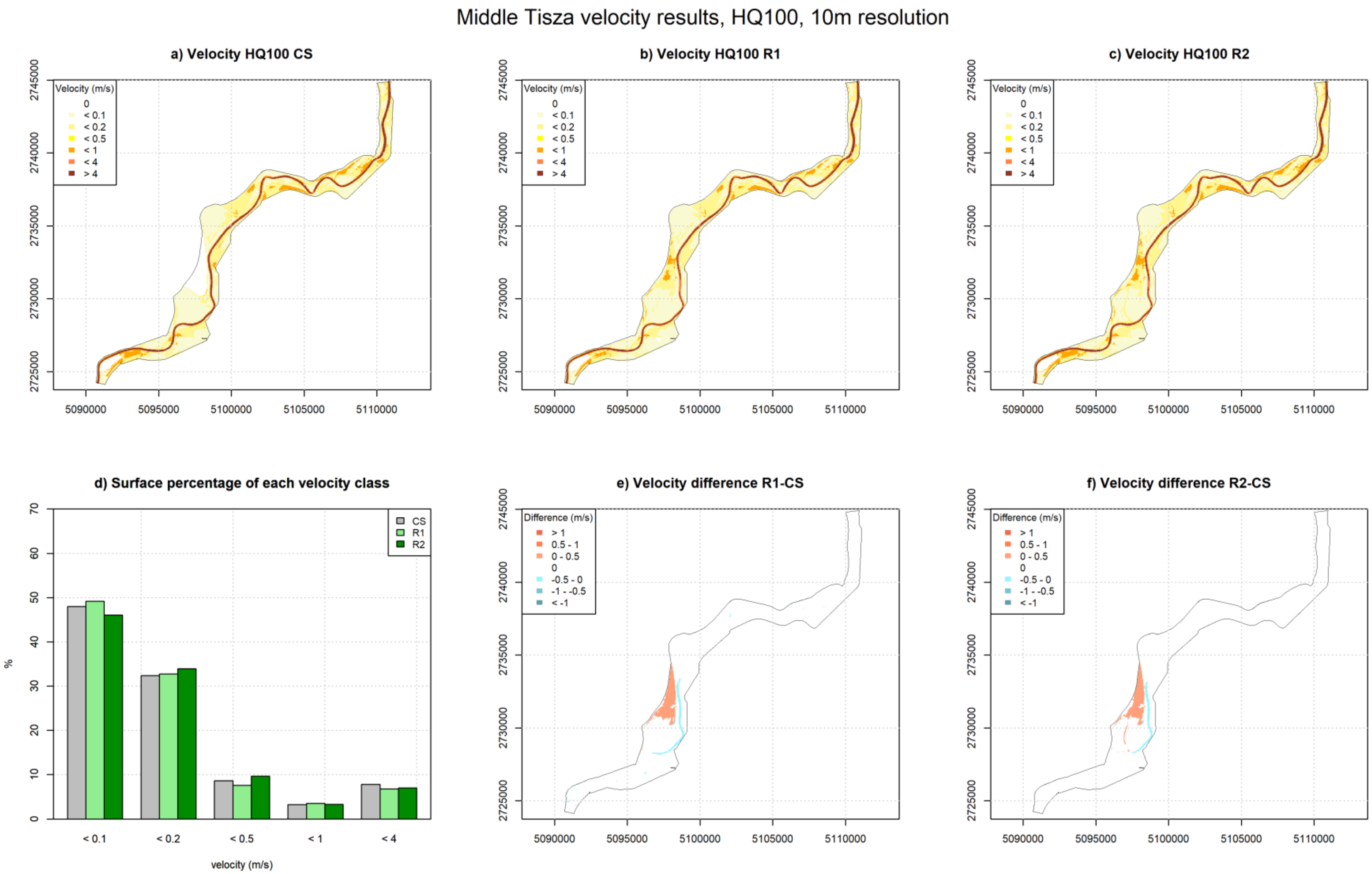


Figure 44: Middle Tisza flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 10m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

5.5 Results of pilot area Morava (SK/CZ)

The results of the hydraulic simulations at the downstream model border of the Morava pilot area (Table 8) show an attenuation in the peak runoff of up to 9.8% in the R2 HQ_{100} scenario and 1.4% to 7.9% in the others. Only in the R2 HQ_2 scenario, there is a slight increase (0.9%) of the maximum runoff value is simulated.

The flood wave translation does not show a consistent trend for the simulations. In the HQ_5 and HQ_{100} events, the peak approaches 11 to 20 hours earlier, while in the HQ_{30} restoration scenarios it is 5 to 7 hours later than in the CS scenario.

Table 8: Results and analysis of the 2D simulations in the Morava pilot area

		HQ_5	**HQ_{30}**	**HQ_{100}**
Q_{max} in m³/s	out CS	667.0	728.2	833.2
	out R1	657.4	684.8	775.5
	out R2	673.3	670.4	751.3
ΔQ_{max} in m³/s	R1-CS	-9.6	-43.4	-57.6
	R2-CS	6.3	-57.8	-81.9
ΔQ_{max} in %	R1-CS	-1.4	-6.0	-6.9
	R2-CS	0.9	-7.9	-9.8
Δt in hours	R1-CS	-20	5	-11
	R2-CS	-20	7	-15
Change in flooded area in %	R1-CS	-24.0	-30.0	-24.2
	R2-CS	-7.1	-16.8	-8.6
Change in volume in %	R1-CS	-20.7	-17.4	-14.1
	R2-CS	-1.9	2.2	6.1
Average water depth in m	CS	0.76	0.80	0.84
	R1	0.70	0.75	0.80
	R2	0.77	0.87	0.91
Average flow velocity in m/s	CS	0.28	0.27	0.27
	R1	0.16	0.16	0.18
	R2	0.16	0.17	0.19

However, looking at these results, the tributary condition in the Morava pilot area has to be considered. The modelled pilot area is influenced by a series of small tributaries and a larger tributary, the Dyje (Thaya) River, on the downstream model part, which carries approximately half mean annual discharge of Morava River. Therefore, the ouflow point from the whole system at the gauging station Moravsky Sv. Jan (downstream of Morava/Dyje confluence) is used to evaluate the effectivity of restoration measures. The real flood waves from 2009 and 2010, which occurred on the upstream boundary of the model on Morava River, were used in hydraulic simulations but the discharge situation on tributaries was not always the same. This affects the output hydrographs obtained by the models and of course influences the ΔQ and Δt quantification. However, the differences which are more dominant among the hydrological scenarios than the restoration scenarios can be explained thereby, like for example the inconsistencies in ΔQ and Δt. The increase in ΔQ during the HQ_5 R2 scenario is partly due to the large share of discharge originating from the Dyje tributary. The discharge of the Morava is in the case of the lowest HQ scenario still below the level where the Polder Soutok would be activated (600m^3/s) resulting in no change for the discharge in the Morava main channel. To the discharge in the main channel the tributary discharge is added resulting in an overall increased discharge. The later approach of the flood wave during the HQ_{10} also originates from the tributary conditions. In the other hydrological scenarios an earlier approach of the flood wave is simulated , because the large portion of the flood discharge originates from the Dyje tributary. However in the case of a HQ_{10} a large portion of the discharge comes from the Morava main channel and less discharge from the Dyje tributary. Thus the effectiveness of the retention in the additional floodplain remains visible until the gauging station and is not attenuated by the Dyje inflow.

The average water depth is decreasing in all R1 scenarios, while it is increasing in all R2 scenarios compared to the CS. The mean flow velocities are reduced in all restoration and hydrological scenarios which is caused by the meandering and changed topography which slows the velocity in the river channel. The spatial distributed results of the water depth, water level and the flow velocities are shown in Figure 46, Figure 49 and Figure 52, Figure 47, Figure 50 and Figure 53 and Figure 48, Figure 51 and Figure 54, respectively. The water depth and water level is in all scenarios decreasing in the area of the polder Soutok and increasing in the floodplains. The effective increase in water height without the modifications of the DEM can be seen in the difference maps of the water level (Figure 47, Figure 50 and Figure 53). The flow velocities follow the same pattern (increasing in floodplains and decreasing in polder area).

The pilot area of Morava River on SK-CZ border is under present conditions located at a heavily modified water body. The present floodplain is very narrow and delineated by flood protection dykes. Moreover, there is a large retention area behind the dykes (Polder Soutok) on the right-side floodplain which is used for releasing flood discharges (from Q_{max} 100 m^3/s which are released at flood dicharge on Morava above 600 m^3/s). Water from the retention area is released back to Morava River near the downstream boundary of the 2D model.

However, it can be stated that restoration measures slightly decrease the discharge in Morava River but markedly increase water level in restored floodplains along the Morava River (presently cut-off) which is a positive effect for ecology. The water level in Morava during flood decreases as the capacity storage of the floodplain increases. Due to the decreased flood discharge in Morava River, the 2D simulations showed lower water level at the existing retention area, the polder Soutok.

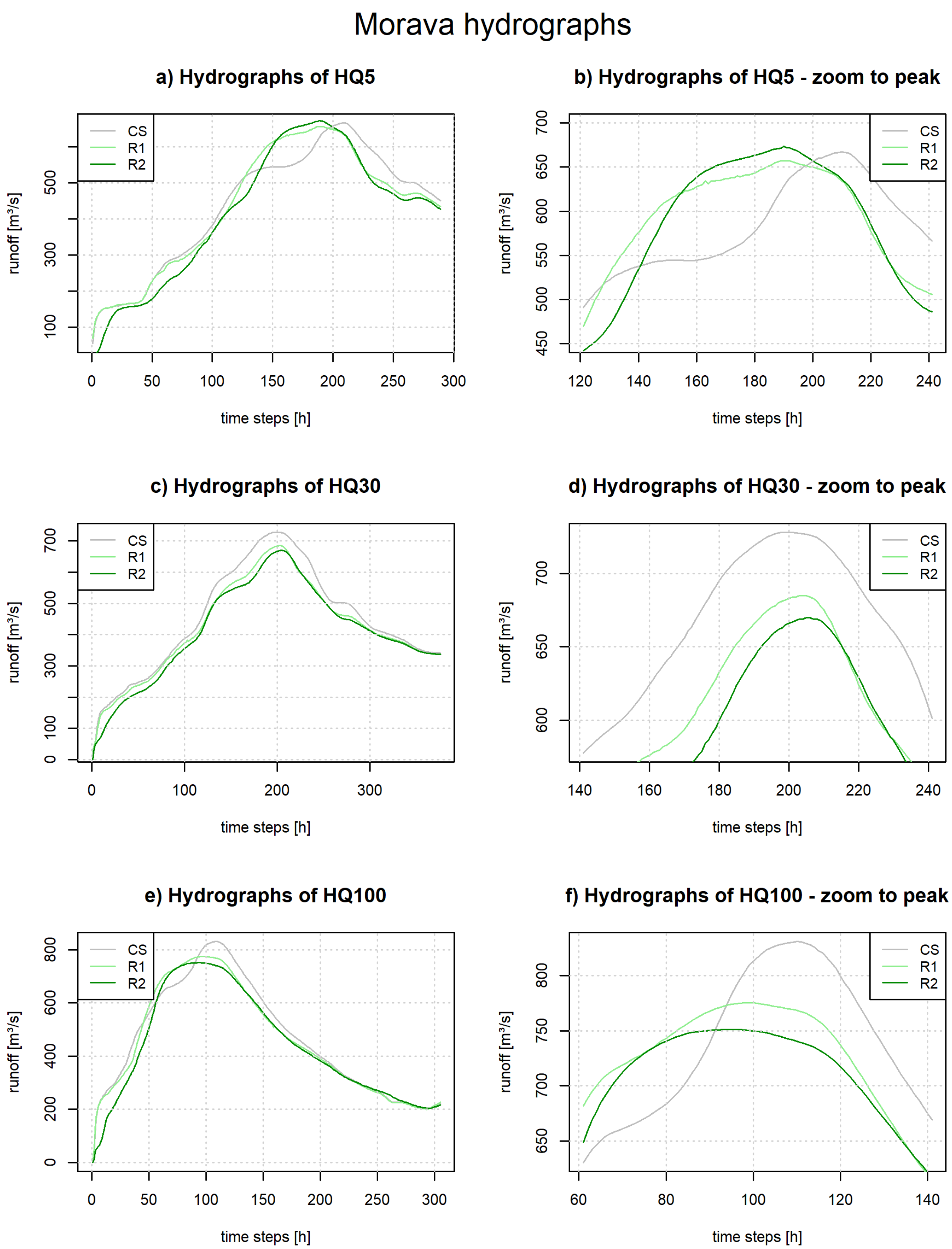


Figure 45: Hydrographs at the downstream model boundary of the Morava pilot area for $HQ_{2\text{-}5}$ (a)+b), HQ10 (c) and d) and HQ100 (e) and f) for CS, R1 and R2. The figures on the right side show a zoom to the flood peak.

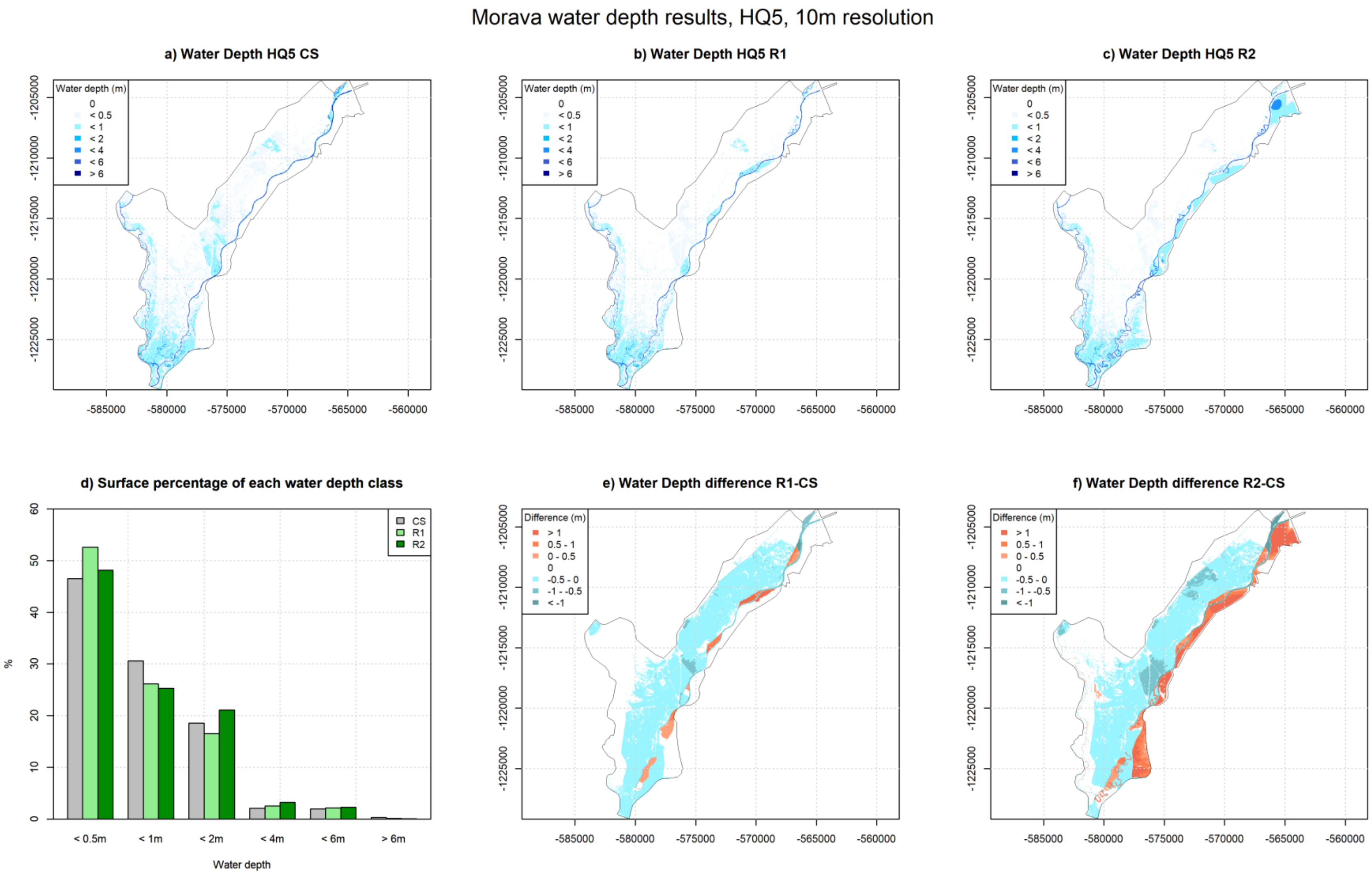


Figure 46: Morava water depth results, and difference maps (R1-CS and R2-CS) for $HQ_{2\text{-}5}$ in 10m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

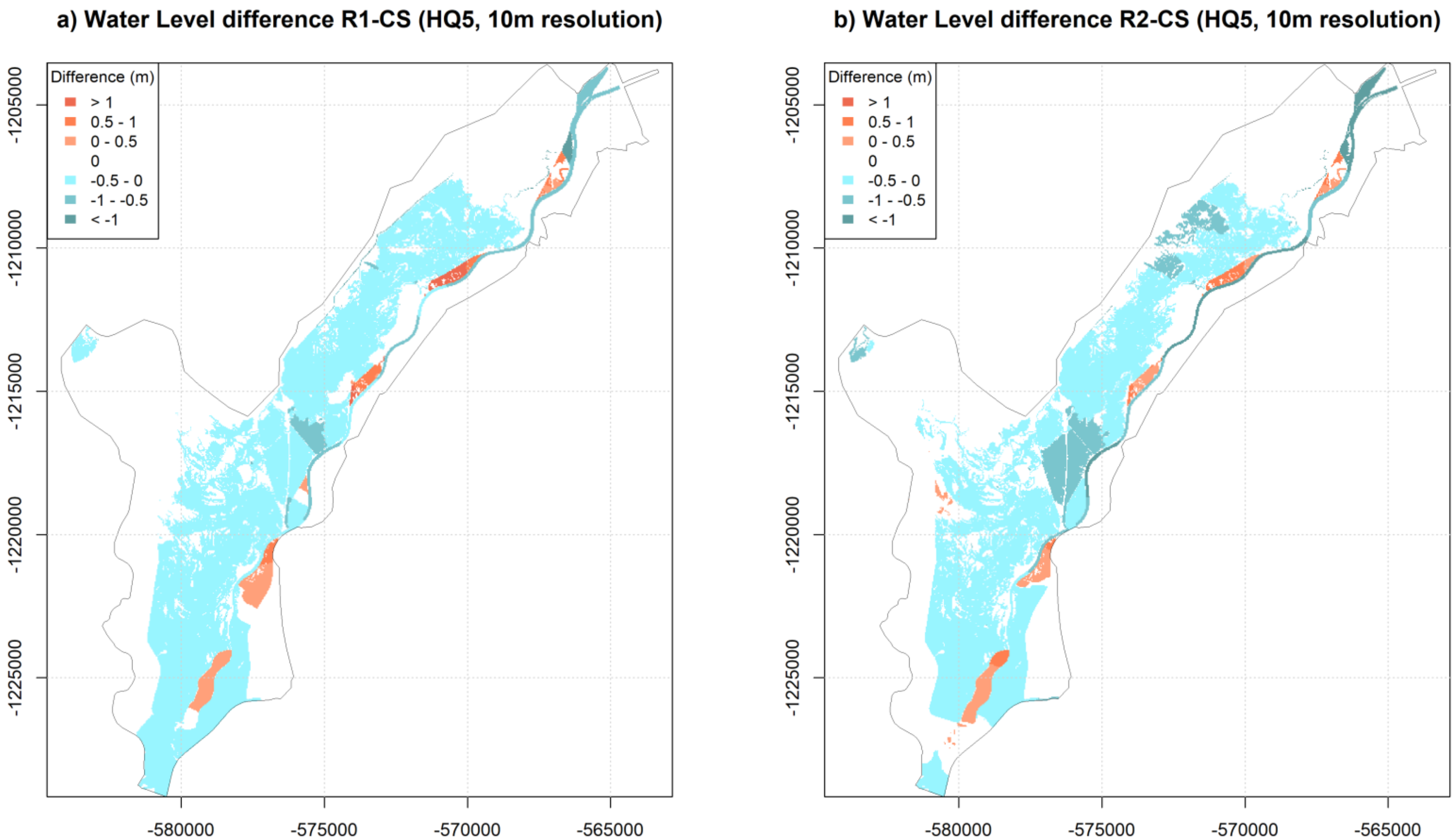


Figure 47: Morava water level difference maps (R1-CS and R2-CS) for HQ_{2-5} in 10m spatial resolution

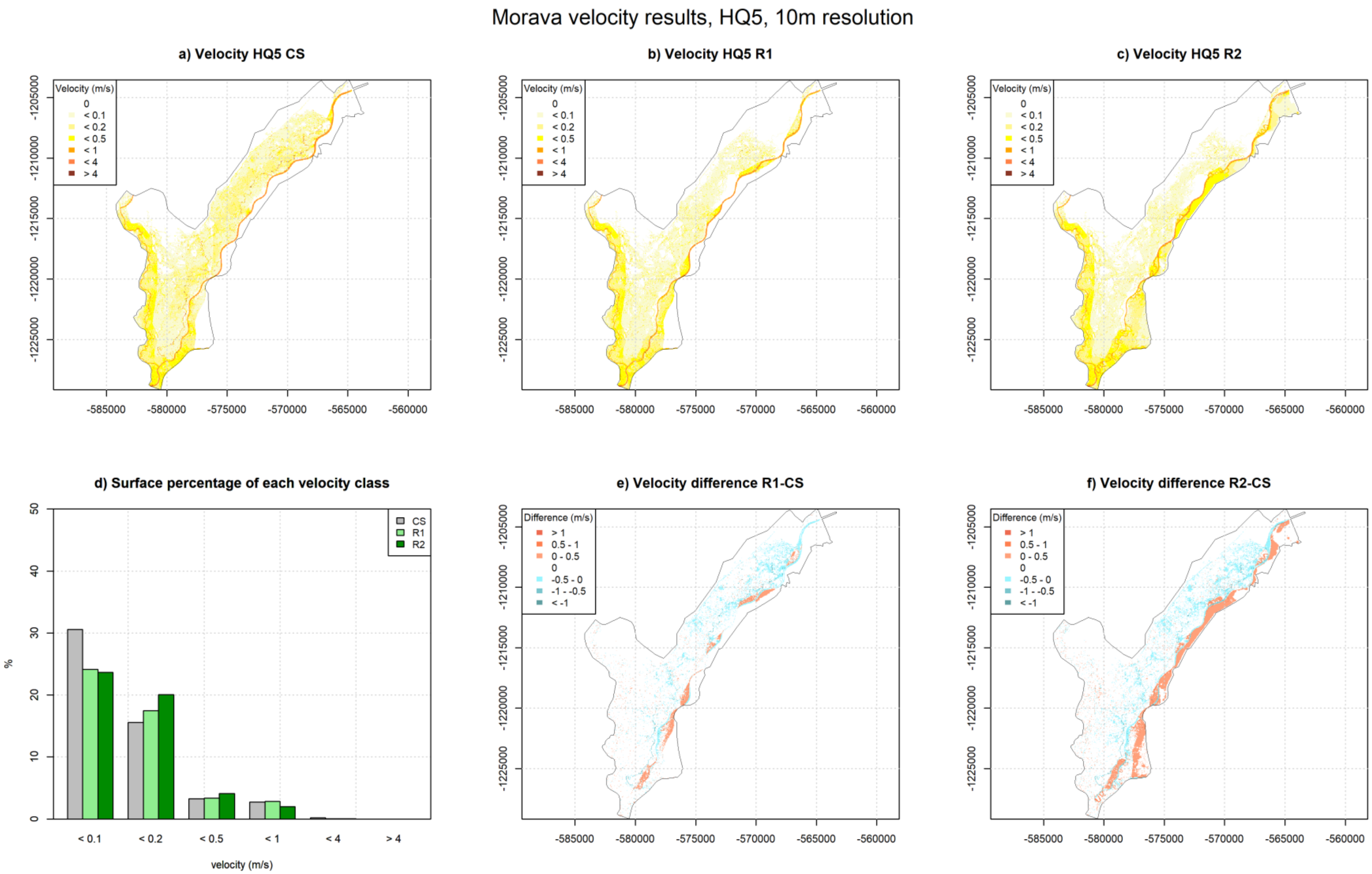


Figure 48: Morava flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{2-5} in 10m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

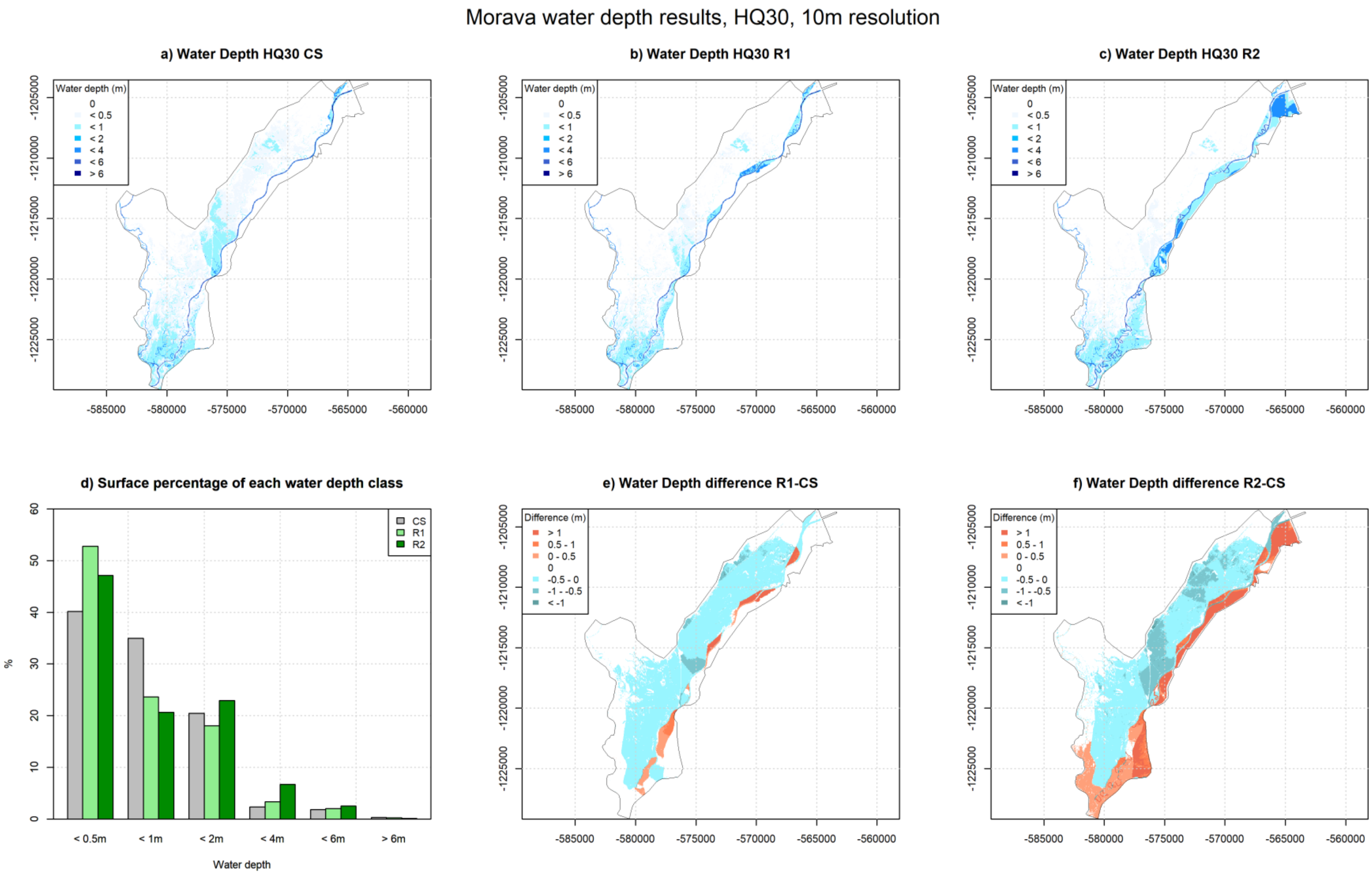


Figure 49: Morava water depth results, and difference maps (R1-CS and R2-CS) for HQ_{30} in 10m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

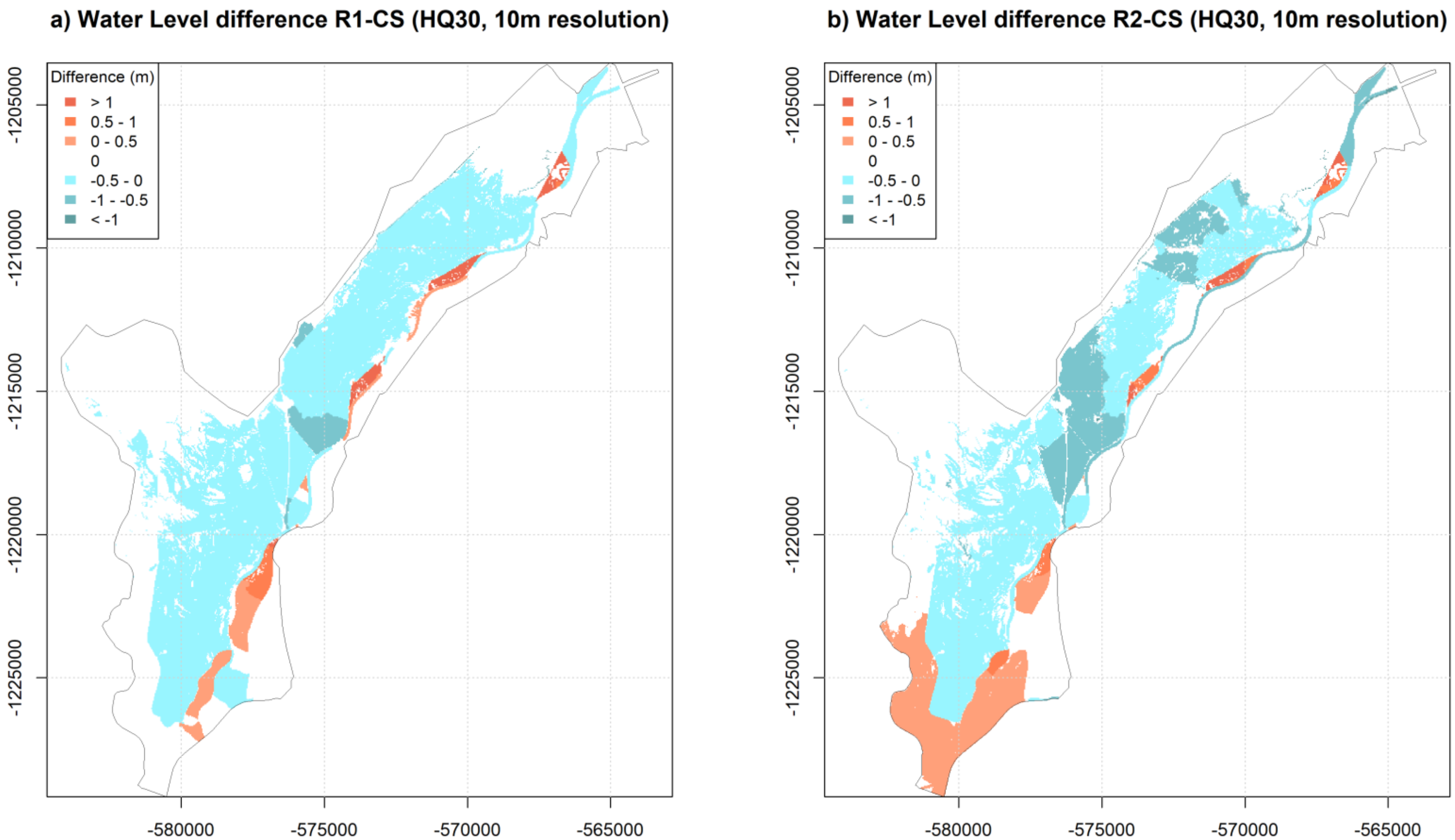


Figure 50: Morava water level difference maps (R1-CS and R2-CS) for HQ_{30} in 10m spatial resolution

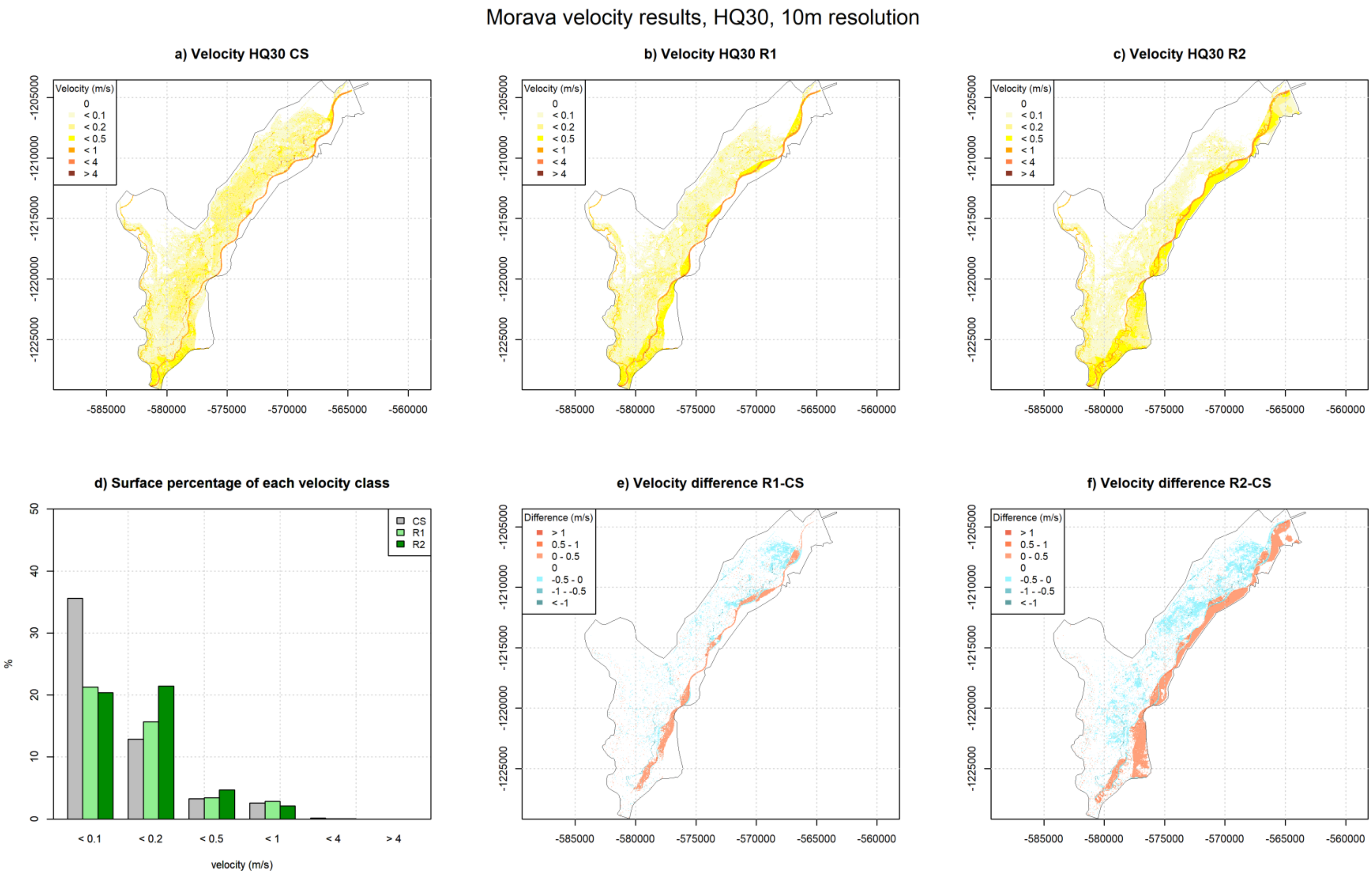


Figure 51: Morava flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{30} in 10m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

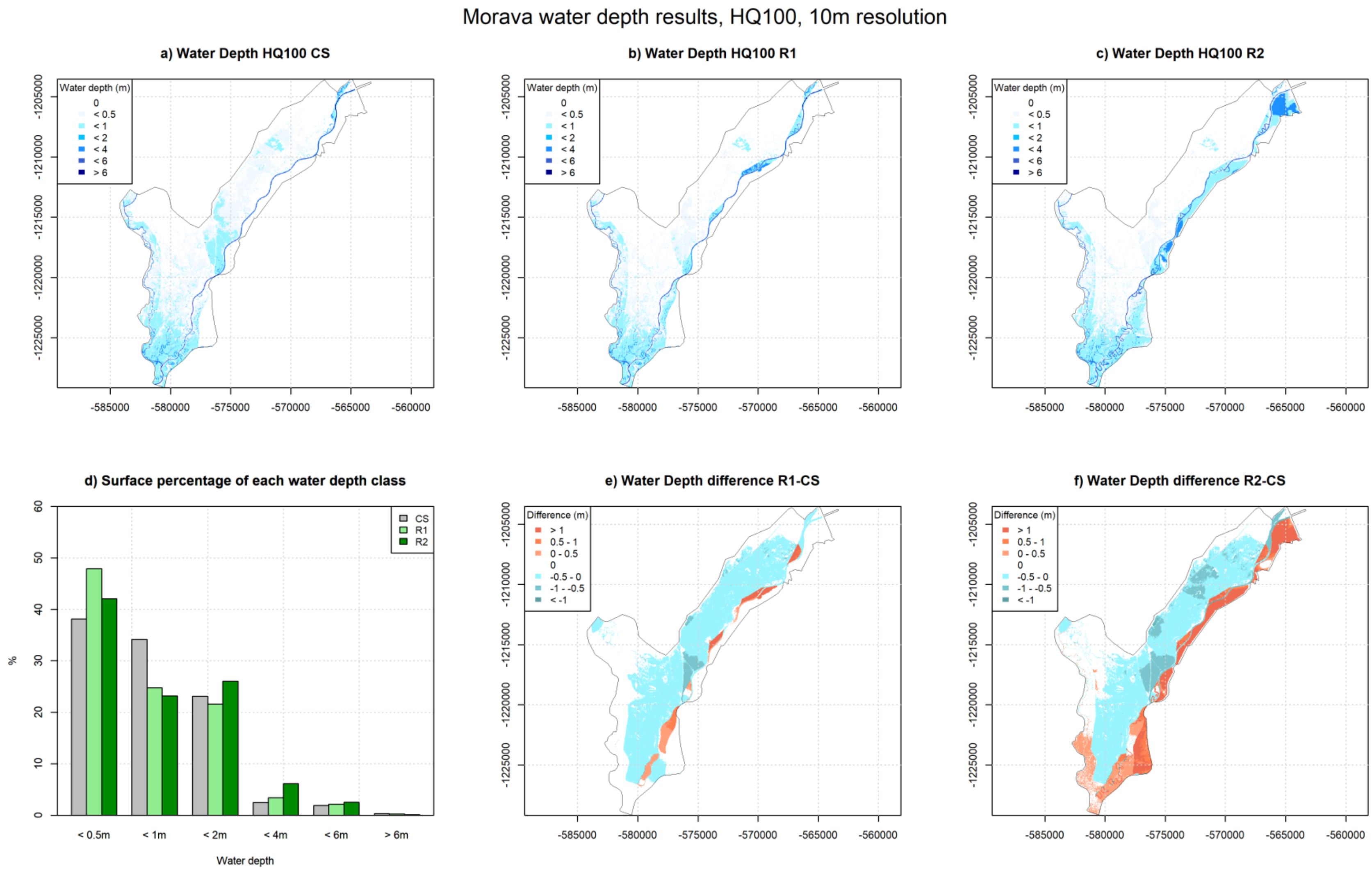


Figure 52: Morava water depth results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 10m spatial resolution and the percentage of each water depth class expressed as percentage of the total surface area.

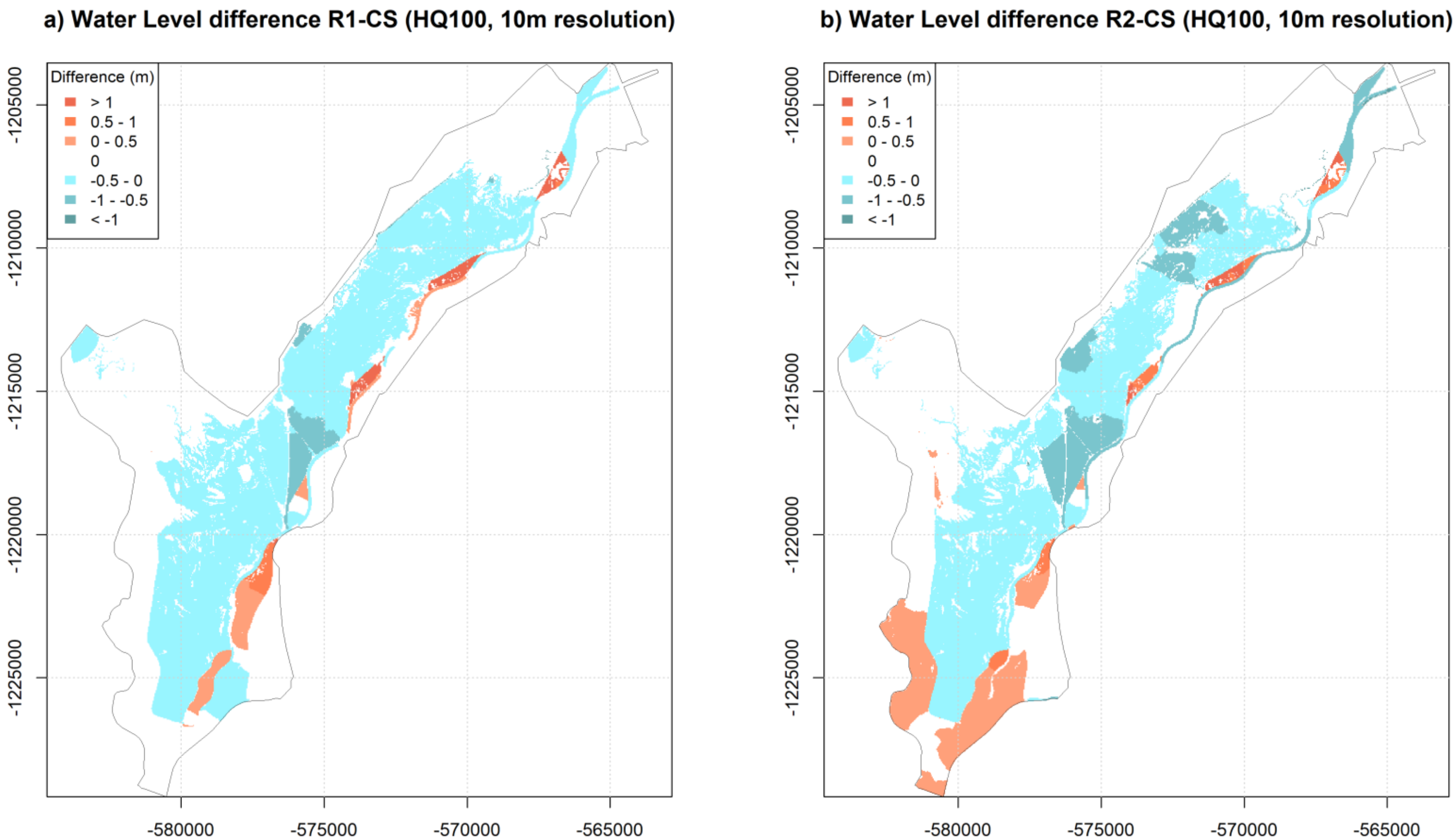


Figure 53: Morava water level difference maps (R1-CS and R2-CS) for HQ_{100} in 10m spatial resolution

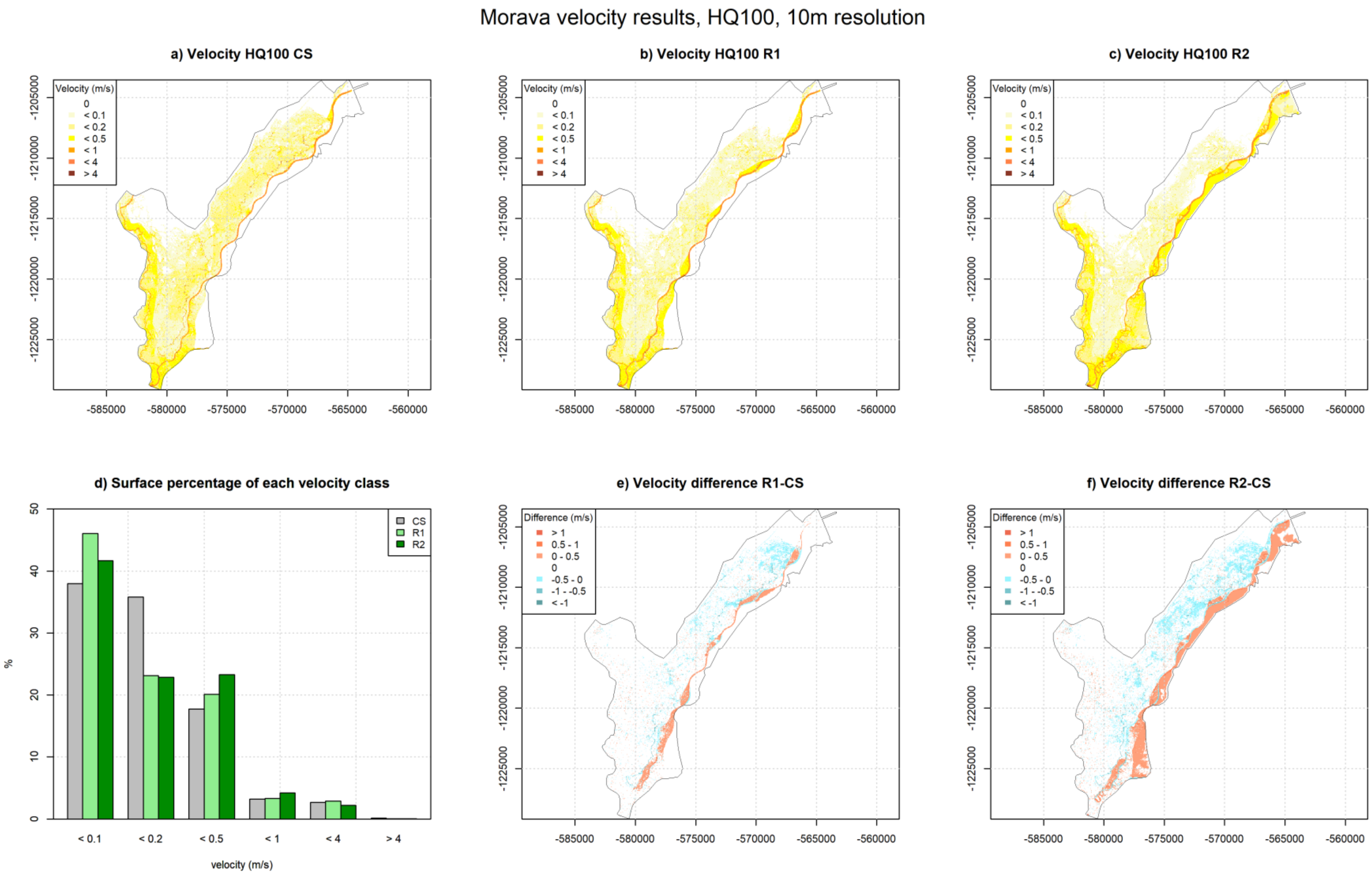


Figure 54: Morava flow velocity results, and difference maps (R1-CS and R2-CS) for HQ_{100} in 10m spatial resolution and the percentage of each flow velocity class expressed as percentage of the total surface area.

6. Comparison and conclusion

In general, all applied hydrodynamic 2D models of the different scenarios are able to reproduce the current state condition and to demonstrate effects of floodplain restoration measures in the five pilot areas. All simulations show a difference between the current state and the restoration scenarios, in the spatial results (e.g. water depth or flow velocity maps) as well as in the hydrographs, confirming a temporal and quantitative transformation of the flood peak. The dimension of the effect is variable and depends on the type of measure and scale of restoration. In addition, the magnitude of the flood mitigation effect is different for the investigated flood events and their shape of the hydrograph.

Figure 55 and Figure 56 show the effects of the implemented restoration measures of R1 and R2 on the flood peak reduction (ΔQ) and the flood wave translation (Δt) during hydrological events of a frequency of 2-5 year, 10-30 year and 100 years (i.e. return period) in each of the five pilot areas. When interpreting those results it is crucial to keep in mind that the measures implemented in R1 and R2 of each pilot area can differ and also that the measures implemented in R1 and R2 among all pilot areas can differ (Table 2). Thus a direct interpretation has to be performed carefully.

Starting with the effects of restoration measures in Begečka Jama it is important to consider that no additional floodplain area or retention channels are implemented, leading to almost no change in ΔQ. However, many measures are simulated concerning the reconnection of lateral river branches or oxbows, thus a translation of the flood peak (Δt) is observable (flood peak approaches later) especially in the HQs with a smaller frequency in R1. In R2 this effect is minor as an additional channel was excavated which lead to a shorter travelling distance for the flood wave. Here eventually an earlier approach is achieved.

In the Bistret pilot area the restoration measures mainly focused on the reactivation of floodplains by dike removals and the creation of a new channel to supply lake Bistret with water. In both restoration scenarios only a small effect on ΔQ can be achieved. The largest effect is simulated for an HQ_{100} in scenario R1. Unlike in R2 in R1 an additional channels for flood retention are implemented, leading to slightly higher effects in ΔQ for higher HQs. However, when considering Δt beneficial effects are simulated for the R2 scenario. The creation of new floodplain areas by the complete dike removal, as implemented in Bistret for R2 but not R1, and the transformation of floodplains towards natural conditions allows a longer retention of flood discharge in the floodplain areas, which again contributes to the discharge 11 to 16 hours later. Yet, the effect decreases with an increasing HQ, as the capacity is limited: Nevertheless, an retention of the flood wave for 11 hours can be still achieved for a HQ_{100}.

Krka restoration scenarios do not differ between R1 and R2 in the type of measure, but in the magnitude in which it is implemented. This becomes also visible in the reduction of maximum discharge (ΔQ) for R1 and R2. Larger reductions are obtained in scenario R2 than R1. This conclusion is also confirmed by the results represented spatially as water level and water depth maps (Figure 29 and Figure 30, Figure 32 and Figure 33, Figure 35 and Figure 36). Effects on Δt cannot be detected, i.e. no translation of the flood wave occurs. It can be assumed, that the highest amount of discharge is still propagated at the same time.

However it is less than in the CS scenario, as a certain amount is stored in the additional retention areas (floodplain forest).

The R1 and R2 scenario of Middle Tisza are focusing on the increase and transformation of floodplain areas to natural conditions. In R2 additionally, afforestation is implemented in the floodplain and an additional retention channel is created. Nevertheless, no distinct effects on ΔQ are achieved with these measures. Yet, a retention of the flood discharge and thus a translation of the flood wave (Δt) is achieved, however with inconsistent magnitudes among the hydrological events. The marginal effect on ΔQ and the more pronounced effect on Δt, suggest, that the flood discharge is retained by the floodplain for a certain amount of time and is then released. Further the shape of the hydrograph with a rather broad flood peak (Figure 38), indicates, that during the first hours (the time the peak is delayed) the floodplain is filled up. However the peak is not yet declining, resulting in a later but equally large flood peak after the floodplain.

Finally restoration measures in the Morava river differ a lot between R1 and R2. R2 includes several measures concerning the river channel itself and the extent of the floodplains, whereas in R1 only floodplain expansions are implemented. Thus, the effects of ΔQ and Δt are variable. Additionally special tributary conditions have to be considered in the Morava model area. It is important to also investigate the lateral inflows from the tributaries as the discharge conditions of the tributaries and the Morava can differ and shift the results. For example, the restoration measures do not seem effective by the means of the flood wave translation for HQ_5 and HQ_{100}, but effective for a HQ_{10}. However, when analyzing the results subjected to the discharge of the Morava main channel and the discharge of the Dyje tributary, it is noted that for the HQ_5 and HQ_{100} the share of discharge of the Dyje is rather high and the effect of the upstream restoration measures is attenuated at the confluence. Thus, the importance to consider local conditions during the evaluation of the effectiveness of restoration measures is once more confirmed.

Overall the largest reduction of the peak discharge (ΔQ) of the investigated flood waves is obtained for the Morava pilot area in an R2 scenario with about 10% (Figure 55). In the other pilot areas a peak reduction of maximum 2% in the R1 and up to 4% in the R2 scenario is simulated. Many scenarios do not show a notable impact on the peak value (e.g. Begečka Jama and Bistret), however this can be explained by the restoration measures. Morava is the only pilot area that investigated a modification of the river course (meandering). Yet, special tributary conditions have to be considered when interpreting results of the Morava pilot area. Some scenarios show even a slight increase of the peak discharge by less than 1% (Morava HQ_5), which can be again explained by the discharges of the tributaries. The HQ_{2-5} event simulation show smaller percentage values in peak reduction than the HQ_{10-30} and HQ_{100} events, explained by the fact that the main river channel is often able to discharge smaller flood magnitudes, without activation of the implemented restoration measures.

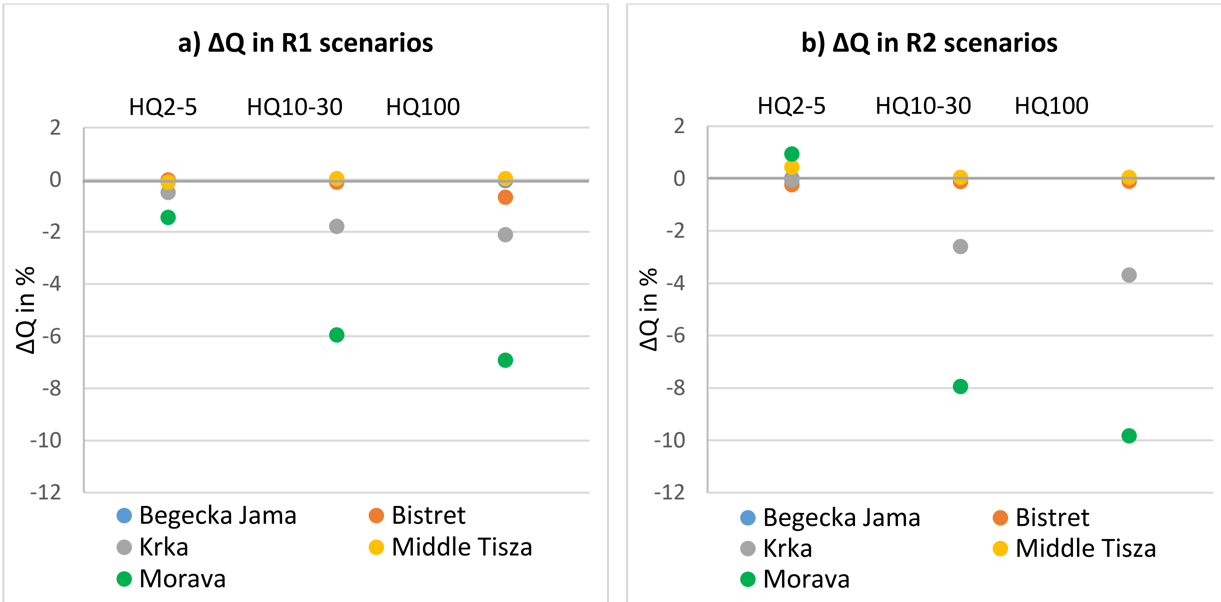


Figure 55: Flood peak reduction (ΔQ) in % compared to the CS in all pilot areas in a) the R1 and b) the R2 scenario

Looking at the ΔQ values of all scenarios in the pilot areas compared with the percentage change in the flooded area, it can be concluded that if measures are implemented in the river channel itself (deepening and widening of the riverbed) a larger increase in the flooded area does not correlate with a reduction in ΔQ, but a decrease of the flooded area correlates with a flood peak reduction. Yet, this is only confirmed if restoration measures on the river channel are implemented. Thus it is crucial to not only consider a single restoration measure but a combination of multiple measures and the joint effectiveness.

Regarding the effect of the time to flood peak, the difference in hours (Δt) between the flood peaks is compared with CS. It is visible that both, an earlier or a later approach of the flood peak is generated with the two scenarios (Figure 56). In the Morava pilot area the earlier flood peak is caused by the interaction of the Dyje tributary flood wave which discharges into Morava just upstream of the lower model border. So for a further analysis of the impact of only the restoration measures, a simulation without discharge from Dyje is a possibility to assess the Morava River restoration effects. However, the situation would be unrealistic and rather restoration measures also affecting the Dyje discharge should be determines and assessed in an integrated way.

For the other pilot areas, in many scenarios the Δt is negligible with a difference below +/- 1h which can be explained by uncertainties in the simulations with a temporal resolution of 1 hour. In the Middle Tisza pilot area, a flood peak delay of 4 to 15 hours can be achieved in all scenarios. The highest values in flood wave translation are simulated in the R2 scenario in Bistret (HQ_{2-5}), which can be explained by the large additional flooded area (increase by more than 300% compared to the CS) created through the dike relocation which causes this retention effect.

An increase in the flooded area through restoration measures mostly generates a later approach of the flood peak. The larger the expansion of the floodplain the more considerable the effectiveness of the measure for flood wave translation. However, the effect on the maximum discharge value is not that distinct by the extension of floodplain area but more by a combination of restoration measures, concerning the river channel, the floodplain extent and the character of the floodplain (natural conditions) as in the Morava R2 scenario.

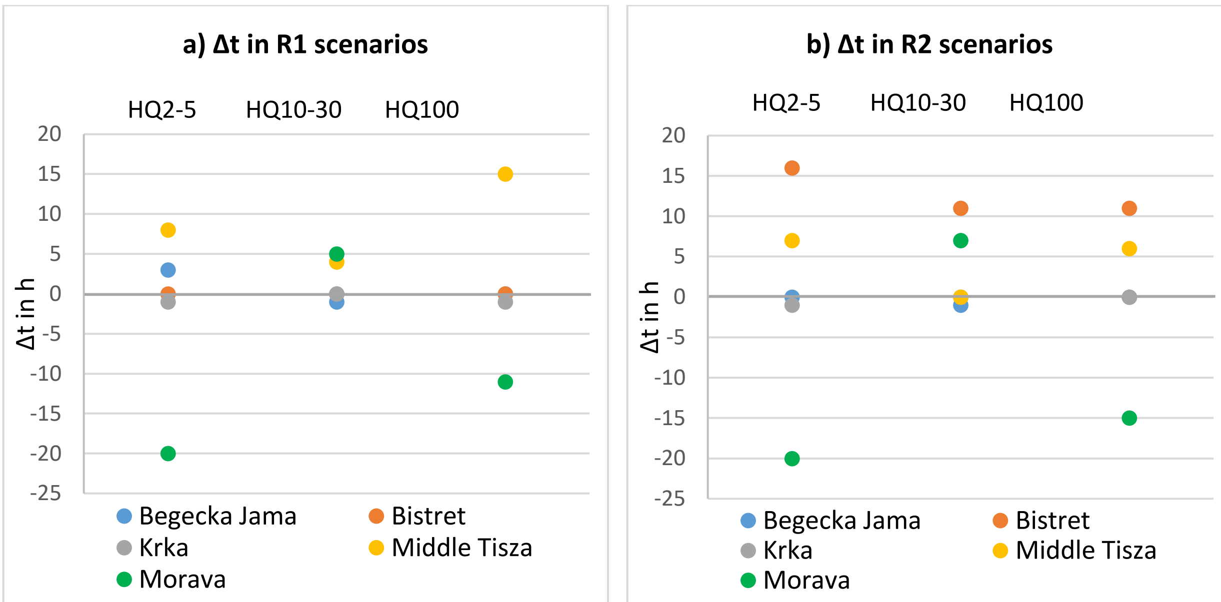


Figure 56: Flood wave translation (Δt) in hours compared to the CS in all pilot areas in a) the R1 and b) the R2 scenario

Besides the comparison of the hydrographs at the downstream model border, the spatial results give detailed information e.g. about the water depth and velocity in each raster cell. Concerning the water depth it is crucial to remember that a deepening of the river channel as restoration measure, can lead to the impression of an increased flooding, why it is important to also consider the water level. However, the effectiveness of the measure is confirmed, as the river channel is than able to transport a larger volume (i.e. larger water depth if width is staying the same), still leading to a later overtopping of the riverbank and thus a later flooding. The spatial results allow to draw conclusions about the habitat suitability, the potential improvements for ecosystem services, and the flood risk in the restoration scenarios. With the calculation of differences to the CS, a change map with very high resolution can be created. This change is visible for all scenarios in the pilot areas and also local effects through the creation of corridors or deepening of old oxbows can be seen.

Due to his ability to create detailed spatial information of restoration effects on the whole floodplain area, 2D hydrodynamic models can be seen as a recommended tool for restoration planning in floodplain management. With these models, it is possible to compare different options in the planning process of potential measures to choose the most effective or most appropriate one, depending on the local restoration purpose.

Within the Danube Floodplain project the 2D modelling results are further processed for the ecosystem service and habitat assessments (D 4.2.2, D 4.2.3) as well as the extended cost benefit analyses in the pilot areas (D 4.3.1, D 4.3.2, D 4.3.4). Further on, they deliver the base for the (pre)feasibility studies presented in D 4.4.2.

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