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Title: Modelling of extreme hydrological events on a Tisza River Basin pilot area – final study
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1. Introduction

The pilot actions of the project within WP6 Activity 6.4 focuses on climate change induced drought and flood related issues. The main goal of this pilot activity is to investigate the impacts of climate change induced drought and flood on a smaller region within TRB. The task is to test the concept of Shared Vision Planning (SVP) in a smaller region of the basin focusing on the Middle part of the TRB and to investigate the drought periods how to optimize the available water resources according to the ecological and irrigation water demands. The overall process is tested via SVP methodology and as a tool via the part of the TIKEVIR System, which was built-up and operated by Hungary.
The Tisza River Basin (TRB) can be considered unique in several aspects among the river basins of Europe. In certain hydrometeorological situations, the chance of extraordinary floods is high. This is especially true at the beginning of the 2000s, when the flood waves set new record high water levels along the Hungarian section of the Tisza River. Over the last decades, drought has also taken more and more challenges to the experts of the local Water Directorates. The occasional extreme low water flow of the river is a problem especially in the flat areas of the Tisza River Basin. The climate change plays a major role in the emergence of these hydrometeorological situations (*Lehner et al 2006*). In the JOINTISZA project a pilot area was selected in the Middle Tisza which is endangered by both extreme situations, such as floods and droughts.
Regarding spatial and temporal distribution of drought in Europe, the major European droughts also impacted Hungary. Hungary has a high risk of developing a drought period, especially typical in the Great Hungarian Plain region (*Tamás 2016*). The drought phenomenon can significantly increase because of the man activity and ineffective water management. It is expected that the extremely long, dry weather conditions will occur more regularly for years in Hungary (*Szalai 2009*). The prevalence of the droughts has increased over the past decades, and especially the rolling drought phenomena have become critical when consecutive years of drought multiply the adverse effects of previous years (*Pálfai 1992*). Regarding to the final report of the Danube River Basin Climate Adaptation Study from *Mauser et al*, the possibility of more intense and more harmful droughts are expected in the Middle Tisza region.
The water demand is also expected to increase in the Great Hungarian Plain which causes new challenges in water management (*Somlyódy 2011*). The local Water Directorate is responsible to provide adequate amount of water (*GDWM 2018*) to satisfy the water needs. This requires river basin planning, and proper water management.
We used the forecasts of climate models produced by the Joint Research Centre. The data sets they generated – according to the predicted hydrological, meteorological, economic, and social conditions – were used in modelling as a boundary condition (*Bisselink et al. 2018*). With the help of these time-series, we aimed to explore possible medium and long-term conflict situations in water resources and to make recommendations for possible measures, thereby helping the water management planning of river basins with similar problems.
The detailed description of the SVP application is described in the background document of the Deliverable 6.4.2, whose title is *SVP Application – Experiences from Pilot Actions*. The background document presents the results of the pilot action, such as the detailed characteristics of the pilot area, the relevant pressures, the application of the SVP method, and the results of the hydrodynamic modelling.

1.1 Pilot area

The selected pilot area is located in the flat region of the TRB in the middle of the Hungarian Great Plain (Figure *1*). The pilot area gets water from the Lake Tisza, which water intake is controlled by the local Water Directorate. This pilot area is selected because only a proper water management work could satisfy the water demands.

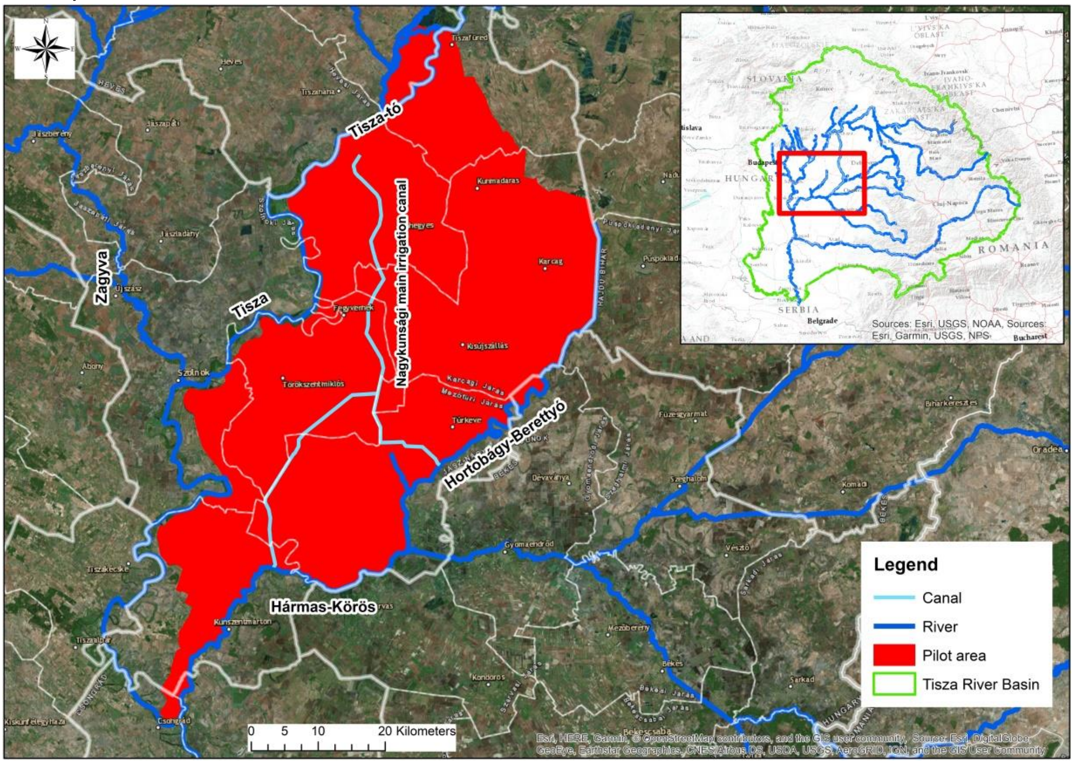


Figure 1. Location of the selected pilot area

The size of pilot area is 2 950.9 km^2. It is bordered by the Tisza River from the west, and by the Lake Tisza from the north. The eastern border is the Hortobágy-Berettyó River and the Tiszafüred main irrigation canal, and the southern border of the area is the Hármas-Körös River. The area is characterized by a very low elevation (79-100 mBf).

Hungary's water network is basically determined by the fact that the country is located in the middle of the Carpathian Basin. In the country, about three-quarter of the water resources is transported by the Danube and the Drava Rivers, while almost only a quarter of the available water resources is transported by the Tisza River.

The Tisza is the second most significant river in Hungary. The Tisza's full gradient is 30 m (5 cm/km) in Hungary. The minimum measured water flow was 56 m^3/s, and the maximum measured value was 2 950 m^3/s at Kisköre. The average discharge value is 507 m^3/s at this Tisza River section.

Table 1 shows the high discharge (HQ) values with different probabilities at the river section near Kisköre:

Table 1. HQ values of the Tisza river at Kisköre

HQ (p=0.001) [m^3/s]	HQ (p=0. 01) [m^3/s]	HQ (p=0. 03) [m^3/s]	HQ (p=0. 1) [m^3/s]
3570	3012	2721	2363

The pilot area gets water from the Tisza Lake, which is the largest artificial surface water in Hungary. The lake was artificially created when the Kisköre Barrage was constructed. The lake is operated as a reservoir, so it has two different operating water levels for summer and winter seasons. The summer water level usually lasts from the middle of March to the end of October, and it is 88.57±0.05 m. The winter water level is 87.47±0.05 m. The surface of the Lake Tisza is 127 km^2, with a volume of 253 million cubic meters; more than 130 million m^3 can be utilized. Lake Tisza can be considered as a multi-purpose water management facility. The main utilizations are: water supply, hydropower (at the Kisköre Barrage), fishing, nature.

In the Middle Tisza region, it is considered to be a water scarcity period if the Tisza's discharge does not reach the 105 m^3/s value above the Tisza Lake. In this case a minimum discharge of 60 m^3/s should be maintained at the river section below the Kisköre Barrage. This flow rate is important to satisfy the water supply needs of Szolnok. The drinking water of the town is provided from the Tisza River. There are three stages of water restriction to limit the water supply of the Körös River through the Nagykunság main irrigation canal. If the water scarcity gets worse, users should be restricted according to the *Hungarian Water Management Act*. First, the non-economic water demands are limited. Due to the further deterioration of the defined criteria and the current hydrometeorological forecasts, following water restrictions are taken into effect.

The main irrigation canal in the pilot area is the Nagykunság main canal. This canal gets water from the Lake Tisza through a water intake structure controlled by the local Water Directorate, and passes the water to the Hármas-Körös and the Hortobágy-Berettyó Rivers. The water inflow is around 20-35 m^3/s in irrigation season (from April to September). The canal is split into two branches near Örményes. The overall length of the main canal is 74.5 km (including the western branch). The eastern branch of the canal is 18.07 km long. The Nagykunság main canal flows out at the 144 + 642 km section of the left bank levee of the Tisza and reaches the Hármas-Körös River at the right 33 + 752 km levee section. The Eastern branch of the Nagykunság main irrigation canal flows out from the Nagykunság main canal, reaches the Hortobágy-Berettyó River at the right 16 + 200 km levee section.

The area has a dry continental climate, and it has the driest climate in Hungary. The annual average temperature is between 10-11°C, and the monthly average temperature in July is around 21°C. The mean annual temperature fluctuation is 23.0-24.5°C. The annual amount of sunshine hours in the Hungarian Great Plain is over 2000 hours.

Based on the measured data of the *Middle Tisza District Water Directorate*, the annual precipitation is about 520 mm in this area, which is the lowest annual average precipitation in the country. The territorial and temporal distribution of the precipitation is also extreme. The annual rainfall also varies within wide limits. Some years (e.g. the year of 2010 when the annual precipitation was 820 mm) had a lot of precipitation and it caused floods and inland excess waters. In the last some decades that even in the same year after a wet period a dry and warm period occurred with heavy drought.

The two most serious drought years of the last decades were the years of 2003 and 2012. In 2003, the annual average precipitation was 20 % below the long-term annual average over the Middle Tisza. The whole year was characterized by dry weather conditions. In the summer months, the spatial and temporal distribution of precipitation were imbalanced. In addition to the low amount of precipitation, the severity of the drought was further increased by the fact that this summer was one of the warmest of all time, which also contributed to high evaporation. The average monthly temperature was above 23 °C in all three summer months. In hydrometeorological point of view, the year 2012 was very similar to 2003.

In these years, the dry, warm weather caused hydrological and agricultural drought over time. The flows of natural watercourses have been reduced. It was very important to store sufficient water in the Lake Tisza and in the irrigation systems of the area and to distribute it as efficiently as possible. The levels of groundwater were also very low in these times.

Climate change can play a major role in the emergence of extreme conditions. Future predictions suggest that even more extreme drought periods may also occur more and more often (*Mauser et al. 2018*). Because of these extreme situations a well performed and appropriate water resource management planning and regulations are important. The pilot study intended to contribute to a better planning process that takes into account the climate change induced impacts on surface water quantity.

The pilot area has some particular characters that were taken into account when it was selected. The required amount of water by the stakeholders in the pilot area can be ensured only by the proper water management of the District Water Directorate (*GDWM 2018*). The water demand is satisfied by a dense canal network of the area from the Tisza River. In a dry period, the Lake Tisza can provide sufficient water for the region, but the water flow is exclusively managed by District Water Directorate into the pilot area.
The special features described above have determined which model type could fit most to assist the water quantity management.

2. Application of the Shared Vision Planning methodology

The Shared Vision Planning methodology has been used in the pilot action. SVP is a collaborative approach to formulating water management solutions that combines three disparate practices: traditional water resources planning, structured public participation and collaborative computer modelling (*Cardwell et al. 2008*). The method is presented in Chapter 2.6. Three Shared Vision Planning events were organized during the project to involve stakeholders in the planning and modelling process. The dates of the workshops were: 26-27 October 2017, 24 May 2018, 28-29 November 2018. The method and the pilot action were presented during the first workshop. Stakeholders also had the opportunity to comment and make suggestions according to the pilot action modelling. At a later stage of the event, the participants were divided into three groups with different topics: water supply, irrigation, flood risk management. The group participants identified the problems, opportunities, aims, and possible performance indicators related to their topics on the pilot area (*Table 2*).

Table 2. Identified problems, conflicts, possibilities, aims, indicators in the topics

	Water supply	Irrigation	Flood risk management
Problems, conflicts	• Subsurface water close to the surface is vulnerable • Wastewaters from settlement less than 2000 PE pollute the soil and subsurface waters • Overuse of subsurface waters • Drinking water used for irrigation • Thermal water overuse • Water effluents without treatment • No proper, or missing water meters • Illegal wells • Water supply systems are out of date • Rainwater harvesting is not solved • Reuse of waters for cleaning the filters is not solved	• Uncertainty of the impacts of climate change on water resources • Spatial and temporal heterogeneity of the amount of available irrigation water • Hard to determine the irrigation demand • High salinity of purified sewage and used thermal water • Limited utilization of alternative water resources • Salt content increase in surface waters • Uninsulated channels • Drinking water for irrigation purposes in the case of gardens • Underground water resources can be used for irrigation • Inappropriate land use	• Significant floods in the past years • Cross-border watersheds • Downstream countries are vulnerable • Flood Protection System's technical conditions • Optimal form of the protection • Rivers change in hydrological aspect • Hydromorphological issues, sedimentation • Uncertainty of the impacts of climate change on flood events • Capacities of the reservoirs • Dense vegetation on the floodplain area • Social conflicts in relations to the flood protection interventions • Economic interests in relations to the flood protection interventions
Possibilities, aims	• Well "Amnesty" till 2019	• Optimization of water supply	• Flood Risk Management planning

	• Measure the quantity for proper water balance calculation • Stop illegal water intakes • Policies/law	• Optimization of drainage rate • Cultivation of native varieties • Water restriction measures • Increasing water retention (in channels, in soil) • Multipurpose use of water and land • Define available water resources and to adapt land use	• Harmonization FRMP in national and basin wide level • Increasing conveyance capacity of the riverbed/floodplain • Increasing capacity of the reservoirs • Harmonization of the flood protection conservation reservoirs' operation system • To inform the downstream countries about the operation of the reservoirs • Improving the data communication between the concerned countries • Joint management of the cross-border areas • Find win-win solutions between the countries
Performance indicators	-	• Irrigation water needs for the catchment • Surface water resources for irrigation • Groundwater resources extracted for irrigation • Amount of the stored water • Increasing water retention • Quality of the irrigation water • Applying of a greening program • Cultivating local, drought-tolerant varieties • Local multipurpose water and land use	• HQ_{100} • Designed Flood Level • Conveyance capacity of the riverbed/floodplain • Storage capacity of the reservoirs

The relevant factors were selected which can be studied with a one-dimensional model (*Table 3*). The prioritization of the relevant problems, opportunities, and goals provided the basis for defining modelling scenarios.

Table 3. The selected relevant issues for the modelling scenarios

	Low-water scenarios (Scenario 1-6)	**Flood scenarios (Scenario 7-10)**
Relevant problems	• Uncertainty of the impacts of climate change on water resources • Spatial and temporal heterogeneity of the	• Significant floods in the past years • Rivers change in hydrological aspect

	amount of available irrigation water • Hard to determine the irrigation water demand	• Hydromorphological issues, sedimentation • Uncertainty of the impacts of climate change on flood events • Capacities of the reservoirs • Dense vegetation on the floodplain area
Relevant aims	• Optimization of water supply • Water supply from reservoir • Water restriction measures • Increasing water retention (in channels)	• Increasing conveyance capacity of the riverbed/floodplain • Increasing capacity of the reservoirs

The study of the Joint Research Centre has been used to take into account the impacts of climate change on water resources and flood events (*Bisselink et al. 2018*). The Scenario 1-6 are studying the optimization of water supply, water supply from the Nagykunság reservoir, water retention and the using of water restriction measures. The Scenario 7-10 are analyse the flood related problems: changes in hydrological trends, sedimentation, capacities of the reservoirs, dense vegetation on the floodplain area. These scenarios are also including the possibilities of increasing the conveyance capacity and the capacity of the reservoirs. The defined scenarios were presented at the second stakeholder event with the first set of results. Stakeholders had the opportunity to comment and make suggestions according to the modelling scenarios. The final results of the pilot action were presented on the third SVP workshop.

3. Possible climate change impacts in the future

The Joint Research Centre (JRC) studied the effects of changing climate, land use, and water demand on water resources in the Danube River Basin using climate induced runoff modelling technique (*Bisselink et al. 2018*). The water resources calculations were done with the LISFLOOD 2.0 model which is a GIS-based spatially-distributed hydrological rainfall-runoff-routing model (*De Roo et al. 2000, Van der Knijff et al. 2010, Burek et al. 2013*). As a result of the runoff modelling, water flow data were made available for our work for the rivers of the Tisza River Basin.

In the JRC analysis, 11 different European EURO-CORDEX climate scenarios have been used (*Table 4*). The Coordinated Downscaling Experiment over Europe (*EURO-CORDEX, Jacob et al. 2014*) is an international climate downscaling initiative that aims to provide high-resolution climate projections up to 2100 (*Bisselink et al. 2018*).

Table 4. EURO-CORDEX climate projections and the corresponding year of exceeding 2°C warming (Bisselink et al, 2018)

Nr.	Climate scenario	Institute	GCM	RCM	Exceeding 2°C Warming
1	CLMcom-CCLM4-8-17_BC_CNRM-CERFACS-CNRM-CM5_rcp85	CLMcom	CNRM-CM5	CCLM4-8-17	2044
2	CLMcom-CCLM4-8-17_BC_ICHEC-EC-EARTH_rcp85	CLMcom	EC-EARTH	CCLM4-8-17	2041
3	CLMcom-CCLM4-8-17_BC_MPI-M-MPI-ESM-LR_rcp85	CLMcom	MPI-ESM-LR	CCLM4-8-17	2044
4	DMI-HIRHAM5-ICHEC-EC-EARTH_BC_rcp85	DMI	EC-EARTH	HIRHAM5	2043

5	IPSL-INERIS-WRF331F_BC_rcp85	IPSL	IPSL-CM5A-MR	INERIS-WRF331F	2035
6	KNMI-RACMO22E-ICHEC-EC-EARTH_BC_rcp85	KNMI	EC-EARTH	RACMO22E	2042
7	SMHI-RCA4_BC_CNRM-CERFACS-CNRM-CM5_rcp85	SMHI	CNRM-CM5	RCA4	2035
8	SMHI-RCA4_BC_ICHEC-EC-EARTH_rcp85	SMHI	EC-EARTH	RCA4	2041
9	SMHI-RCA4_BC_IPSL-IPSL-CM5A-MR_rcp85	SMHI	IPSL-CM5A-MR	RCA4	2044
10	SMHI-RCA4_BC_MOHC-HadGEM2-ES_rcp85	SMHI	HadGEM2-ES	RCA4	2030
11	SMHI-RCA4_BC_MPI-M-MPI-ESM-LR_rcp85	SMHI	MPI-ESM-LR	RCA4	2044

Discharge time-series were made available for our work for every boundary condition calculated from the JRC runoff model. Time-series were from 2011 to 2099 for each 11 climate projections. In addition to the boundary conditions, discharge data were also available for an internal river section of the Tisza, which was the inflow section of the river into Lake Tisza. This point was an important control point in the Middle Tisza from water management point of view. Using the data of this control section it was possible to examine how much water flows into the area from the Tisza River. If the discharge of this river section decreases below 105 m^3/s water shortage can be considered, and when discharge falls below 60 m^3/s, water restrictions may be needed. Statistical analysis has been made for the 11 discharge time-series of this river section, which can be used to quantify future trends.

Based on the results of the statistical analysis, the months of September and October will have the highest probability of decreasing the discharge below 60 m^3/s at the river section near Tiszafüred. The return time for extreme low-water periods is 3-4 years in all 11 climate projections. Based on the data released by the JRC, the occurrence of more and more long-lasting low-water periods are also predicted for the second half of the century. For example, the data, which is based on the "SMHI-RCA4_BC_ICHEC-EC-EARTH_rcp85" climate projection, has a 128-day period below 60 m^3/s.

In addition to the extreme low-water conditions, some climate scenarios have also generated extraordinary flood waves. In the case of two projections (CLMcom-CCLM4-8-17_BC_CNRM-CERFACS-CNRM-CM5_rcp85, IPSL-INERIS-WRF331F_BC_rcp85), the maximum discharge is above 4 000 m^3/s, which would pose a serious flood risk to the Middle Tisza in the future, with special regard to the Kisköre Barrage. This flowrate is also higher than the HQ value with 1000-year return period.

It is based on the statistical analysis to define which climate scenario should be used as the boundary condition of the hydrodynamic model. According to the analysis, the “SMHI-RCA4_BC_ICHEC-EC-EARTH_rcp85” is selected to study low-water periods, and the "IPSL-INERIS-WRF331F_BC_rcp85" climate projection to study major flood events.

The detailed description of the statistical processing can be found in the background document of Deliverable 6.4.2.

4. 1D hydraulic modelling of the water system of the pilot area

In its current structure, the database of the model includes the 600 km long river section between Tiszabecs and Szeged from the Tisza. The model also includes the channels of the pilot area. The total length of streams involved into calculations exceeds 2 000 km. We installed 102 bridges and 19 inline structures into the model (*Vizi et al. 2018*). The model contains the Nagykunság irrigation canal, which is the most important irrigation channel of the pilot area.

Figure 2 shows the complete hydrodynamic model:

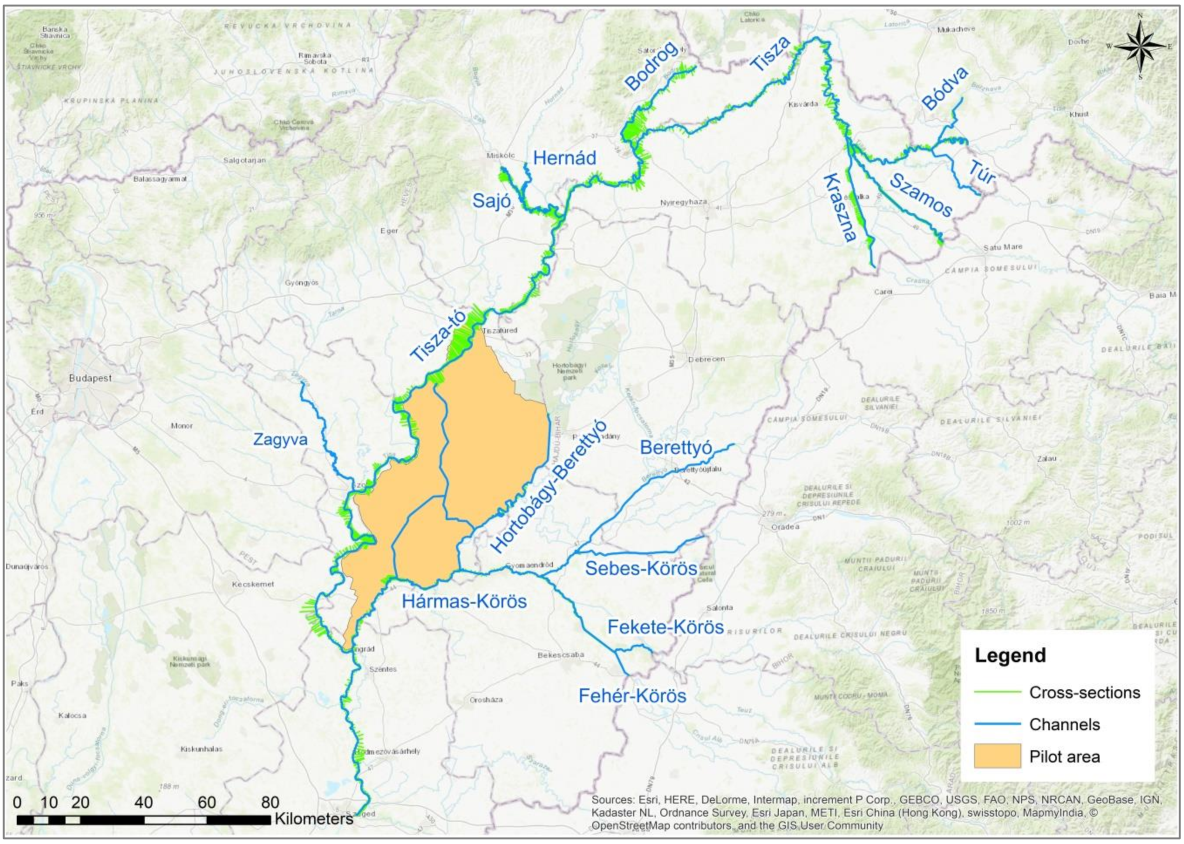


Figure 2. The layout and the boundary conditions of the model

We have advanced the stream system of the model by more than 2 000 cross sections. The cross sections are the basis of the one-dimensional models. The calibration and the roughness coefficient are only party compensate the possible inaccuracies of the cross-sections. The model stability is greatly improving if the cross sections are as dense as possible. Based on previous modelling experiences, the optimal distance between cross sections - from model point of view - is 400 - 800 m for the Tisza, and 200 - 400 m for the tributaries of the Tisza. For the irrigation canals, the optimal distance is 200 - 400 m.

The hydrodynamic model has 14 upstream, and 1 downstream boundary condition. The boundary conditions of the rivers are located on the Hungarian border sections. We have chosen these points to minimize the impact of the boundary conditions on modelling results in the pilot area. At each point there are discharge data available for input data.

The water usage has been quantified in the model based on the water needs shown in *Figure 3*. These values based on the nationwide survey of the Hungarian Chamber of Agriculture (HCA). The model includes the total 44 million m^3 annual water demand of the Nagykunság irrigation system (*HCA 2018*). Water consumptions of the irrigation sections in the Nagykunság irrigation system appears as point-like extractions in the model.

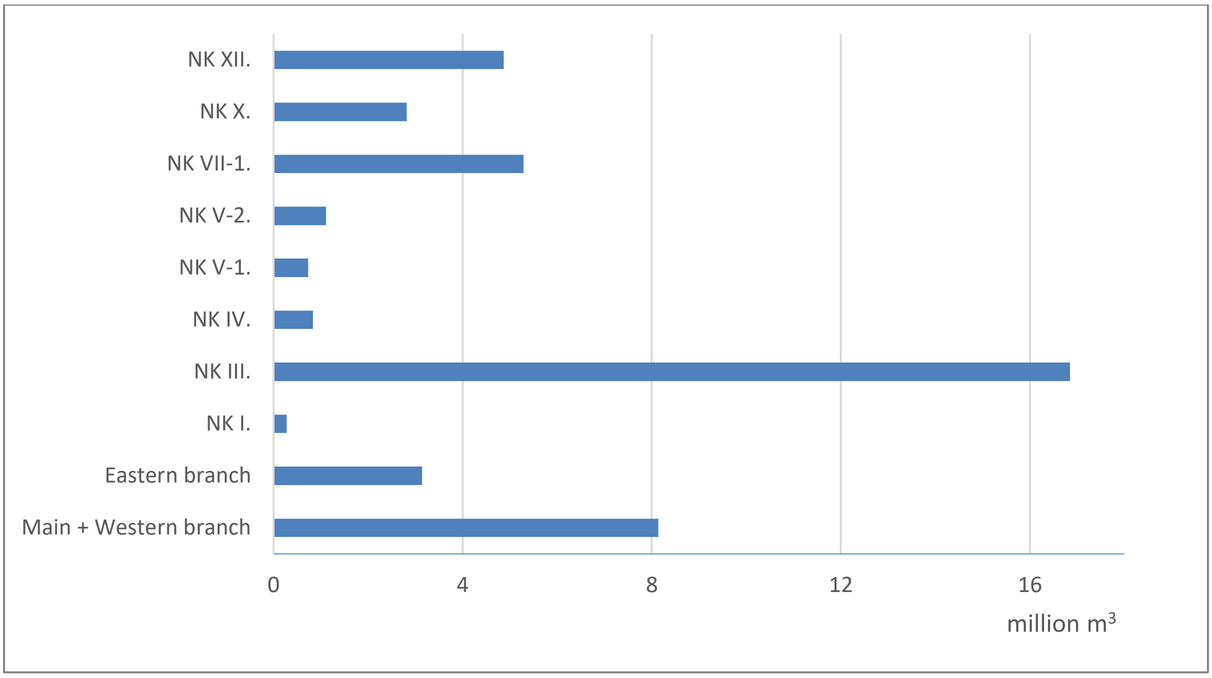


Figure 3. Water demand in the Nagykunság main irrigation system

It was also necessary to determine how water consumption is distributed during an irrigation period. It is highly depends on the hydrometeorological characteristics of a year. In order to determine the distribution between the months, we used the water consumption experiences of the past twenty years. We have assumed that more water supplies are needed in July and August. 65% of the annual water demand is consumpted during these two months. These values are also input data for the hydrodynamic model, when no water restriction measures are needed. The water restrictions take into effect according to the *Hungarian Water Management Act*. The ratio of the restriction has to be determined. The distribution of the cultivation branches is known in the area, so the restricted water supply can be defined from 1 August to 30 September.

The applied HEC-RAS model gives detailed description of the entire river system and provides an opportunity for taking into consideration the hydraulic engineering structures, as well as bridges, barrages, culverts, overflow weirs, floodgates, bottom stages, bottom sills, side overflows and gates, static reservoirs, pump head stations and water intakes (*US Army Corps of Engineers 2016*). The model includes 102 bridges, and 16 inland structures, and it also contains water intakes. We took into the model every irrigation section of the Nagykunság irrigation system as a point like water intakes. The model also contains every directly water use along the Nagykunság main irrigation canal, so water consumption can be tested as a simple drainage. We used the possible water demand values for input data which are based on the survey of the Hungarian Chamber of Agriculture (*HCA 2018*).

For calculation of the water discharge capacity of the main river bed of Tisza as well as for taking the flood plain vegetations into consideration we used the roughness (smoothness) factors given in the Table 1 in the course of calibration of the model. We determined the vegetation on the flood plain by aerial photographs, i.e. by ortho-photographs, as well as by the results of on-site inspections. The roughness factor was changed crosswise according to flood plain vegetation. The roughness (smoothness) factor assigned to these was determined on the base of the prescriptions of the Hungarian standard, as well as on the base of values applied also by HEC-RAS and proposed by *Chow (1959)*.

The calibration of the model was accomplished gradually, starting with the shorter sections. We assembled together the individual section and then performed the river sections.

The calibration of Tisza and its tributaries was made for the low-water period of the year 2012. On the river section between Tiszabecs and Szeged, the difference between the calculated water level and the observed was between 0 and 10 cm in absolute values, which can be considered as a very good result. The pilot area's canal network calibrated separately. We used data from the year of 2013 to calibrate the irrigation canals. The difference between the calculated water level, and that of observed was between 0 and 10 cm, like the river network. After the calibration was made, the separate water streams were connected.

5 Results of hydraulic modelling

5.1 Low-water scenarios (Scenario 1-6)

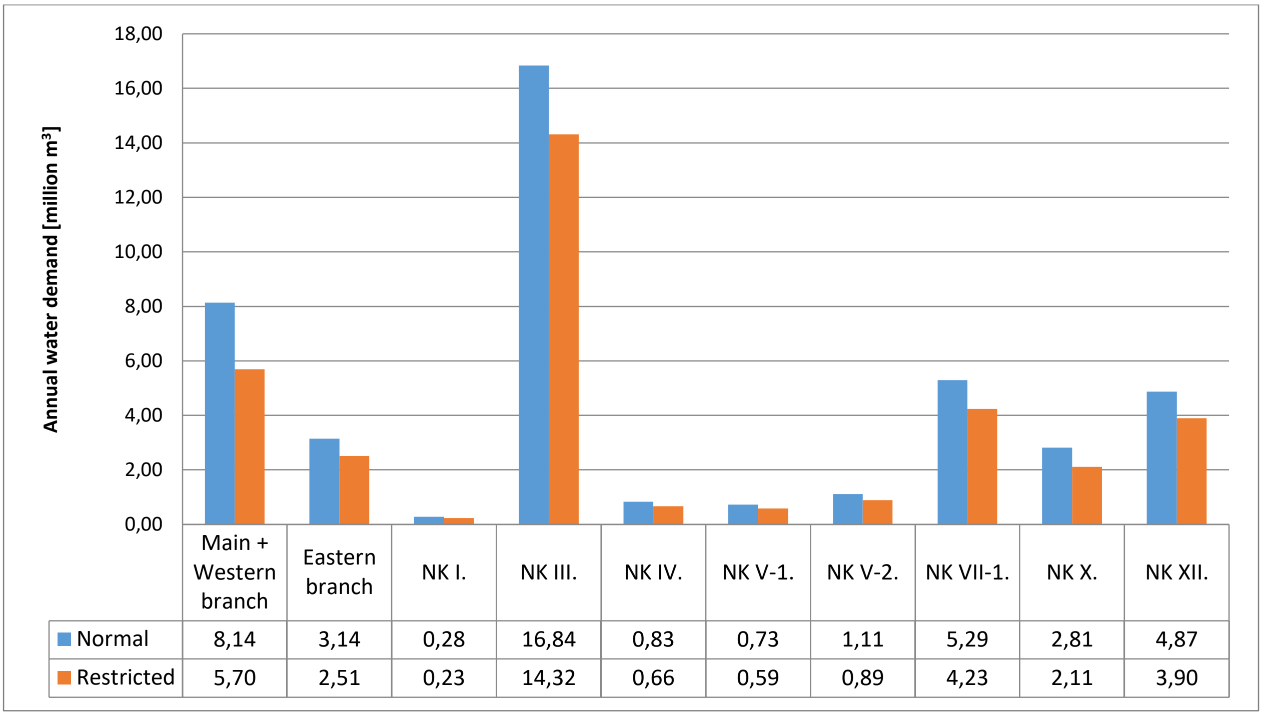
The Scenarios 1 - 6 (see *Table 3*) are long-lasting low-water periods, whereby the water flow to the area is lower than the sum of water flowing to the tail-water at Kisköre Barrage and of into the irrigation canals from the Lake Tisza.

The boundary conditions are selected based on the statistical analysis of the water discharge datasets produced by the JRC. As described in Chapter 6.3, the "SMHI-RCA4_BC_ICHEC-EC-EARTH_rcp85" climate scenario is selected to study low-water periods. In this climate scenario, there are several periods with water scarcity. The timeseries of the year of 2085 includes an extreme low-water period, which data sets of the year have been used as the boundary conditions of the model. At the river section of the Tisza near Tiszafüred, for more than 3 months, the discharge of the river is below 105 m^3/s, which is a period with water scarcity.

In the Scenario 1 - when the river's discharge falls below 100 m^3/s - the water level of the Lake Tisza gradually began to decrease. The trend continues for two months when the discharge at the upper section of the river increase above 100 m^3/s. During the critical period, the amount of water which is drained from the Lake Tisza to the Nagykunság main irrigation canal is continuously ensured and corresponding to the water demands. We studied how quickly the stored water of Lake Tisza would be consumed.

During the critical period, the amount of water which is drained from the Lake Tisza to the Nagykunság main irrigation canal is limited corresponding to the water restraint plan (*MTDWD, 2018*). The amount of water, which is flow in to and out from the Nagykunság main irrigation canal are controlled. Water demands are still satisfied in the Scenario 2 and 3. We studied the impact of the I. and II. level water restraint in Scenario 2 and 3. The III. level of water restraint is taken into effect in Scenario 4, when the transferred amount of water from Lake Tisza to the Nagykunság main irrigation canal is reduced to 0 m^3/s. In this case, we deviated from the rules, and we completely abandoned the use of water along the canal.

In Scenario 5, the III. level of water restraint is also taken into effect, but the transferred water to the Nagykunság main irrigation canal is not 0 m^3/s. The water supply is only enough for the minimum allowed water consumption in August and September, which is allowed in the *Hungarian Water Management Act*. *Figure 4* shows the difference between the normal and limited amount of used water in the area. The water restriction lasts from 1 August from 30 September.



	Main + Western branch	Eastern branch	NK I.	NK III.	NK IV.	NK V-1.	NK V-2.	NK VII-1.	NK X.	NK XII.
Normal	8,14	3,14	0,28	16,84	0,83	0,73	1,11	5,29	2,81	4,87
Restricted	5,70	2,51	0,23	14,32	0,66	0,59	0,89	4,23	2,11	3,90

Figure 4. Difference between the normal and the restricted water supply

In Scenario 6, the minimum allowed water uses are satisfied in an alternate way. The water is not transferred to the Nagykunság main irrigation canal from the Lake Tisza during the critical period, but the minimum water supply is ensured. The water resource of the Nagykunság reservoir is used for this purpose. It is possible way to retain water in the reservoir to ensure that minimum amount of water which is allowed during this time, but the main aim of the reservoir is to reduce flood level, not the water supply. We used the supposition that the reservoir was loaded during an earlier period, so maximum 99 million m^3 water could be available for water supply.

Figure 5 shows the discharge time series at the influence section of the Nagykunság main irrigation canal. Water discharge values show how the transferred amount of water is limited during the critical period.

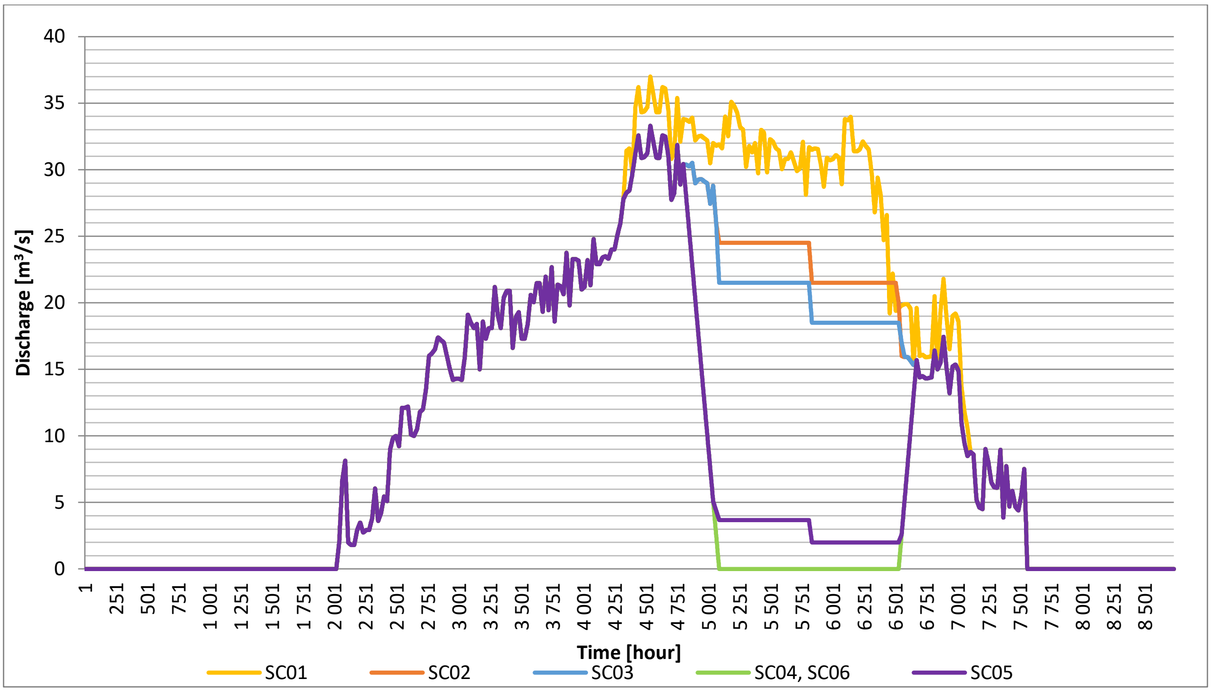


Figure 5. Discharge at the inlet point of the Nagykunság main irrigation canal

Figure 6 shows the development of water level at Kisköre Barrage in the modelled year. In the first half of the year there is enough water flow in the river to maintain the operating water level (88.67 ± 0.05 m) of the reservoir. Then in the summer months, the river discharge gradually decreases until it reaches the critical 60 m^3/s value at the river section near Tiszafüred. Water supply of the Körös River is limited during this time in Scenario 2, 3, 4, 5 and 6, and the water restriction measures take into effect on the water uses in Scenario 4, 5 and 6. The low water condition lasts for two and a half months. Once the river's discharge increases above 60 m^3/s again at the inflow section of the Lake Tisza, the water restrictions are ended. The results of the different scenarios show the difference between the alternate ways of water limitation and water supply, and how these measures affect the Lake Tisza. The minimum water levels at Lake Tisza are the following in the different scenarios:

- Scenario 1: 85.76 m,
- Scenario 2: 87.15 m,
- Scenario 3: 87.40 m,
- Scenario 4: 88.29 m,
- Scenario 5: 88.21 m,
- Scenario 6: 88.29 m.

The results clearly show the positive effect of the water restriction measures on the water resources of Lake Tisza. The highest water level was achieved when the water was not transferred to the Nagykunság main irrigation canal.

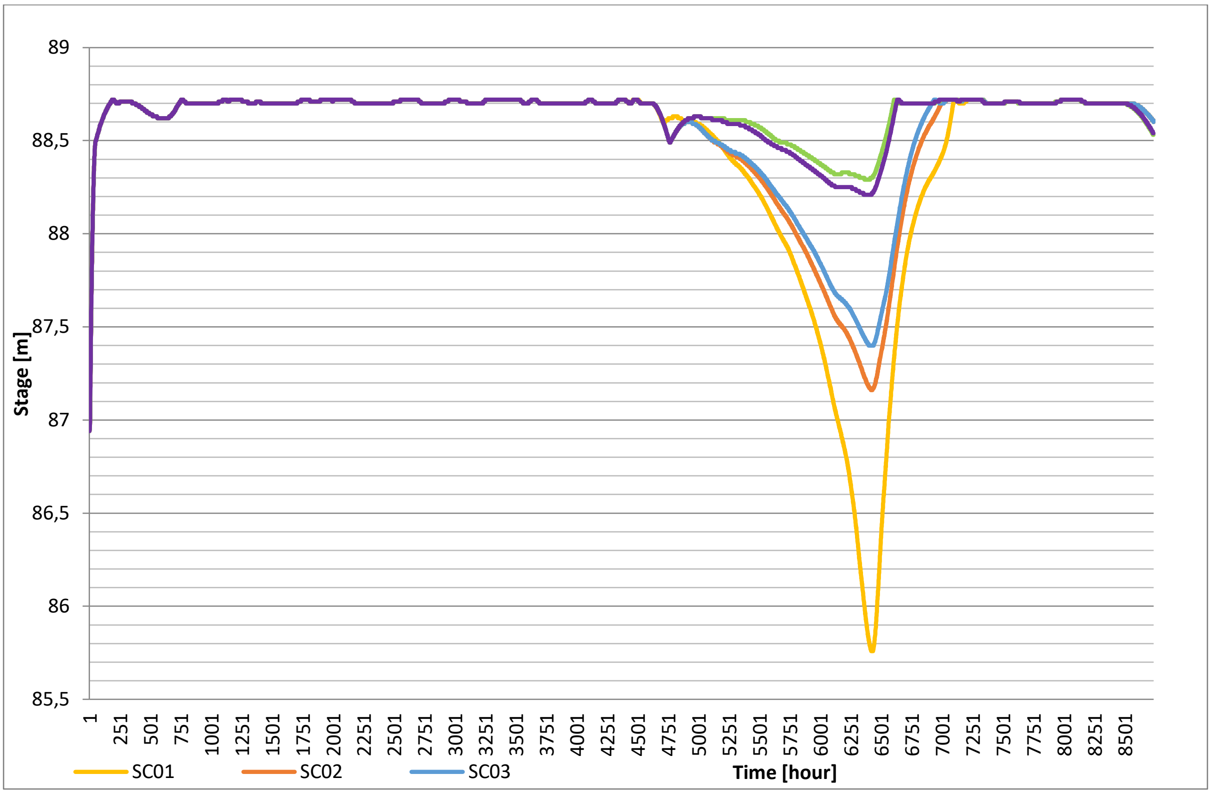


Figure 6. Water level at headwater of Kisköre Barrage

According to the regulations a specific flowrate must be secured from the eastern branch of Nagykunság main irrigation canal to the Hortobágy-Berettyó, as well as from the western branch of Nagykunság main irrigation channel to the Hármas-Körös (*MTDWD 2018*) in each scenario. In the model scenarios the minimum flowrate were guaranteed at the outflow sections of the Nagykunság main irrigation canal.

Figure 7 and 8 shows the development of water flow at outflow section of the Western and Eastern branches of the Nagykunság main irrigation canal in the modelled year. The time series shows that the water discharge is corresponding to the water restraint measures.

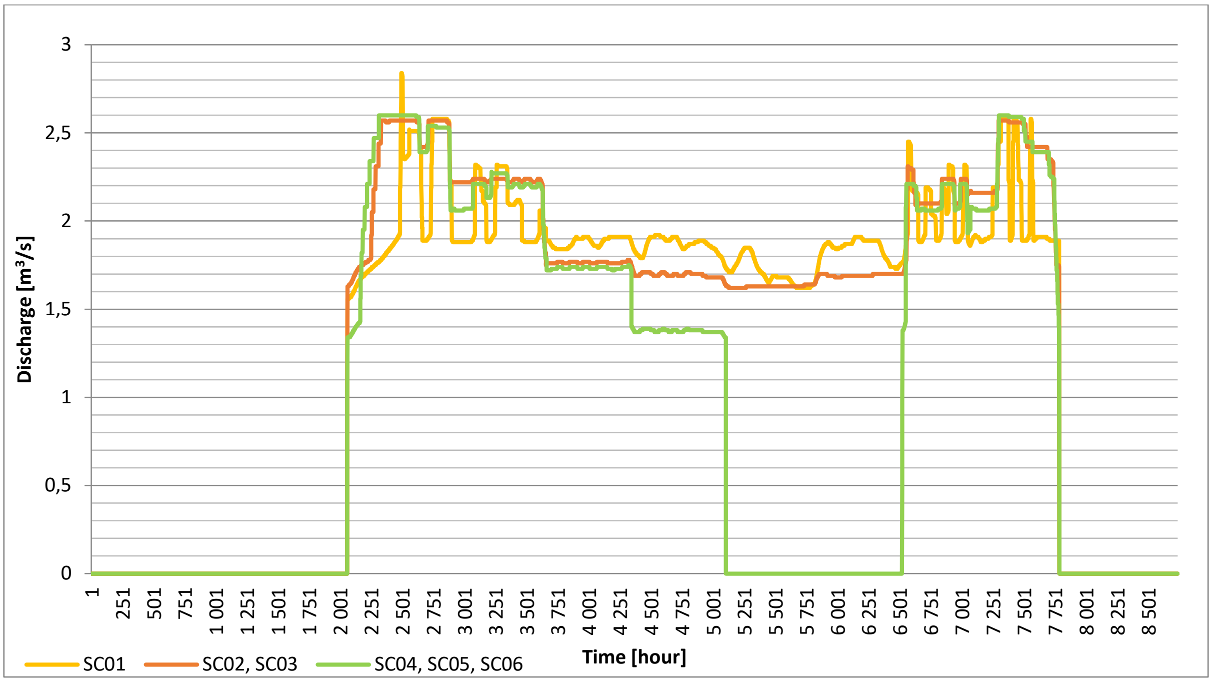


Figure 7. Discharge at the outflow section of the Western branch of the Nagykunság main irrigation canal

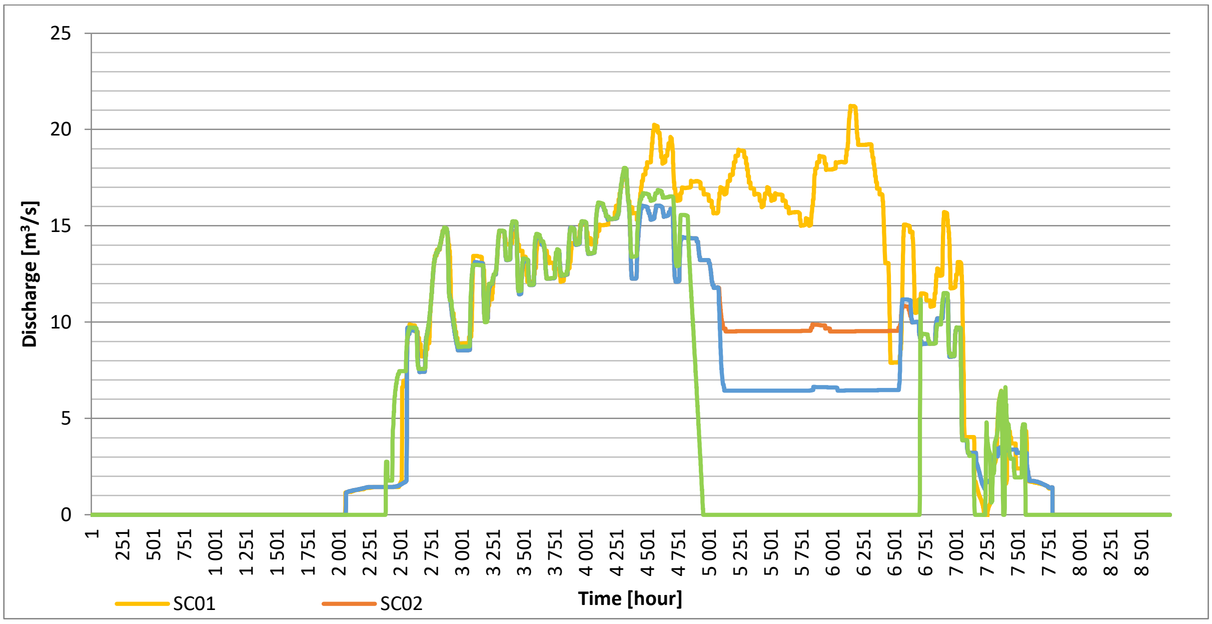


Figure 8. Discharge at the outflow section of the Eastern branch of the Nagykunság main irrigation canal

Figure 9 shows the importance of the drained water from the Nagykunság main irrigation canal to the Hármas-Körös in the different modelling scenarios. In the summer season, only 5.9 m^3/s water comes from the upper section of the river. Due to water restraints, from the Hortobágy-Berettyó 19.9 m^3/s water is transferred to Körös at Mezőtúr in Scenario 1, 14.6 m^3/s in Scenario 2, 11.6 m^3/s in Scenario 3, and 0.4 m^3/s in Scenario 4. 5 and 6. Large part of this amount of water comes indirectly from the Eastern branch of the Nagykunság main irrigation canal. The next point of influence is located at Öcsöd, where 1.62 m^3/s water is transferred from the Western branch of the Nagykunság main irrigation canal in Scenario 1, 2 and 3, and 0 m^3/s in Scenario 4, 5 and 6. This longitudinal profile shows the conditions of August 11, 2085.

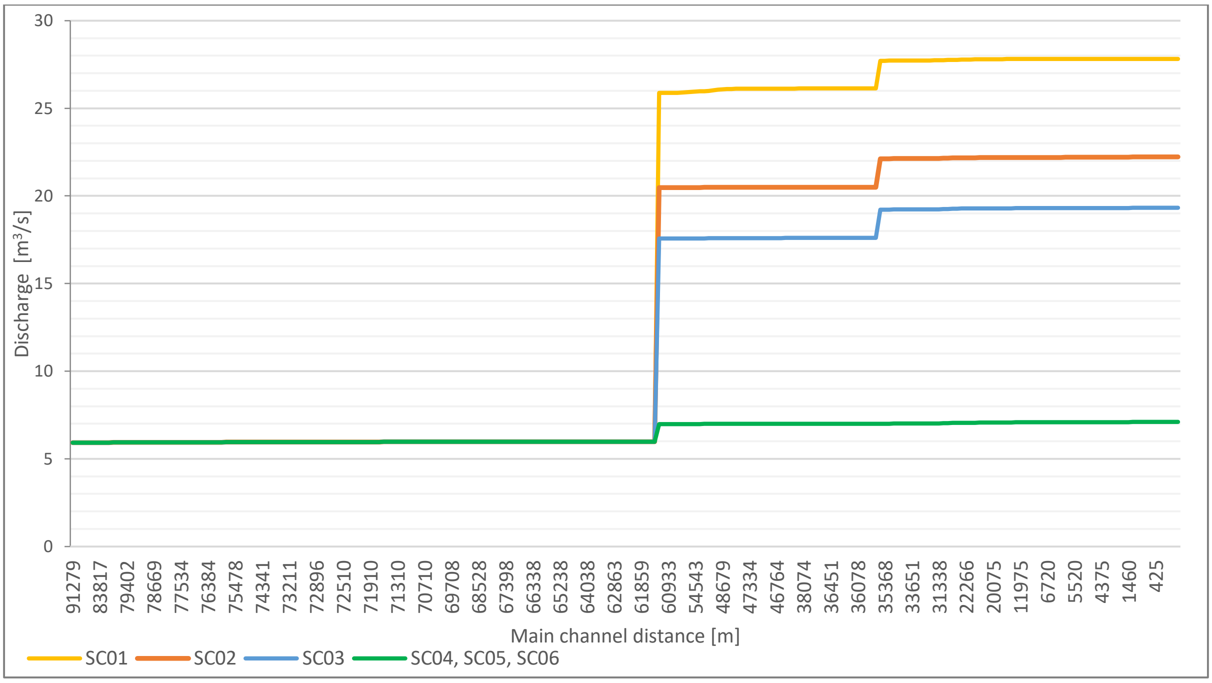


Figure 9. Longitudinal profile of the Körös River between Gyoma and Kunszentmárton

The results of Scenario 1-6 show what is happening with the water resources of the Lake Tisza in an extreme low-water situation with the different level of water restrictions. The model runs also show that the Lake Tisza is able to supply the area with water for a long time, but in extreme cases the water level may become critically low. The outputs show that the minimum water level at Kisköre is higher with the water restrictions. In turn, the water supply to the Hármas-Körös is decreases (*Table 5*).

Table 5. Difference between the different Scenario results

Scenario	Water restriction	Difference in min. water levels at Lake Tisza [m]	Remaining water resources [million m³]	Difference in water supply to Körös [%]	Annual water use limitation [%]
Scenario 1	-	0.00	33	0.00	0.00
Scenario 2	I. level	+1.39	52	32.5	0.00
Scenario 3	II. level	+1.64	60	51.0	0.00
Scenario 4	III. level	+2.53	124	100.0	50.0
Scenario 5	III. level	+2.45	117	100.0	20.0
Scenario 6	III. level	+2.53	124	100.0	20.0

The results show that the water restriction can assure more water resources in the Lake Tisza. There could be more water in the river if we not transfer water to the Nagykunság main irrigation canal. In this case, we should consider alternative water supply measurements. Using reservoirs for this purpose can be a good solution. The quality of the retained water may cause problems, if the water is in the reservoir for a long time.

5.2 Flood event scenarios (Scenario 7-10)

The Scenarios 7 - 10 (see *Table 3*) are long-lasting flooded periods, whereby the water flow is approaching the HQ value with 1000 years return period. In these model versions, we implemented measurements which are increasing the conveyance capacity and showing the importance of the reservoirs in the Middle Tisza.

Scenario 7 is not containing any measurement, and the reservoirs are not used. Scenario 8 shows the effects of the three flood reservoirs along the Tisza River. The roughness coefficient (n) is reduced in Scenario 9 by 20 % from Tiszafüred to Szolnok on both overbanks. In Scenario 10, the roughness

coefficient (n) is reduced by 50 %, which means that maximum forests without undergrowth are allowed on the floodplain.
The boundary conditions selections are also based on the statistical analysis of the water flow datasets produced by the JRC. As described in Chapter VI.4, the "IPSL-INERIS-WRF331F_BC_rcp85" climate scenario is selected to study floods. In this climate scenario, there are several periods with remarkable floods. The timeseries of the year of 2091 includes an extreme flooded period, which data sets of the year have been used as the boundary conditions of the model. At the river section of the Tisza near Tiszafüred, for more than 3 months, the discharge of the river is exceeding 2 800 m^3/s.
Figure 10 shows the development of water level at Kisköre Barrage in the modelled year. From August to September there is a remarkable period with several flood waves. With the help of the reservoirs and the increased conveyance capacity, the maximum water level values can be reduced. The highest high-water level was 91.62 m at Kisköre in 2000, and the Designed Flood Level (DFL) is 92.00 m.

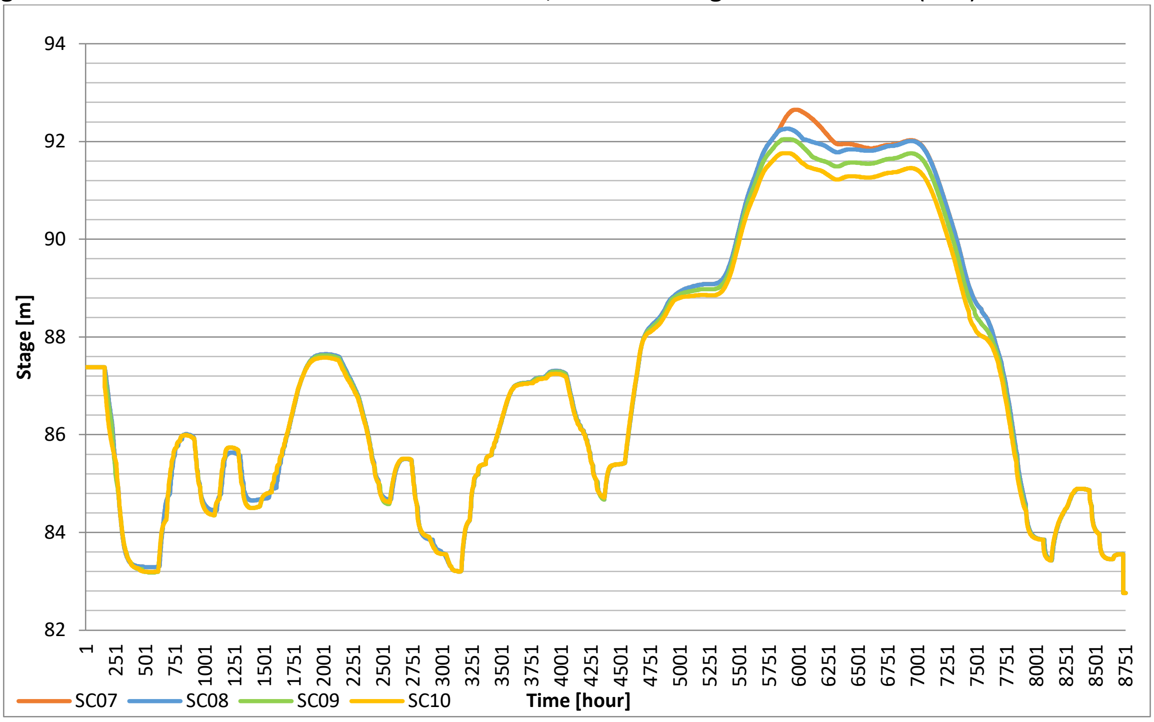


Figure 10. Water level at the Kisköre Barrage

The maximum water levels at Kisköre are the following in the different scenarios:

- Scenario 7: 92.65 m,
- Scenario 8: 92.26 m,
- Scenario 9: 92.05 m,
- Scenario 10: 91.76 m.

The combined capacity of the three reservoirs is 443 million m^3. The 39 cm water level reduction is due to this transferred water to the reservoirs in Scenario 8. Further water level decreasing is achieved with the combined effect of the reservoirs and the increased conveyance capacity of the floodplain in Scenario 9 and 10.
Figure 11 shows the development of discharge at Kisköre Barrage. The discharge was between 3 300 and 3 600 m^3/s in each Scenario which are close to the HQ value with 1000 years return period. The reservoirs and the increased conveyance capacity increase the discharge of the river at Kisköre.

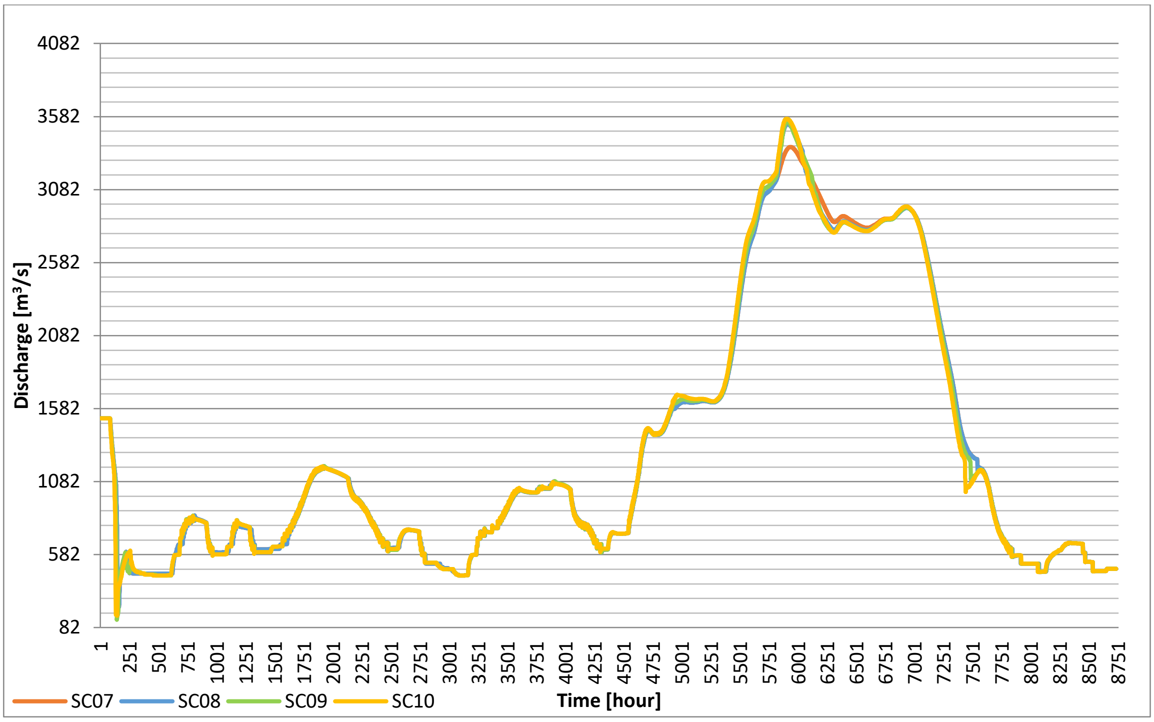


Figure 11. Discharge at the Kisköre Barrage

The backwater effect of the Kisköre Barrage was also studied because it could cause serious problems at a high-water level. The results of the modelling show that the difference between the water level of the upstream and downstream section is 24 cm at the flood peak. Another factor has been studied that the barrage is designed for a 4 000 m^3/s maximum discharge (*Ihrig 1973*). Based on the results, there would be no problem to transfer a flood waves around 3 600 m^3/s peak through the Kisköre Barrage.

The potential impact of measurements has also been studied at the downstream section of the Tisza River. The maximum discharge values are the following at Csongrád in the different scenarios:

- Scenario 5: 3 342 m^3/s,
- Scenario 6: 3 122 m^3/s,
- Scenario 7: 3 156 m^3/s,
- Scenario 8: 3 177 m^3/s.

The difference between the maximum values of the Scenario 7 and 10 shows the positive effects of the reservoirs. In contrast, increasing the conveyance capacity may have negative effect at the downstream of the river, which can be seen from the maximum discharge values of Scenario 9 and 10. *Figure 12* shows the discharge values on a lower section of the Tisza near Csongrád between August and November. The difference between the maximum water levels of the scenarios is only 8-10 cm at this river section (*Figure 13*).

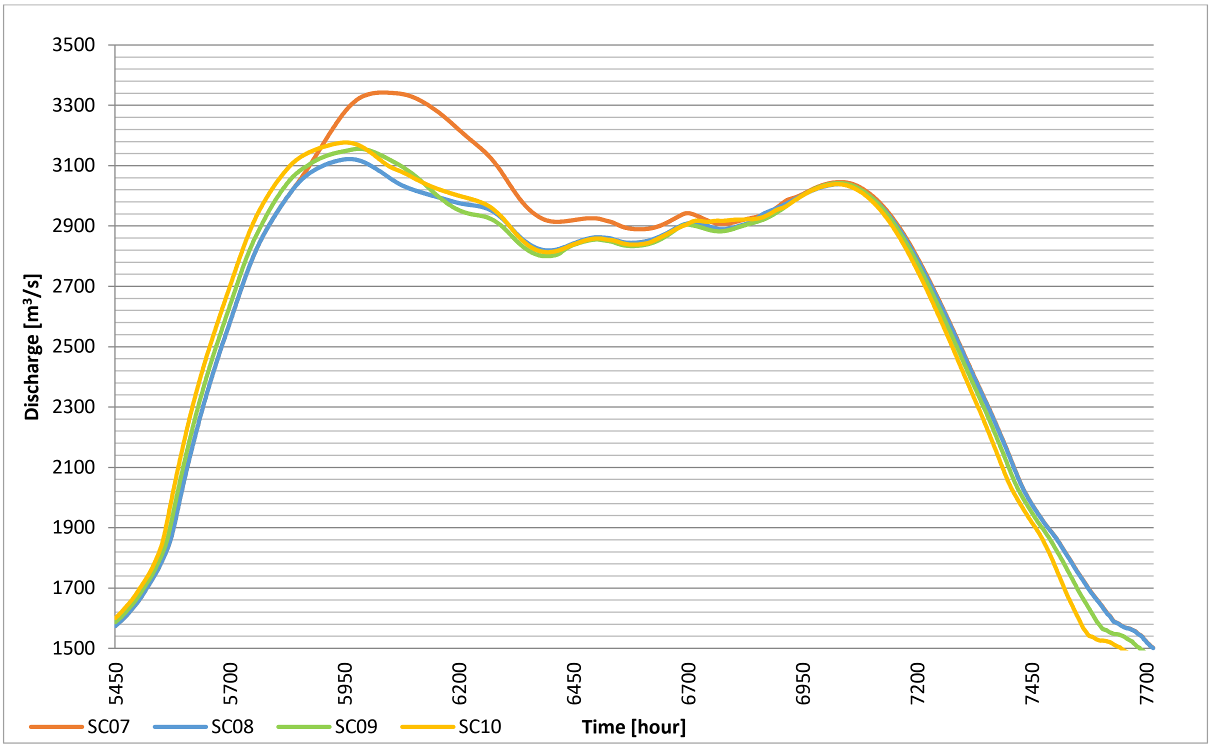


Figure 12. Discharge at Csongrád from 16 August to 1 November

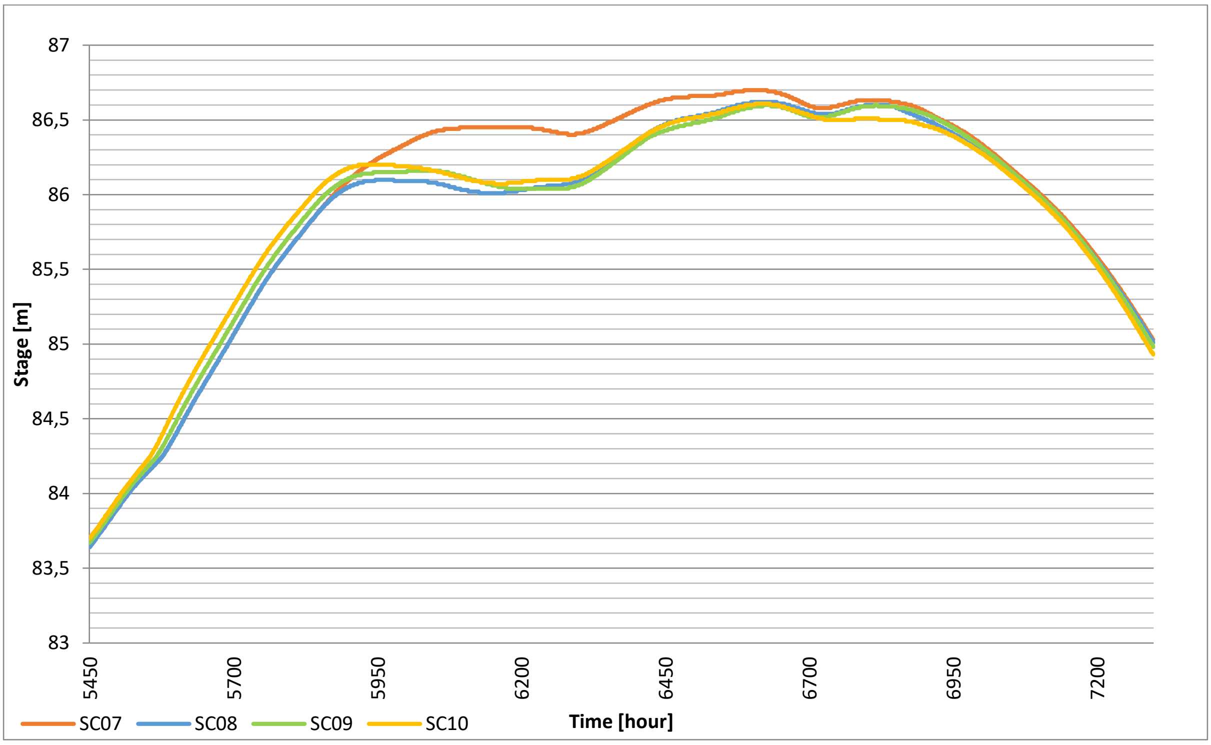


Figure 13. Water level at Csongrád from 16 August to 1 November

This extreme flood begins during the irrigation period. Regardless of this, adequate water should be provided for different purpose in the pilot area under the flood event. A special measure has been implemented in the model. When an extraordinary flood is going down the Körös, the barrage at the outflow section of the Hortobágy-Berettyó at Mezőtúr has to be closed. In such cases, water is transferred from the Hortobágy-Berettyó to the Körös with pumps. If the capacity of the pumps is not enough to drain the water at Mezőtúr, it is possible to pass the water to the Körös through the Nagykunság main irrigation canal (*Figure 14*).

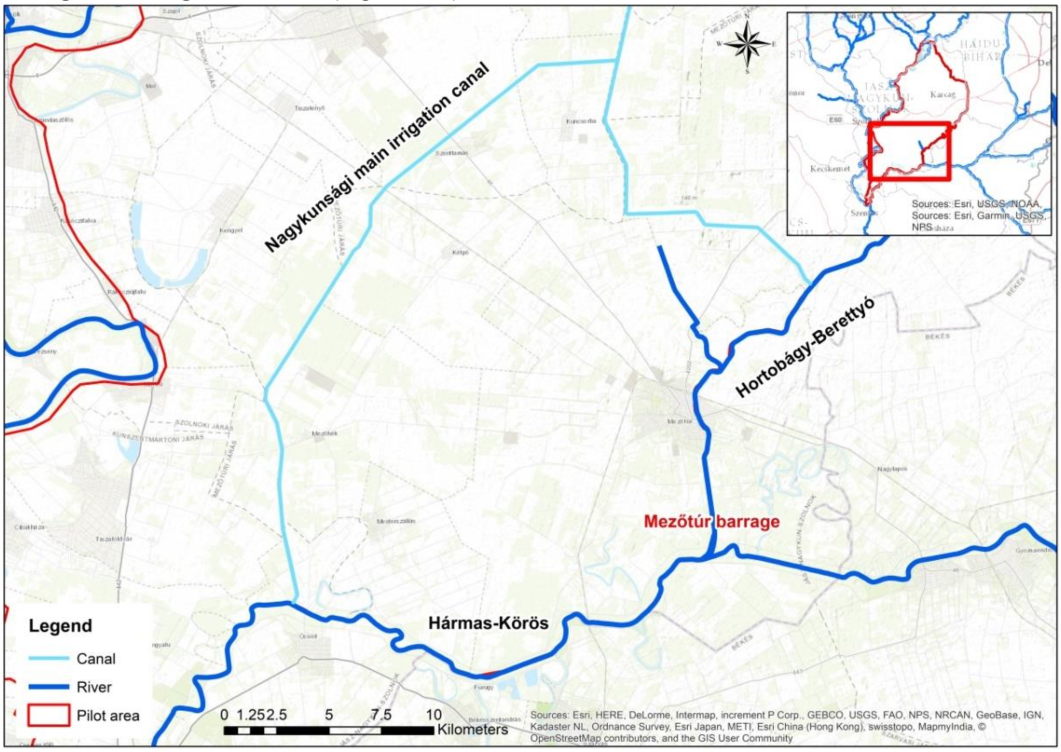


Figure 14. Alternative flow direction when the Mezőtúr Barrage is closed

Figure 15 shows the water level and discharge during this period. In the critical period, up to 40-60 m^3/s water can be transferred from Hortobágy-Berettyó to the Nagykunság main irrigation canal. The negative discharge value shows the period, when the water flows to the opposite direction compared to the normal operational procedure.

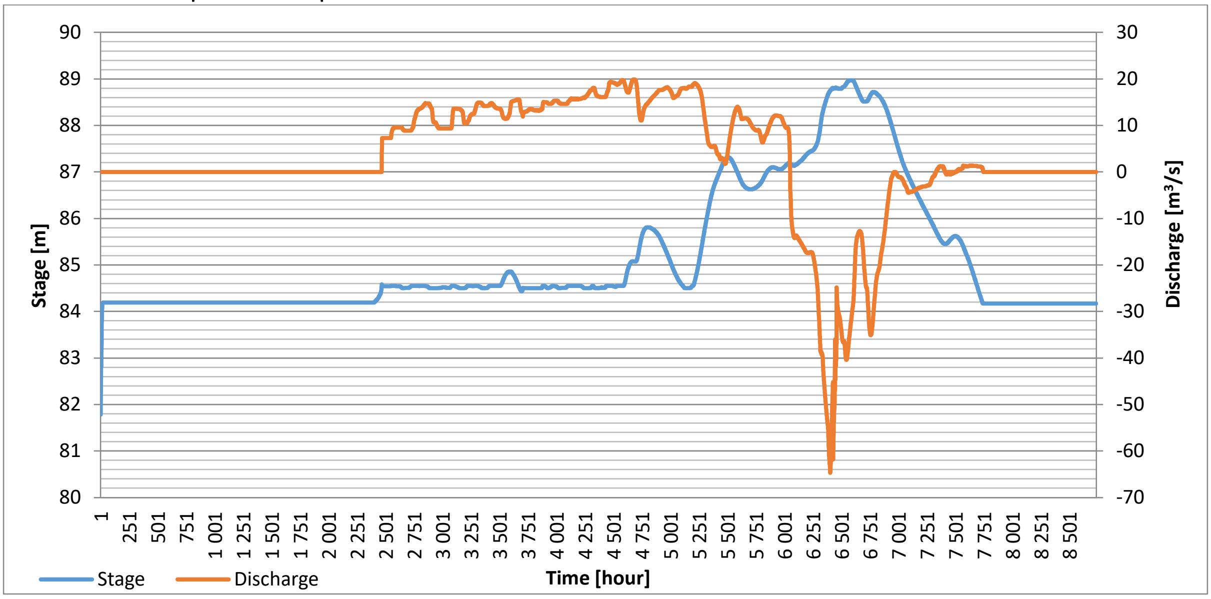


Figure 15. Water level and discharge at the outflow section of the Eastern branch of the Nagykunság main irrigation canal

Figure VI.16 shows the water level and discharge at the outflow section of the western branch of the Nagykunság main irrigation canal. The water flow is lower at this canal section, due to the water uses of the pilot area. The amount of water abstractions which considered are the same as in the low-water scenarios.

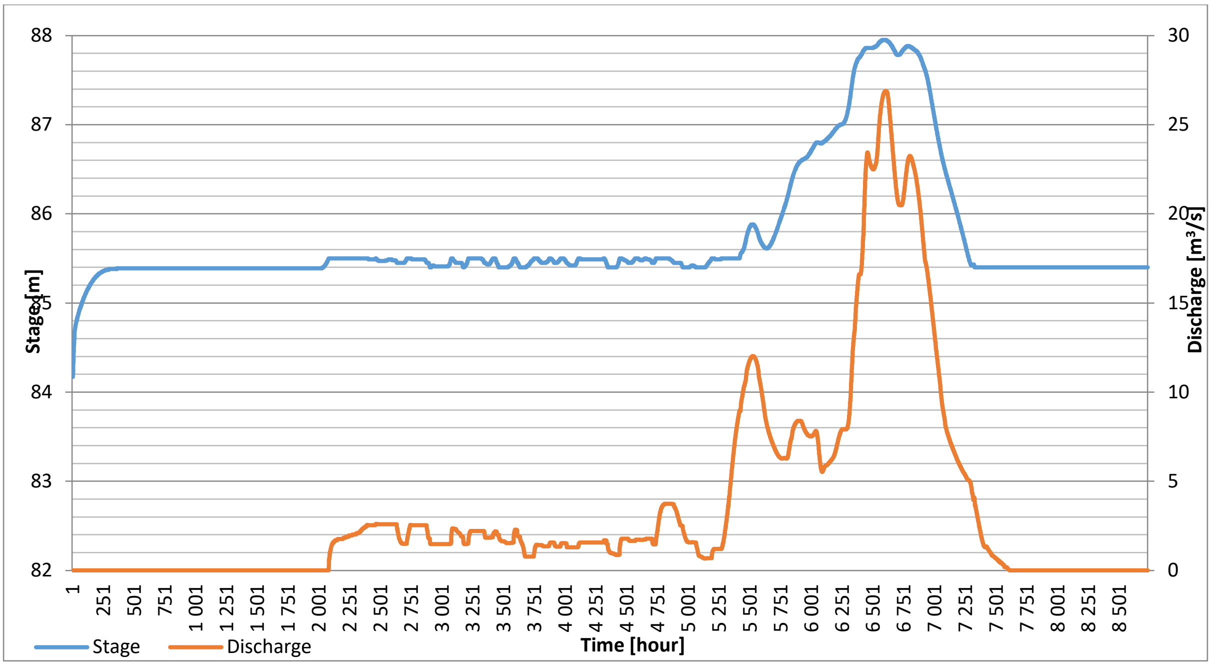


Figure 16. Water level and discharge at the outflow section of the Western branch of the Nagykunság main irrigation canal

We studied the impacts of the reservoirs and the increased conveyance capacity with the Scenario 7-10. The waterflow is approaching the HQ value with 1000 years return period. *Table 6* shows the differences between the flood scenario results. The water level reducing effect of the three reservoirs is 11 cm at Kisköre with this extraordinary flood. A further 21 and 29 cm water level reduction could be achieved by reducing the roughness of the floodplain. The water level could be reduced to the DFL in Scenario 9. At the same time, the discharge is increased because of the increased conveyance capacity. There was less difference at Csongrád at this high-water level.

Table 6. Differences between the Scenario 7-10 results

Scenario	Applied measurement	Difference in flood peak at Kisköre [cm]	Difference in flood peak at Kisköre [m³/s]	Difference in flood peak at Csongrád [cm]	Difference in flood peak at Csongrád [m3/s]
Scenario 7	-	-	-	-	-
Scenario 8	Reservoirs	-39	+155	-8	-221
Scenario 9	Reservoirs + reduced roughness by 20 %	-60	+170	-10	-186
Scenario 10	Reservoirs + reduced roughness by 50 %	-89	+193	-9	-166

The backwater effect of the Kisköre barrage was also studied. The difference between the headwater and downstream water level of the barrage is 24 cm, which is acceptable for such a high-water level. An alternate flow direction has also applied to the model. During an extraordinary flood on the Hármas-Körös, the water could be drained from the Hortobágy-Berettyó to the Hármas-Körös through the Nagykunság main irrigation canal. A 40-60 m^3/s discharge could be transferred to the canal to help manage the flood.

6.6. International aspects of the pilot area study

The main aim of this pilot activity was to investigate the impacts of climate change induced drought and flood related issues on a smaller region. The Middle Tisza pilot was selected because of the special hydrological characteristics. The natural runoff of the area is not too relevant, the water needs are satisfied with the help of artificial irrigation canal systems. Floods, inland excess waters, and droughts also occur often in the pilot area. The JRC studies stated that these extreme hydrometeorogical events can happen more and more frequently in the future. In addition, increasing of water demand is also expected. The implementation of water management planning on TRB level has a very high priority to reduce the damages caused by these events.

In order to make the planning process more effective, the Shared Vision Planning methodology was applied. The main goal of the SVP method is to provide the stakeholders the opportunity to share their opinions and suggestions during the pilot action / planning work. As a result, through modelling, issues had been studied which were relevant to the local stakeholders. This method also provides an opportunity to bring local stakeholders closer to planning and implementing organizations.

The natural surface runoff to the surface water sources is not significant in this region. Due to this special feature, it could be satisfactory for water allocation management purposes to run one dimensional hydrodynamic model for water quantity issues. The HEC-RAS model software was used for this purpose. Experience shows that the water movement of the river network and the artificial canals is described with suitable approximation with this model. There are also proper alternatives to define the operation of hydraulical structures, reservoirs, and water uses. It should be noted that the connection between surface water and groundwater is not part of the model, which could be great importance during a low water period.

With low-water modelling scenarios the effects of the water restriction measures were investigated. These scenarios have shown that the Tisza Lake could supply the area with enough water for a long time. However, large decrease in the water level of the Lake Tisza could cause major ecological, economical, and social problems along the reservoir. The low-water scenarios have also highlighted a previously known problem, namely how lowland areas are vulnerable to extreme hydrometeorological events. For this reason, the water management of the countries with this characteristic (e.g. Hungary, Serbia) are highly dependent on the incoming discharges from the neighbouring countries.

The results show that the water restriction can assure more water resources in the Lake Tisza. Obviously there will be more water in the river if we not transfer water to the Nagykunság main irrigation canal. In this case, we should consider alternative water supply measurements. Using reservoirs for this purpose can be a good solution. The quality of the retained water may cause problems, if the water is in the reservoir for a long time. Further studies are recommended in this topic.

There would be a good solution to keep more water in the area with some alternate ways to avoid the water restriction measures. Constructing reservoirs in deep areas to hold back excess water, and the development of the canal network are realistic options. Reforming the agricultural practices can also improve the hydrology of the area, such as reforming the current land use structure, abandoning monocultural plant production and the development of irrigation technologies.

SVP events have also shown that it is difficult to determine the optimal process of the water restriction. The water limitation procedure, which is set out in the *Water Management Act* can also cause conflict between water users.

The flood event scenarios have given the opportunity to study the importance of the flood reservoirs, and the increased conveyance capacity in the Middle Tisza. The stakeholders have identified the dense vegetation on the floodplain, and the decreasing conveyance capacity as serious problems. Many flood protection measures (e.g. EVP) in Hungary are trying to moderate the risk of these problems. Using the flood reservoirs can also help reduce these negative impacts. However, it is important that these measures can be accepted at international level.

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