2D NUMERICAL SIMULATIONS OF 2012 FLOOD WAVE PASSAGE THROUGH HPP SYSTEM ON THE RIVER DRAVA

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Abstract

An extreme flood event on the River Drava in November 2012 was the highest in the last 60 years. It has caused over-spilling of levees and breaching on several levee sections, and consequently produced an extensive flooding of neighbouring settlements and farm fields and property damages in Slovenia and Croatia. This paper shows the results of the hydrological and hydraulic analysis of the flood wave propagation from Austria, through Slovenian hydro power plants to HPP system in Croatia. The hydrological analysis includes the flood flow transformation through the chain of HPPs. The detailed hydraulic analysis was performed on the HPP Varaždin for which a 2D hydrodynamic model has been developed. The model simulations showed the impact of the over-topping and breaching of levees on the extreme flows and flood wave propagation on the HPP Varaždin.

Keywords

flood wave, hydraulic analysis, hydrological analysis, 2d mathematical model, River Drava

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1 INTRODUCTION

The flood wave on the River Drava from November 2012 compared to historical flood events was exceptional on several grounds. Considering the peak discharge of 3311 m^3/s and the flow rates on the HPP Varaždin this was the highest flood wave on the Croatian part of the River Drava in the last sixty years. The highest historical recorded flood wave was in 1966 before the construction of HPPs in Croatia with the peak discharge of 2843 m^3/s on g.s. Varaždin. The second highest recorded flood event was in October 1998 after the construction of the HPP Varaždin with the peak discharge of 2221 m^3/s. The threefold flow increase on the HPP Varaždin within just 6 hours resulted in a very steep upward flood hydrograph. The November 2012 flood wave has caused over-spilling and breaching of levees on several locations, and consequently produced a great amount of damage on hydro-power and flood protection systems. In turn, the extensive flooding of the surrounding settlements occurred with damages to the local population, environment and industry. Furthermore, the flood wave entered the Croatian area during the night hours which was an aggravating circumstance for the monitoring of flood wave and hazards.

This paper shows the propagation of the 5/Nov/2012 flood wave through the Slovenian and Croatian hydro power systems and provides analysis of collateral events that caused its unexpected transformation in the area of the HPP Varaždin. The hydrological analysis is not given in any comprehensive way, as the emphasis is placed on the characteristic elements of wave transformation and on the distinctiveness and complexity of this exceptional flood event.

Fig. 1 Chain of HPPs on the River Drava in Austria, Slovenia and Croatia

The first part of the paper shows the wave propagation from the Austrian HPP Labot through the Slovenian hydro power systems and the Croatian HPPs (**Fig. 1**). The flood wave entered the Slovenia area (HPP Labot) on the 5th Nov 2012 around 16:00 hrs and in the next 11 hours caused the flow increase by 2060 m^3/s, reaching the peak flow of 2592 m^3/s at 15:00 hrs. This sudden increase of discharge is one of the main reasons for flood damages in the downstream sections. The flood wave peak on the HPP Formin of 2840 m^3/s was recorded on the 5th Nov at 23:00 hrs. The peak flow of 3311 m^3/s on the HPP Varaždin was 471 m^3/s higher than the peak on the HPP Formin, which is also one of the particularities of this flood event.

The second part of the paper gives an analysis of flood wave propagation through 3 Croatian hydro power plants, and focuses on the area of the HPP Varaždin. A detailed hydrodynamic model of the area between HPP Formin and HPP Varaždin was not available. For the hydraulic analysis of 5/11/2012 flood wave a 2d hydrodynamic model of this area was developed. The model comprises the River Drava old channel from HPP Formin dam till HPP Varaždin dam, HPP Formin outlet canal from HPP Formin powerhouse to the restitution into the River Drava's old channel and two River Drava tributaries, Dravinja and Pesnica. The flood wave caused two levee breaches of the HPP Formin outlet canal so one of the goals of the hydraulic analysis was to determine the impact of the levee breaches on the flood wave transformation. On the hydrodynamic model several simulations of flood wave were made, which enabled new insights into the complexity of flood wave propagation on the area.

The input data for the analysis were used from several sources in Slovenia and Croatia [1], [2], [3]. The discharge data was used for HPP Labot, HPP Vuhred, HPP Ožbalt, HPP Mariborski otok and HPP Zlatoličje. The discharge and water levels data for 2010, 2011 and 2012 flood events were used for the analysis of flood wave transformation in the area between HPP Formin and HPP Varaždin, and comprised: dam and powerhouse of HPP Formin, dam and powerhouse of HPP Varaždin, gauging stations Borl and Ormož on the River Drava, g.s. Videm on the River Dravinja and g.s. Zamušani on the River Pesnica.

2 PROPAGATION OF 5/NOV/2012 FLOOD WAVE THROUGH SLOVENIA AND CROATIA

The River Drava rises in the South Tyrol in Italy, and flows eastwards through Austria, Slovenia, Hungary and Croatia, where it meets the Danube near Aljmaš. The River Drava is 719 km long and is also the fourth largest and the fourth longest Danube tributary. Along the upper reaches, in Austria, Slovenia and Croatia, 21 large hydro power plants were constructed. Ten of them are in Austria, eight in Slovenia and three in Croatia. The last Austrian hydropower plant on the River Drava is HPP Labot.

About 2 km downstream from HPP Labot, the River Drava forms the state border between Austria and Slovenia. The first in chain of Slovenian HPP system is HPP Dravograd followed by HPP Vuzelnica, HPP Vuhred, HPP Ožbalt, HPP Fala, HPP Mariborski otok, HPP Zlatoličje and HPP Formin. The chain of HPP system in Slovenia has small reservoir volumes up to HPP Formin (**Tab. 1**) so there is little or no storage capacity for flood flows in the upper Slovenian reservoirs.

The River Drava enters Croatia near Dubrava Križovljanska settlement. There are three hydro power plants in Croatia. The first in chain is HPP Varaždin followed by HPP Čakovec and HPP Dubrava. The reservoir of HPP Varaždin of 8.0 hm^3 is significantly smaller compared to the ones of the HPP Čakovec of 51.0 hm^3 and 93.5 hm^3 of the HPP Dubrava (**Tab. 1**).

Tab. 1 Characteristics of the hydro power plants in Slovenia and Croatia [1], [2]

HPP	Country	Type	Reservoir [hm^3]	Installed flow [m^3/s]	Total spilling capacity [m^3/s]
HPP Dravograd	Slovenia	impoundment	5.6	420	5400
HPP Vuzelnica	Slovenia	impoundment	7.1	550	5600
HPP Vuhred	Slovenia	impoundment	10.3	550	5800
HPP Ožbalt	Slovenia	impoundment	10.5	550	5800
HPP Fala	Slovenia	impoundment	4.2	550	4800
HPP Mariborski Otok	Slovenia	impoundment	13.1	550	5600
HPP Zlatoličje	Slovenia	diversion	4.5	530	4800
HPP Formin	Slovenia	diversion	17.1	500	4800
HPP Varaždin	Croatia	diversion	8.0	500	4800
HPP Čakovec	Croatia	diversion	51.0	500	4800
HPP Dubrava	Croatia	diversion	93.5	500	4800

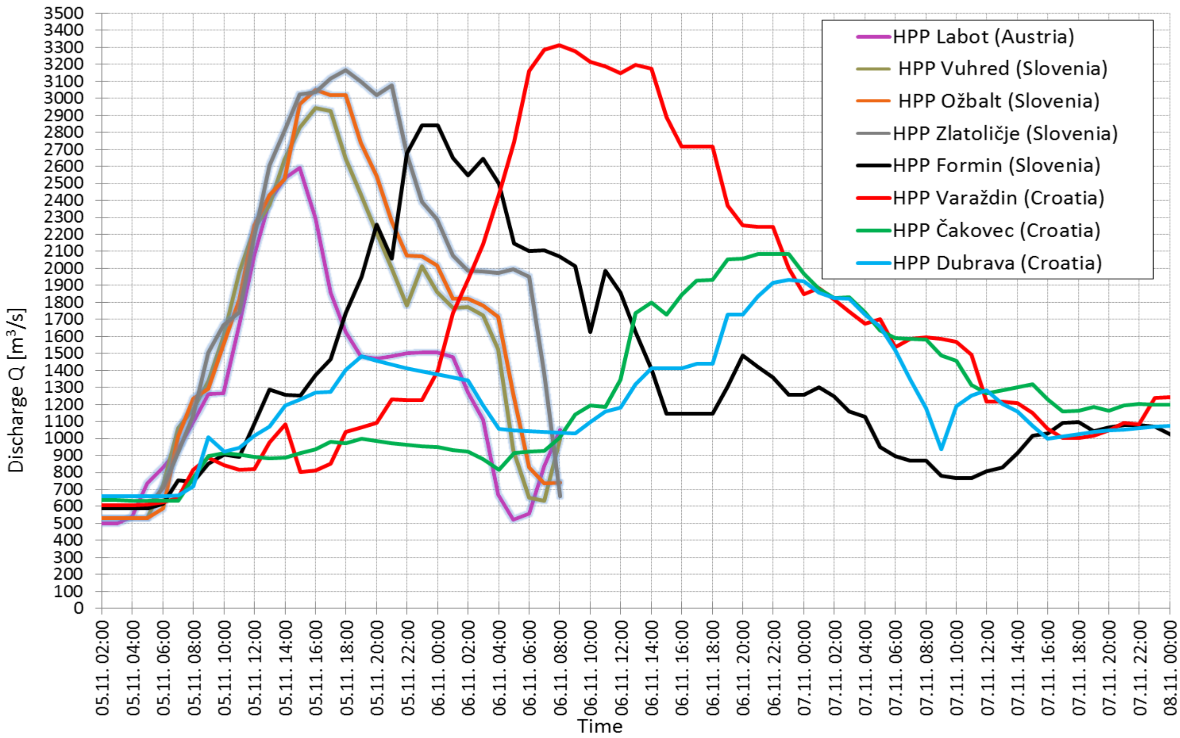


Fig. 2 Flood event 5/Nov/2012 - Flow hydrographs on HPPs in Austria, Slovenia and Croatia

Fig. 2 shows recorded hydrographs on HPP Labot in Austria, HPPs Vuhred, Ožbalt, Zaltoličje and Formin in Slovenia and also on HPPs Varaždin, Čakovec and Dubrava in Croatia during the 5/Nov/2012 flood wave (sources [1], [2], [3]). Considering the fact that the HPP system on Zlatoličje, Formin, Varaždin, Čakovec and Dubrava is a diversion type of the hydro power plant, the hydrograph of these systems represents a total discharge of a dam and a powerhouse.

Tab. 2 shows the timing and the peak flow on the chain of HPPs on the River Drava. The flood wave entered Slovenia on the 5th Nov at 16:00 hrs and in the next 11 hours caused the flow increase by 2060 m^3/s. The peak flow of 2592 m^3/s on the HPP Labot was reached on the 5th Nov at 15:00 hrs. On HPP Fomin the flood wave peak of 2840 m^3/s was reached on the 5th Nov at 23:00 hrs. The highest peak flow of 3311 m^3/s in Croatia was recorded on HPP Varaždin on the 5th Nov at 08:00 hrs.

Tab. 2 Discharges and timing of the peak flows [1], [2]

HPP	Country	Discharge at peak Q [m^3/s]	Time at peak	Peak discharge diff ΔQ [m^3/s]	Time between two peaks Δt [hrs]
HPP Labot	Austria	2592	5/11/2012 15:00		
HPP Vuhred	Slovenia	2945	5/11/2012 16:00	+353	1
HPP Ožbalt	Slovenia	3040	5/11/2012 17:00	+95	1
HPP Zlatoličje	Slovenia	3170	5/11/2012 18:00	+130	1
HPP Formin	Slovenia	2840	5/11/2012 23:00	-330	5
HPP Varaždin	Croatia	3311	6/11/2012 08:00	+471	9
HPP Čakovec	Croatia	2085	6/11/2012 21:00	-1226	13
HPP Dubrava	Croatia	1930	6/11/2012 23:00	-155	2

The flow hydrographs show sudden, almost simultaneous flow increase on HPPs Labot, Vuhred, Ožbalt and Zlatoličje. The peak flows on these HPPs on the 5th Nov were 2592, 2945, 3040 and 3170 m^3/s at 15:00, 16:00, 16:00 and 18:00 hrs. While passing through the reservoir of HPP Formin the first transformation of flood wave occurred. According to the hydrographs on **Fig. 2** it can be seen that:

- The peak flow of 2840 m^3/s on HPP Formin (black line) occurred on the 5th Nov at 23:00 hrs, and it was 330 m^3/s lower than the peak flow on HPP Zlatoličje.
- The peak flow of 3311 m^3/s on HPP Varaždin (red line) occurred 9 hours later, on the 6th Nov at 08:00 hrs. The peak flow on HPP Varaždin was 471 m^3/s higher than the peak flow on HPP Formin.
- The flow rates on HPP Čakovec were significantly reduced due to the combined water losses on levee over-spilling and breaching and on infiltration. The peak flow of 2085 m^3/s on HPP Čakovec (green line) occurred 13 hours later than on HPP Varaždin, on the 6th Nov at 21:00 hrs. It was 1226 m^3/s lower than the peak flow on HPP Varaždin.
- The peak flow of 1930 m^3/s on HPP Dubrava occurred 2 hours later, on the 6th Nov at 23:00 hrs, and it was 155 m^3/s lower than the peak flow on HPP Čakovec.

The hydrographs on the 5/Nov/2012 and the past hydrographs show that the flood wave transformation in the area between HPP Formin and HPP Varaždin was unexpected, as were the recorded flow rates on HPP Varaždin (red line **Fig. 2**). The sum of the peak discharges of the two tributaries (Dravinja and Pesnica) of 200 m^3/s, and the extensive levee over-spilling in the area, shows that that the peak flow on HPP Varaždin of 3311 m^3/s was unpredictable. The discharge was 471 m^3/s higher than the peak flow of 2840 m^3/s on HPP Formin. The unexpected increase of the peak flow on HPP Varaždin is associated with the levee breaches of HPP Formin outlet canal, and that was the main task of the hydrodynamic model simulations.

3 FLOOOD WAVE ON 5/NOV/2012 IN THE AREA BETWEEN HPP FORMIN AND HPP VARAŽDIN

3.1 Description of the area

The area between HPP Formin and HPP Varaždin has complex hydrographic characteristics (**Fig. 3**). The area is bordered with the HPP Formin canal in the north and with the high terrain in the south. The inlet canal connects the reservoir and the powerhouse, whereas the outlet canal connects the powerhouse with the River Drava's old channel. During the low and the medium inflows the majority of the flow is diverted through the powerhouse and only a minor part (biological minimum) is discharged through the River Drava's old channel. An opposite split occurs during high inflows when the majority of flows are discharged over the dam to the River Drava's old channel. The installed flow capacity of HPP Formin powerhouse is 500 m^3/s and the spilling capacity of HPP Formin dam is 4300 m^3/s. Two main tributaries of the River Drava are the Dravinja stream (left tributary) and the Pesnica stream (right tributary). In the area there are four gauging stations: g.s. Borl and g.s. Ormož on the River Drava, g.s. Videm on the Dravinja stream and g.s. Zamušani on the Pesnica stream. An average flow of the River Drava near Varaždin is 330 m^3/s, and the average maximum annual flow is 1286 m^3/s [4].

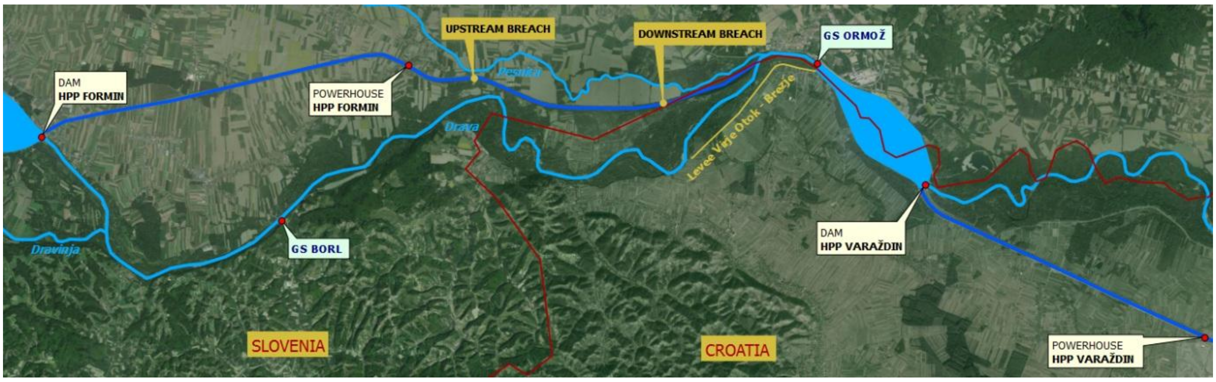


Fig. 3 The River Drava section between HPP Formin and HPP Varaždin

The Drava River valley between HPP Formin and HPP Varaždin has a complex morphology. From the mouth of the Dravinja stream, the river valley width is reduced from 2300 m to 800 m near Zavrč settlement in the downstream direction. The valley then widens to 1700 m near Veliki Lovrečan settlement, and then again gently reduces towards the beginning of the Virje Otok-Brezje levee to 1100 m. From the beginning of the Virje Otok-Brezje levee the valley width is reduced first to 580 m near the mouth of HPP Formin outlet canal, than to 290 m near the Virje Otok settlement and finally to 210 m at the road bridge in Ormož.

3.2 Hydrographs of flood waves

For a general overview of the unusual transformation of the 5/Nov/2012 flood wave, a comparison (**Fig. 4**) of input (solid line) and output (dashed line) hydrographs in the area between HPP Formin and HPP Varaždin is given for the flood waves in 2010, 2011 and 2012 (according to [1], [2]).

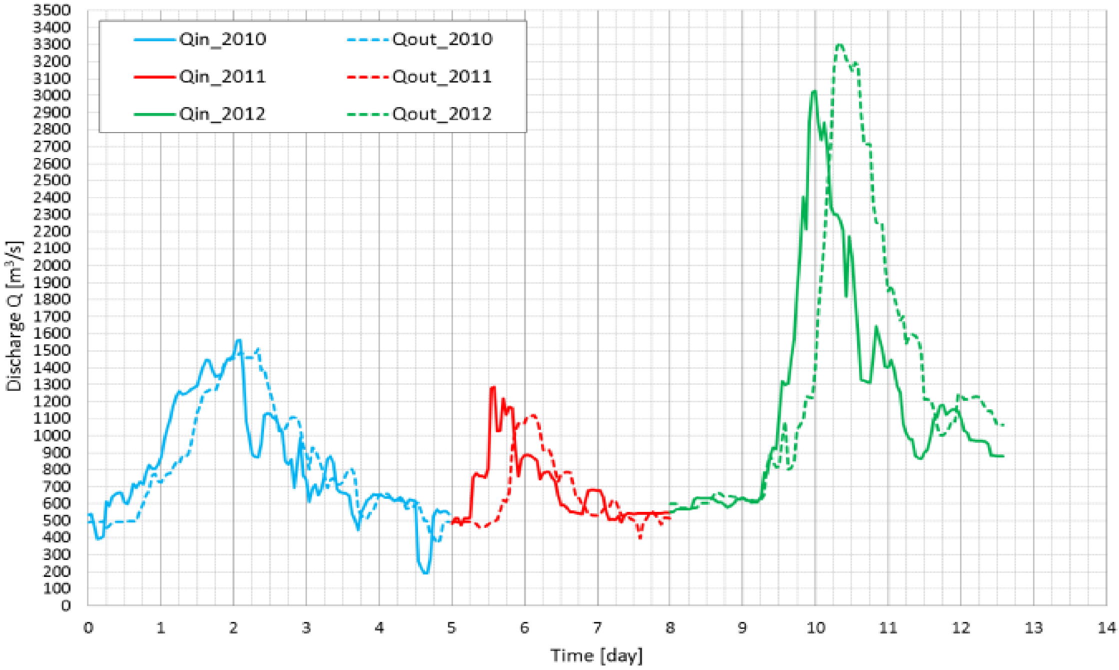


Fig. 4 Comparison of flow hydrographs for flood events in 2010, 2011 and 2012

The discharge Q_{in} represents the sum of flows on the dam and the powerhouse of HPP Formin together with the Dravinja and Pesnica streams. The discharge Q_{out} represents the sum of flows on the dam and the powerhouse of HPP Varaždin. The flood wave hydrographs in 2010 and 2011 are actually typical in this area and show that the highest output flows from the area (Q_{out}) are generally lower than the highest input flows (Q_{in}). However, the highest output flow in November 2012 was 300 m^3/s (10%) higher than the highest input flow.

The rate of the 5/Nov/2012 flood wave onset can be seen when compared to the theoretical flood hydrographs (**Fig. 5**). Based on the statistical analysis of flood waves in 2005, 2008, 2009, 2010 and 2011, the theoretical flood hydrographs for g.s. Borl were produced [5]. It can be seen that the peak discharge in 2012 has between 100 and 1000 years return period. The upward branch of the 2012 flood hydrograph corresponds to the upward branch of the 1000 years theoretical flood wave (**Fig. 5**).

The flood inflows of the River Drava and the Dravinja and Pesnica streams were estimated (**Tab. 3** and **Fig. 6**) in several previous and one recent study ([5], [6], [7]). The estimated discharges from 1974 and 2013 show relatively small differences of the total input flows, while the flows from VGI 1997 study are slightly higher. **Tab. 3** shows that the peak input flow of the 5/Nov/2012 flood wave (Q_{in}=3100 m^3/s) has 200 years return period.

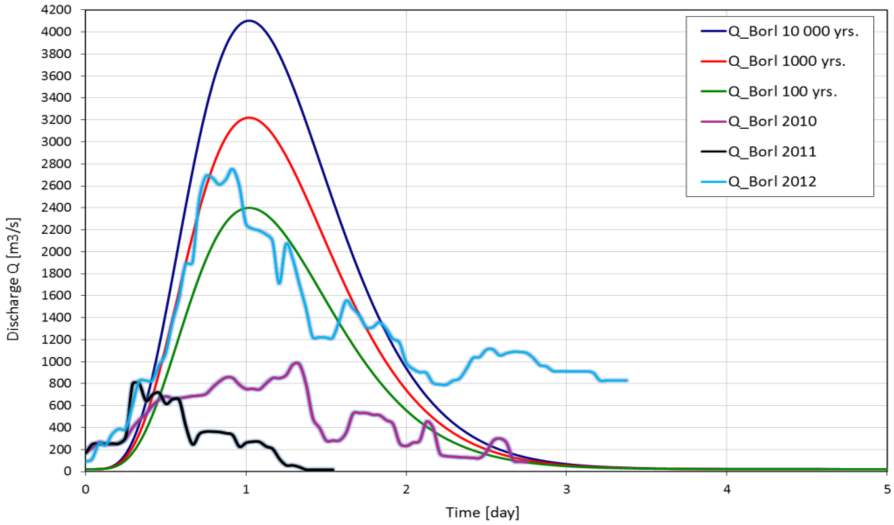


Fig. 5 Comparison of theoretical and measured hydrographs of the River Drava on g.s. Borl

Tab. 3 Comparison of estimated total flood inflows

Discharge Q [m³/s]			Return period [years]		
No.	**Study**	**Including**	**100**	**1000**	**10.000**
1	Franković 1974	before construction of HEF and HEV	2800	3700	4600
2	VGI Ljubljana 1997	$Q_{damHEF} + Q_{phHEF} + Q_{Dravinja}$	2897	4208	-
3	IEE 2002	$Q_{damHEF} + Q_{phHEF} + Q_{Dravinja} + Q_{Pesnica}$	2600	-	-
4	IEE 2013(*)	$Q_{damHEF} + Q_{phHEF}^{(*)} + Q_{Dravinja}$	2849	3671	4553
5	IEE 2013	$Q_{Pesnica}$	166	223	279
6	IEE 2013(*)	$Q_{damHEF} + Q_{phHEF}^{(*)} + Q_{Dravinja} + Q_{Pesnica}$	3015	3894	4832

(*) discharge through HPP Formin powerhouse was assumed at 450 m^3/s

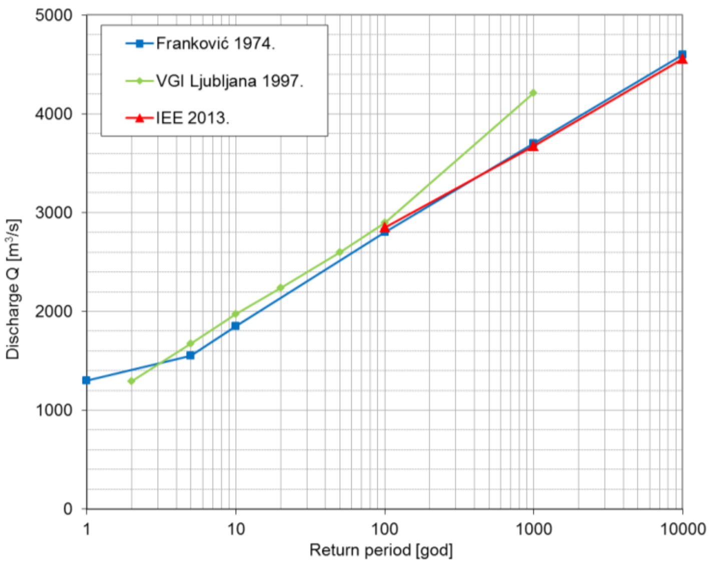


Fig. 6 Comparison of estimated total flood inflows

3.3 Levee breached on the HPP Formin outlet canal

During the 5/Nov/2012 flood wave the two levee breaches of the HPP Formin outlet canal occurred. The upstream breach was 150 m wide and is located 1.3 km downstream from the HPP Formin powerhouse. **Fig. 7** gives a comparison of the outlet canal geometry before (blue line) and after the breach (red line), and shows the extreme power of flow at the breach. The sudden flow of water washed away the right levee of the outlet canal and has left up to 12 m of sand and silt deposits in the outlet canal. The sudden flow of water also demolished the left bank of the canal, and eroded up to 50 m wide and 8 m tall part of the adjacent land.

(a) Aerial photograph of the levee breach [1] (b) Canal before and after the breach [1]

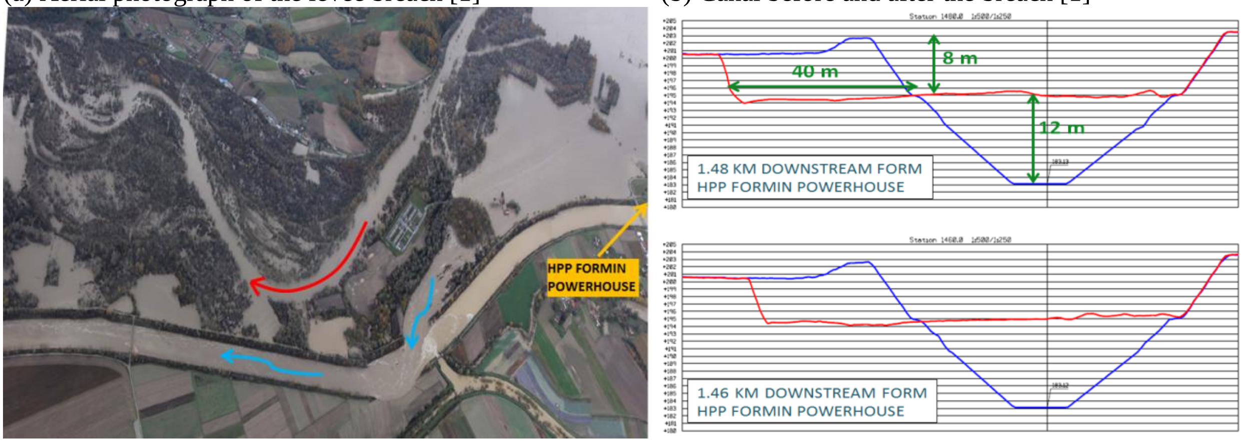


Fig. 7 Upstream levee breach of HPP Formin outlet canal

The downstream breach was 200 m wide and is located 6.3 km downstream from the HPP Formin powerhouse (**Fig. 8**). According to the DEM report [1], the breach caused a 6 m tall levee damage leaving 300,000 m^3 of soil deposits in the outlet canal. The River Drava actually created a new riverbed through which diversion of flows to the outlet canal was evident even after the flood wave passage.

Fig. 8 Downstream levee breach of HPP Formin outlet canal (photo taken 9/Nov/2012) [1]

3.4 Transformation of 5/Nov/2012 flood wave between HPP Formin and HPP Varaždin

Hourly discharge recordings are shown for the dam and powerhouse of the HPP Formin and HPP Varaždin (**Fig. 9**) and for the Dravinja and Pesnica streams (**Fig. 10**), the data were provided from [1], [2]. The discharge Q_{tot} represents the total discharge for dam and powerhouse $Q_{tot}=Q_{dam}+Q_{ph}$. During the flood wave passage the two levee breaches of the HPP Formin outlet canal occurred as well as over-spilling and breaching of the Virje Otok-Brezje levee. The peak flow on the HPP Varaždin $Q_{tot.max}$=3311 m^3/s (6th Nov at 08:00 hrs) was significantly higher than the peak flow on the HPP Formin $Q_{tot.max}$=2840 m^3/s (5th Nov at 23:00 hrs). The HPP Varaždin peak flow was 471 m^3/s higher than the peak on the HPP Formin. The peak flows of the Dravinja 109 m^3/s and the Pesnica of 85 m^3/s [3] were insufficient to provide the recorded flow increase of 471 m^3/s on the HPP Varaždin (**Fig. 10**).

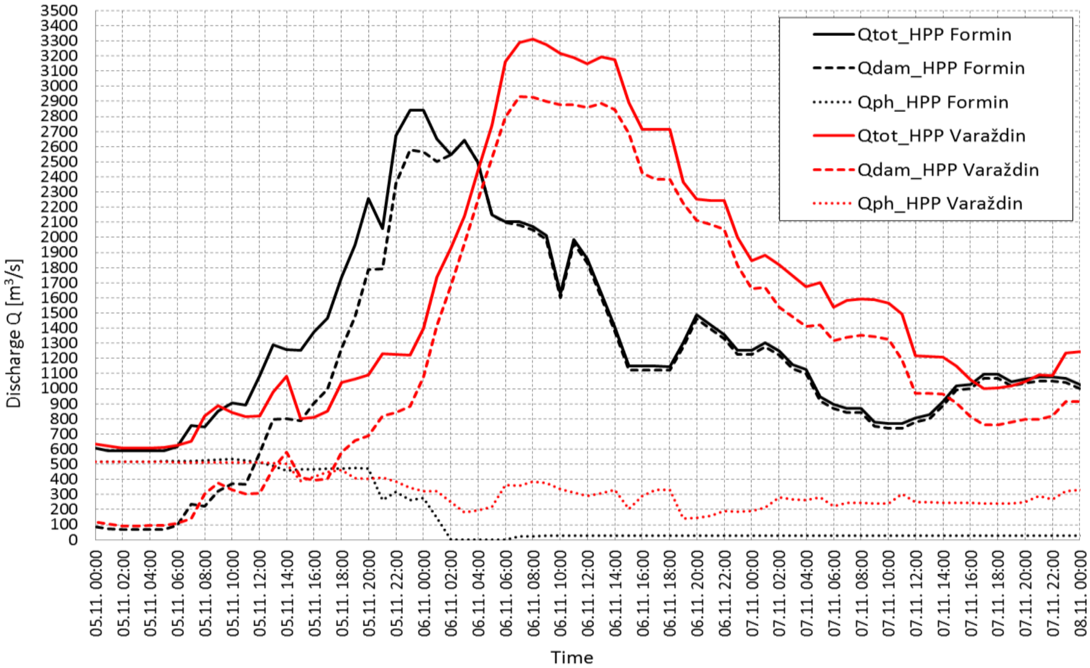


Fig. 9 Flow hydrographs on HPP Formin and HPP Varaždin on 5th November 2012

The discharge through the HPP Formin powerhouse (Q_{ph}) shows that on the 6th Nov between 00:00 and 02:00 hrs the powerhouse failure occurred. The failure is considered to be connected to the upstream levee breach of the HPP Formin outlet canal. The breach was located 1.3 km downstream from the powerhouse and caused backwater rising in the outlet canal and eventually the flooding of the powerhouse and the switchyard (**Fig. 7**).

On the 6th Nov, in the period from 02:00 to 06:00 hrs, an unexpected and an unnatural water level rising was recorded [2] on g.s. Ormož (**Fig. 11**). A 1.4 m water level on g.s. Ormož occurred at the time of the powerhouse failure, so the upstream levee breach of the outlet canal is most likely the main cause of the sudden water level rising.

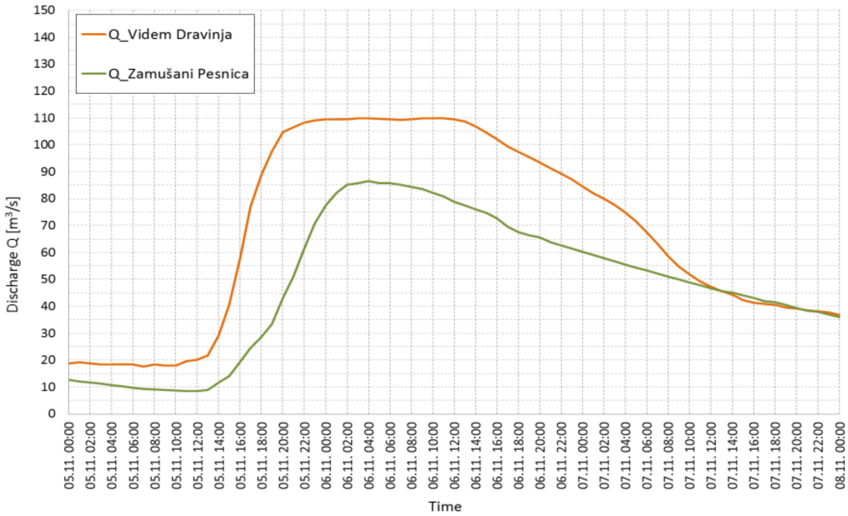


Fig. 10 Flow hydrographs of the Dravinja and the Pesnica stream during 5/Nov/2012

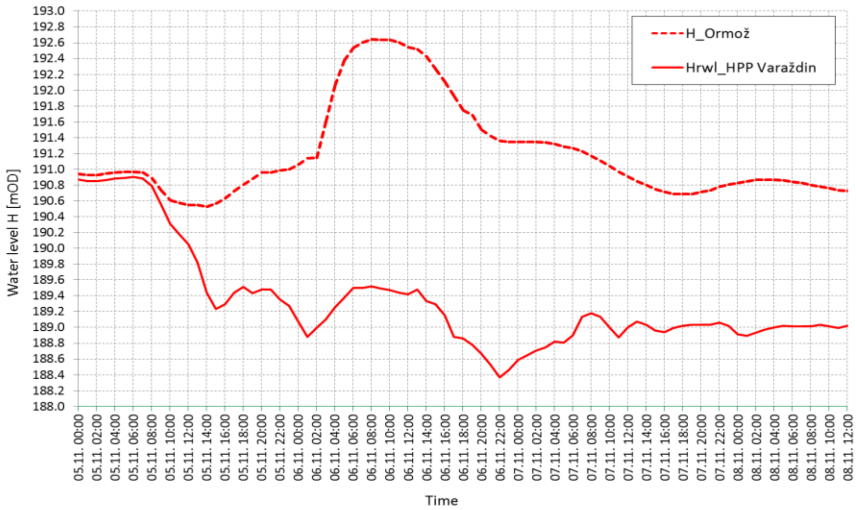


Fig. 11 Water levels on HPP Varaždin on 5th November 2012

4 HYDRAULIC ANALYSIS OF 5/NOV/2012 FLOOD WAVE

During the 5/Nov/2012 flood wave the levee of HPP Formin outlet canal was breached on two locations. The recorded hydrographs show that the two breaches of outlet canal caused the over-spilling of great amount of water from the River Drava’s old channel to the outlet canal, which resulted in flow acceleration, shorter flood wave duration together with sudden increase of water levels and discharges on the HPP Varaždin.

During the passage of the flood wave an over-spilling and breaching of the Virje Otok-Brezje levee also occurred. The exact time of the outlet canal breaches is not known. But it is known that the over-spilling of Virje Otok-Brezje levee began on the 6th Nov at 04:30 hrs and that the breach happened on the 6th Nov after 11:00 hrs.

The analysis of the 5/Nov/2012 hydrographs on the HPP Formin, HPP Varaždin and HPP Čakovec showed that the flood wave on HPP Varaždin was unnatural. The flood wave transformation between HPP Formin and HPP Varaždin is probably the consequence of the levee breaching of the outlet canal. As there was no data on the exact timing of the outlet canal levee breaching it was necessary to: (a) consider all possible causes of flow increase on HPP Varaždin, (b) verify credibility of discharge recordings on HPP Varaždin and (c) estimate over-spilling on the levee Virje Otok-Brezje. Due to the complexity of the river system and due to high flood damages, a detailed hydraulic analysis was performed by using a 2d hydrodynamic numerical model.

4.1 Development of the hydrodynamic model

For the purpose of the analysis of the 5/Nov/2012 flood wave transformation between HPP Formin and HPP Varaždin a 2d hydrodynamic model was developed by using the Delft3D software package (Deltares Systems). The hydrodynamic model was developed on the basis of the recent terrain and bathymetry surveys. The model comprised the River Drava's old channel between the HPP Formin dam and the HPP Varaždin reservoir, and also the HPP Formin outlet canal from the powerhouse to the confluence with the River Drava's old channel (**Fig. 12**). The model also included the Dravinja and Pesnica streams, as well as all line objects in the modelled area, such as roads and levees. The total length of the modelled area was 27+675 m.

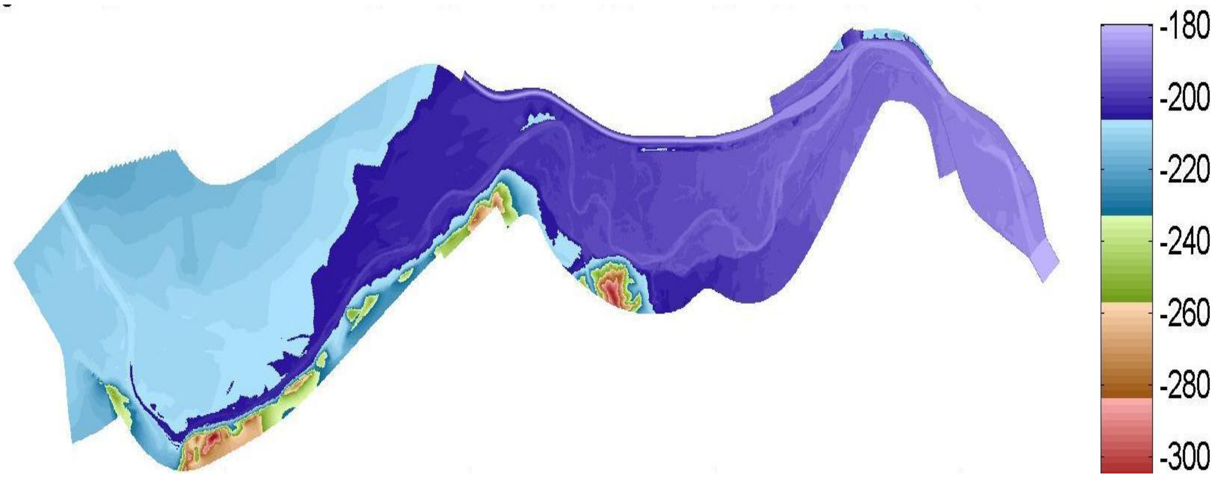


Fig. 12 Bathymetry of modelled area

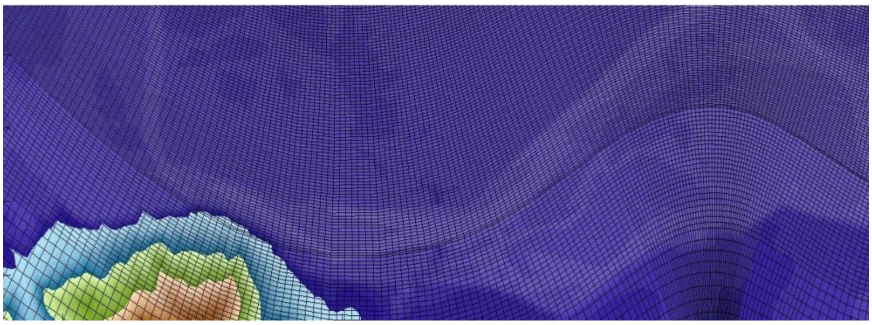


Fig. 13 Othogonal curvilinear grid of the model with bathymetry

The upstream open model boundaries are the dam and the powerhouse of the HPP Formin, which are both defined as a time-varying discharge. The downstream open model boundary is the upper water level at the HPP Varaždin dam, which was defined as a time-varying water level. The two tributaries, the Dravinja and Pesnica streams, are modelled as sources.

On the River Drava's old channel, from the HPP Varaždin dam to the HPP Formin dam, 41 no. control cross sections (P0-01 to P0-41) were set, together with 17 no. cross sections along the HPP Formin outlet canal from the restitution at the River Drava's old channel till the HPP Formin powerhouse (P1A-17 to P1A-34). The model control point was g.s. Ormož for which water level measurements were available.

The initial analysis for the discharges above 100 m^3/s showed that the measured discharges on g.s. Borl on the River Drava are higher than the combined discharges of the HPP Formin dam and the Dravinja stream. It was concluded that the stage-discharge curve for g.s. Borl should be improved especially for higher flow rates. As the stage-discharge curve needs more adjustments, the discharges at g.s. Borl were excluded as a model control point.

The model calibration was made for g.s. Ormož by comparing the recorded and the computed water levels for the flood event from the 18th Jun 2011 at 01:00 hrs until the 22nd Jun 2011 at 00:00 hrs. The differences between measurements and calculations for g.s. Ormož were between ±5 cm with the largest deviation of 9 cm (**Fig. 14a**).

The model parameters were verified for the flood event from the 17th Sept 2010 at 01:00 hrs untill the 21st Sep 2010 at 00:00 hrs. The differences between measured and calculated water levels on g.s. Ormož were between ±5 cm with the largest deviation of 7 cm (**Fig. 14b**).

(a) Model calibration results for 6/2011 (b) Model verification results for 9/2010

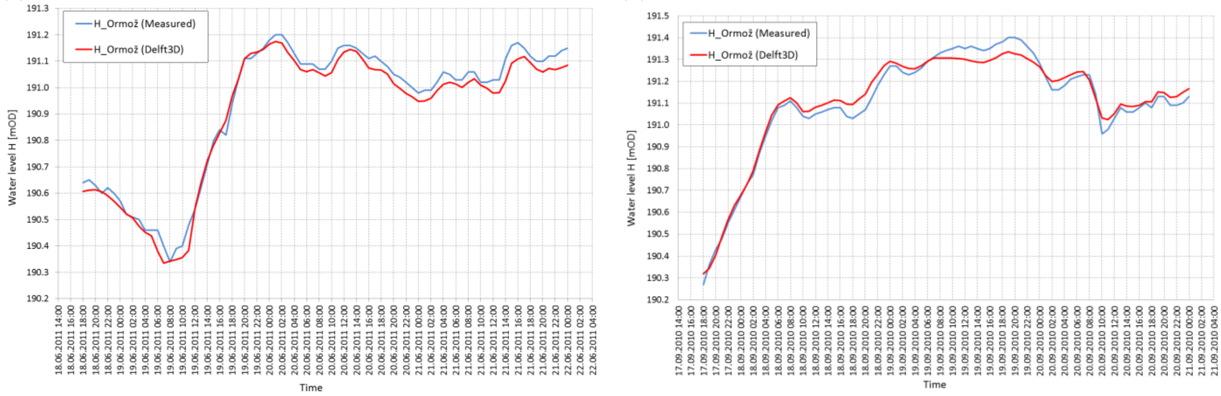


Fig. 14 Model calibration and verification results of water level on g.s. Ormož

The adopted Mannings roughness coefficients are as following: 0.027 $m^{-1/3}s$ for the River Drava's old channel from the HPP Formin dam to g.s. Borl, 0.026 $m^{-1/3}s$ for the River Drava's old channel from g.s. Borl to the HPP Varaždin dam, 0.180 $m^{-1/3}s$ for the woodland areas and 0.200 $m^{-1/3}s$ for the pasture areas.

4.2 Results of the model simulations

After the development and the calibration of the model several flood wave simulations were performed. The upstream open model boundaries were the recorded discharges of the HPP Formin dam and the powerhouse (**Fig. 9**), and the downstream boundary (Hrwl) were the recorded upper water levels of the HPP Varaždin dam (**Fig. 11**). The discharges of the Dravinja and Pesnica streams were also available (**Fig. 10**).

The specific objective of the hydraulic analysis was to determine the discharge through the HPP outlet canal as a result of embankment breaches and its impact on the measured discharges and water levels on g.s. Ormož. In order to obtain the timing and the peaking of the recorded water levels on g.s. Ormož the breaches of the HPP Formin outlet canal had to be included in the model. The breaches were modelled by the diverting of a provisional discharge from the overbank area of the River Drava (near the breach) into the outlet canal. In the simulations the following parameters were varied: the amount of flow diverted into the outlet canal, and the starting time of diversion (levee breaching) which was different for the upstream and the downstream breach. The model also enabled the free over-spilling of the Virje Otok-Brezje levee.

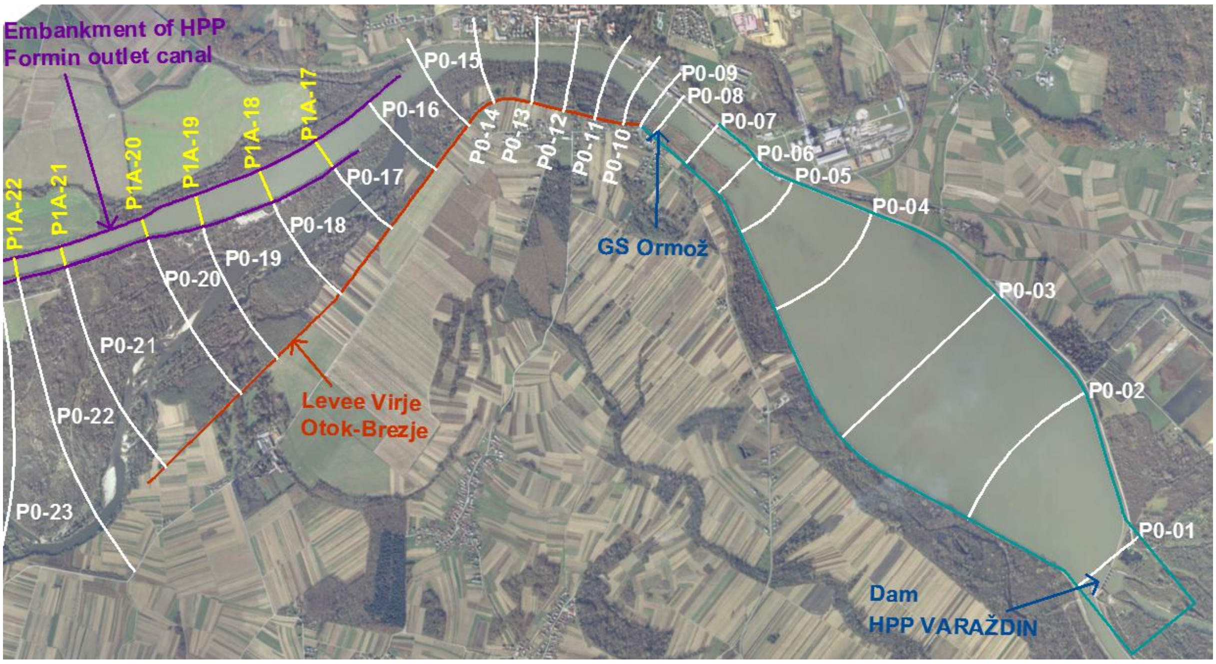


Fig. 15 Locations of control cross sections

Fig. 15 shows the locations of model control cross sections along the River Drava's old channel (P0-01 to P0-23) and along the HPP Formin outlet canal (P1A-17 to P1A-34). The most interesting cross sections on the River Drava's old channel are: cross section P0-17 located before HPP Formin outlet canal restitution into the River Drava's old channel, cross section P0-16 located after the restitution and cross section P0-08 at g.s. Ormož. The interesting cross section on the HPP Formin outlet canal is P1A-17 located before the canal restitution into the River Drava's old channel.

Fig. 16 shows measured and calculated water levels on g.s. Ormož for simulations A and B. The simulation A includes the levee breaches of the outlet canal and the simulation B is without the breaches.

The model results show that the deviations of the measured and calculated water levels for the simulation A (red solid line) are within 10 cm. The results of the simulation A are given until the 6th Nov at 11:00 hrs, after which the Virje Otok-Breze levee breach occurred. In this way another unknown element was avoided but the quality of the hydraulic analysis was retained because the peak flow on the HPP Varaždin occurred before 11:00 hrs.

The results for the simulation B show that for the case without levee breaches, the water level rising on the g.s. Ormož (red dashed line) is significantly slower and the peak computed water level is -60 cm lower than the highest recorded water level.

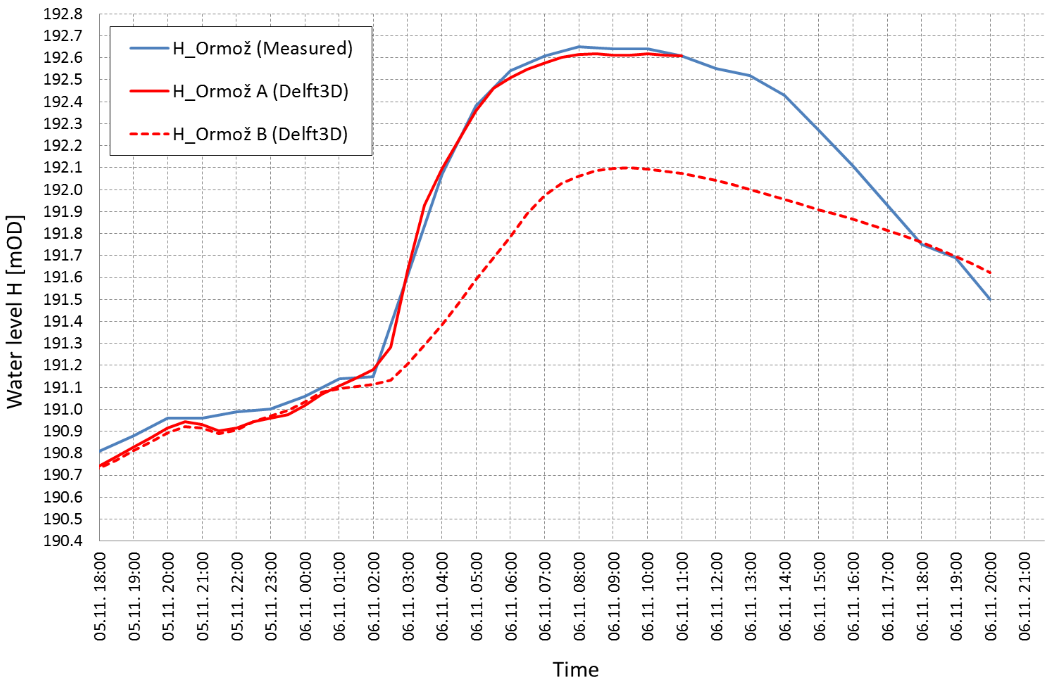
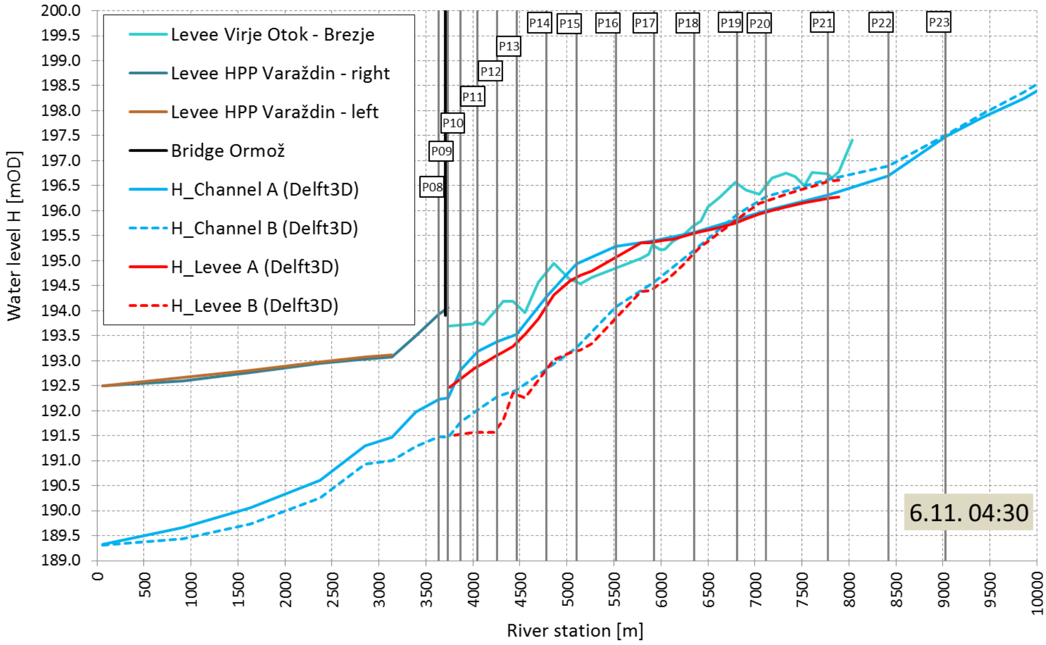


Fig. 16 Comparison of measured and computed water levels values on g.s. Ormož

The longitudinal water level profiles from simulations A and B are presented for two characteristic timings: for the beginning of over-spilling of the Virje Otok-Brezje levee on 6/Nov/2012 at 04:30 hrs (**Fig. 17a**) and for the peak flow on the HPP Varaždin on 6/Nov/2012 at 08:00 hrs (**Fig. 17b**). The computed water levels for simulation A show that over-spilling of the Virje Otok-Brezje levee begins at 04:30 hrs which fully corresponds to the actual event. At the time of the flow peaking on the HPP Varaždin, the over-spilling of the Virje Otok-Brezje levee occurs on a 1800 m long section between cross sections P0-14 and P0-19. This section has cca 50 cm higher flood levels than the levee crest levels (**Fig. 17b** and **Fig. 18**). The simulation B results show that the overtopping of the Virje Otok-Brezje levee is significantly lower in comparison to the simulation A.

The spatial views of flood extents are given for simulations A for the beginning of the over-spilling of the Virje Otok-Brezje levee (**Fig. 19a**) and for the peak flow on the HPP Varaždin (**Fig. 19b)**. On the longitudinal profiles the over-spilling of the Virje Otok-Brezje levee is visible at 04:30 hrs but on the flood extent it is visible at 05:00 hrs.

(a) 6/Nov, time 04:30 hrs, start of over-spilling of the Virje Otok-Brezje levee



(b) 6/Nov, time 08:00 hrs, time of peaking on HPP Varaždin

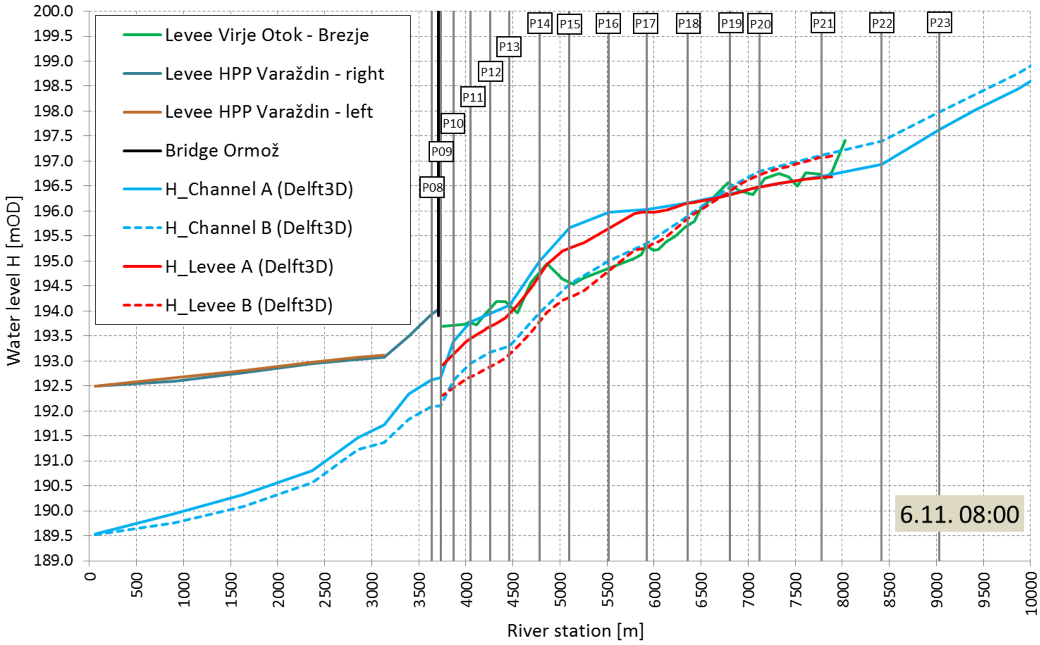
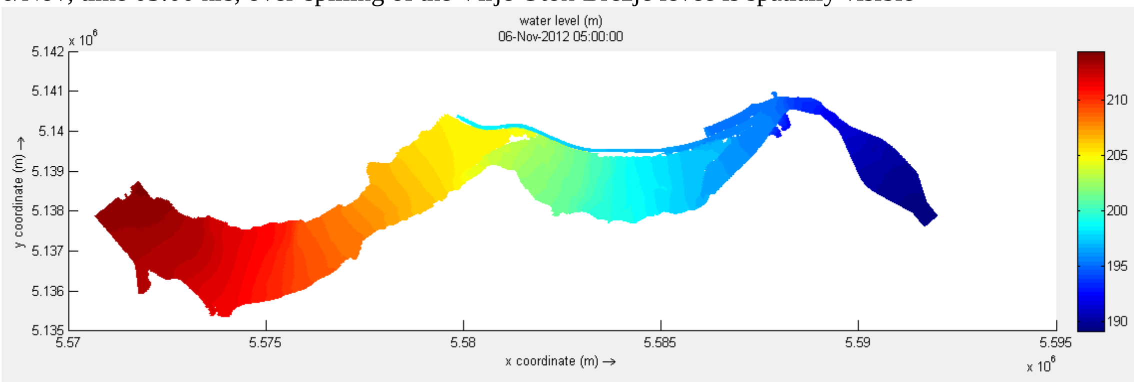


Fig. 17 Longitudinal profile of computed water levels from simulations A and B with levee crest level and locations of control cross sections

Fig. 18 Over-spilling of the Virje Otok-Brezje levee (time unknown, source Internet)

(a) 6/Nov, time 05:00 hrs, over-spilling of the Virje Otok-Brezje levee is spatially visible



(b) 6/Nov, time 08:00 hrs, time of flood wave peaking on the HPP Varaždin

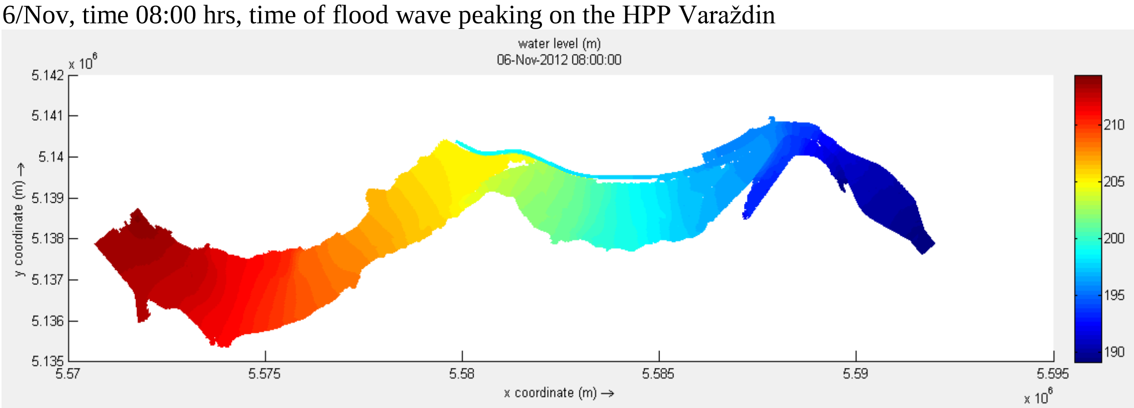


Fig. 19 Spatial view of computed water levels from simulation A

Fig. 20 shows the discharges on cross sections P0-17, P1A-17, P0-16 and P0-08 from simulation A (solid line) and from simulation B (dashed line). The measured peak flow on HPP Varaždin was 3311 m^3/s on the 6th Nov at 08:00 hrs. The peak flow on g.s. Ormož (P0-08) is 3335 m^3/s on the simulation A (6th Nov at 08:00 hrs), and is 2600 m^3/s on simulation B (6th Nov at 09:00 hrs). In order to achieve the measured water level on g.s. Ormož, the discharge separation at the peak is 2400 m^3/s through the HPP Formin outlet canal (P1A-17) and 1270 m^3/s through the River Drava's old channel (P0-17). At the peak flow the over-spilling of the Virje Otok-Brezje levee reaches a value of 520 m^3/s (**Fig. 21**).

The results for simulation B show that the over-topping of the outlet canal occurs in the downstream part even without levee breaching. The discharge separation at the peak is 400 m^3/s in outlet canal (P1A-17) and 2100 m^3/s through the River Drava's old channel (P0-17).

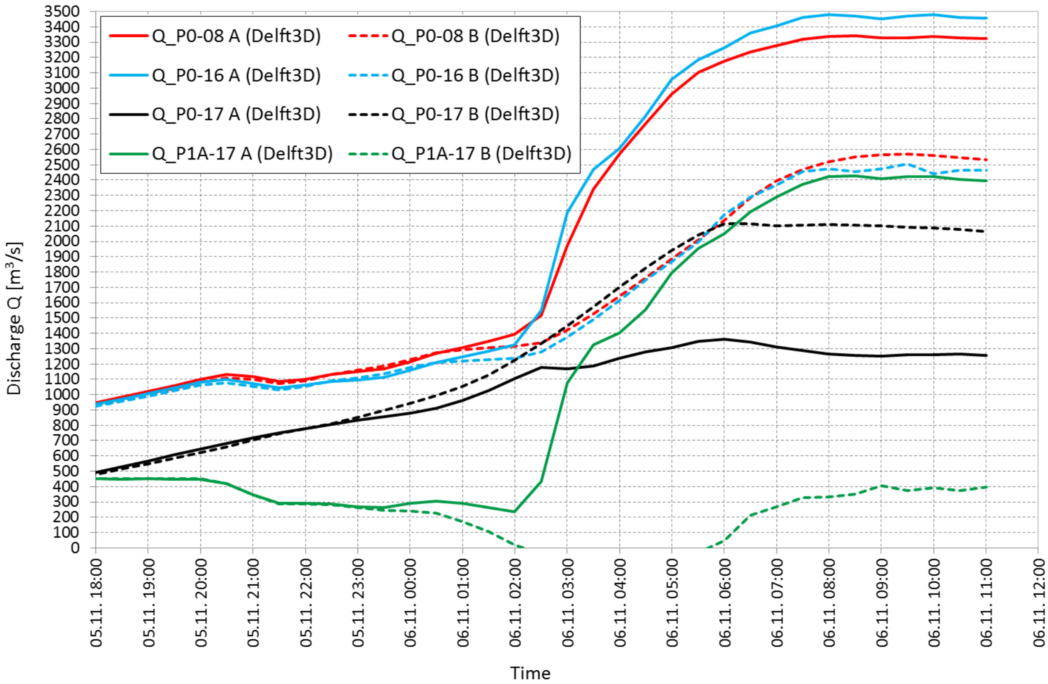


Fig. 20 Computed discharges at control cross sections

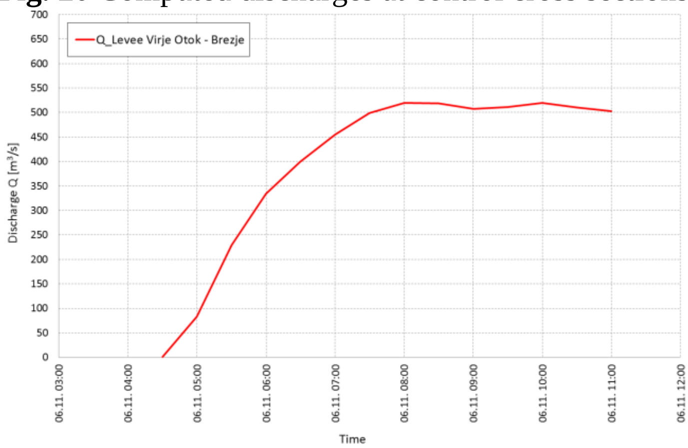


Fig. 21 Computed over-spilling over the Virje Otok-Brezje levee

5 CONCLUSIONS

The 5/Nov/2012 flood wave on the River Drava was the highest flood event in the last 60 years in the Croatian part of the river. The flood wave on g.s. Borl was between a 100 and a 1000 years return period when compared to the theoretical flood waves, but when compared to the estimates of total input flow rates this was a 200 years return period flood. The flow hydrographs on HPPs in Slovenia and Croatia showed an unexpected flood wave transformation in the area between the HPP Formin and the HPP Varaždin.

The levee breaches on the HPP Formin outlet canal caused the flow diversion from the River Drava’s old channel to the outlet canal. The mathematical simulations showed that that sudden increase of recorded water levels and discharges on the HPP Varaždin can only be a consequence of this levee breaching of the HPP Formin outlet canal. The sudden flow increase on HPP Varaždin was a result of the flow acceleration in the outlet canal and of the shorter flood wave duration. The flood wave propagation through the outlet canal was also the most likely cause of over-topping of the Virje Otok-Brezje levee, as the simulation B without breaches showed negligible over-spilling of the levee.

The case without breaches (simulation B) showed that over-spilling to the outlet canal occurs even without the levee breaches. Considering the damages to the flood protection systems and the surrounding areas, further considerations to the design of the HPP Formin outlet canal and the Virje Otok-Brezje levee are required.

On the 28 km long section of the River Drava’s old channel between HPP Formin and HPP Varaždin there are two critical subsections for flood wave propagation. The first subsection is near settlement Zavrč where the valley width is narrowed from 2300 m to 800 m. This is also the section of the upper breach of the outlet canal levee. The second critical subsection is just upstream of the Ormož bridge. The conveyance on this section is significantly reduced as the confluence of the HPP Formin outlet canal and the old river channel is located on the narrowest river channel width. The over-topping of the Virje Otok-Brezje levee occurred on this second critical section. In order to increase the level of flood protection of the area, additional measures for the enhancement of flood wave conveyance should be considered.

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