PROPAGATION OF 2012 FLOOD WAVE THROUGH HPP SYSTEM ON THE RIVER DRAVA

ABSTRACT

The flood wave on the River Drave in November 2012 produced an extensive flooding of neighbouring settlements and farm fields and property damages in Slovenia and Croatia. This extreme flood event was the highest in the last 60 years and has caused over-spilling of levees and breaching on several levee sections. This paper shows the results of the hydrological and hydraulic analysis of the flood wave propagation in Slovenia and Croatia. The hydrological analysis includes the flood flow transformation through the chain of HPPs. The detailed hydraulic analysis was performed on the section between HPP Formin and 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

INTRODUCTION

The flood wave on the River Drave from November 2012 compared to historical flood events was exceptional on several grounds. Considering the peak discharge of 3311 m³/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 m³/s on g.s. Varaždin. 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.

Fig. 1 Chain of HPPs on the River Drava in Austria, Slovenia and Croatia
Fig. 2 shows recorded hydrographs on HPP Labot in Austria, HPPs Vuhred, Ožbalt, Zlatoličje and Formin in Slovenia and also on HPPs Varaždin, Čakovec and Dubrava in Croatia during the 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.

![Fig. 2 Flood event Nov/2012 - Flow hydrographs on HPPs in Austria, Slovenia and Croatia](image)

The flow hydrographs show sudden, almost simultaneous flow increase on HPPs Labot, Vuhred, Ožbalt and Zlatoličje. While passing through the reservoir of HPP Formin the first transformation of flood wave occurred. 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.

**FLOOD WAVE IN THE AREA BETWEEN HPP FORMIN AND HPP VARAŽDIN**

![Fig. 3 The River Drava section between HPP Formin and HPP Varaždin](image)

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. 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].

The rate of the Nov/2012 flood wave onset can be seen when compared to the theoretical flood hydrographs (Fig. 4). 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. 4).

![Fig. 4 Comparison of theoretical and measured hydrographs of the River Drava on g.s. Borl](image)

During the 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. 5 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. 5 Upstream levee breach of HPP Formin outlet canal](image)

Hourly discharge recordings are shown for the dam and powerhouse of the HPP Formin and HPP Varaždin (Fig. 6) 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 m³/s and the Pesnica of 85 m³/s [3] were insufficient to provide the recorded flow increase of 471 m³/s on the HPP Varaždin.

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 (Fig. 5). On the 6th Nov, in the period from 02:00 to 06:00 hrs, an unexpected and unnatural water level rising was recorded [2] on g.s. Ormož. 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.

**HYDRAULIC ANALYSIS OF 2012 FLOOD WAVE**

The analysis of the Nov/2012 hydrographs on the HPP Formin, HPP Varaždin and HPP Čakovec showed that the flood wave on HPP Varaždin was unnatural. 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.

**Fig. 6 Flow hydrographs on HPP Formin and HPP Varaždin on 5th November 2012**

For the purpose of the analysis of the Nov/2012 flood wave transformation a 2d hydrodynamic model was developed in Delft3D package 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. 7). 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. 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.

The model was calibrated and validated by comparing the recorded and the computed water levels on g.s. Ormož for the flood events in 2010 and 2011. The differences between measurements and calculations for g.s. Ormož were between ±5 cm with the largest deviation of 9 cm (Fig. 8a).

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

Fig. 8 Model calibration and verification results of water level on g.s. Ormož

RESULTS OF THE MODEL SIMULATIONS

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. 9 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.

![Graph showing measured and computed water levels](image_url)

**Fig. 10** Comparison of measured and computed water levels values on g.s. Ormož

**Fig. 10** 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.

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-Breze levee on 6/Nov/2012 at 04:30 hrs (**Fig. 11a**) and for the peak flow on the HPP Varaždin on 6/Nov/2012 at 08:00 hrs (**Fig. 11b**). The computed water levels for simulation A show that over-spilling of the Virje Otok-Breze levee begins at 04:30 hrs which fully corresponds to the actual event. The simulation B results show that the overtopping of the Virje Otok-Breze levee is significantly lower in comparison to the simulation A.
(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. 11 Longitudinal profile of computed water levels from simulations A and B with levee crest level and locations of control cross sections

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. 12). 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.

Fig. 12 Spatial view of computed water levels from simulation A, time 6/Nov, time 05:00 hrs, over-spilling of the Virje Otok-Brezje levee is spatially visible
Fig. 13 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. 14).

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. 13 Computed discharges at control cross sections](image)

![Fig. 14 Computed over-spilling over the Virje Otok-Brezje levee](image)
CONCLUSIONS

The 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.

References