SIMULATION OF LEVEE BREACHES USING DELFT MODELS IN A CASE OF THE RIVER DRAVA

Igor Kerin
[1]University College Cork, ERI, MaREI, Beaufort Building, Haulbowline Rd, Ringaskiddy, Co. Cork, Ireland
igor.kerin@ucc.ie

Sanjay Giri
Deltares, Boussinesqweg 1, 2629 HV Delft, Netherlands
Sanjay.Giri@deltares.nl

Damir Bekić
[3]University of Zagreb, Faculty of Civil Engineering, Kaciceva 26, 10000 Zagreb, Croatia
damir.bekic@grad.hr

KEY WORDS

Hydraulic analysis, flood wave, hydrograph, Hydro Power Plant, outlet canal, levee, breach, 2d hydrodynamic model, computational speed, Real Time Control.

ABSTRACT

This paper focuses on the modelling of levee breaches by using Delft 3D model and a new Delft-FM model where Real Time Control module was used. The pilot study is placed on the bordering section of the River Drava between Slovenia and Croatia around the Hydro Power Plant Formin system. The major flood event on the River Drava in November 2012 caused significant damages in Slovenia and Croatia. During flood event, the levee breaches occurred at several locations around the HPP Formin system. Two different numerical models were developed to simulate propagation of the November 2012 flood event in order to replicate the corresponding water levels and flow rates on the complex river system of the HPP Formin. The Delft 3D and Delft FM models were developed as part of collaboration between University of Zagreb and Deltares in Delft-FM pilot cases. Delft-FM was also coupled with the Real Time Control module. The numerical model results were intercompared and also compared to the measured water levels and flow rates. The levees in the Delft FM model were defined as line elements with defined heghts of levee sill in order to reduce the number of grid cells, hence reducing the computational time. Real Time Control was used to lower levee sill heights at location of the levee breaches. In Delft 3D levees were modelled as part of bathymetry which was not changed at the time of breach. Delft-FM successfully confirmed the time of levee breaches. The utilization of a Real Time Control tool allowed the simulation of levee breaches in a more realistic way than in the Delft 3D model. The paper shows that the Delft FM simulations were up to 4 times slower than Delft 3D simulations for the same number of computational points. However, the unstructured grid model (flexible mesh) allows for a substational reduction of computational points on complex geometries. This resulted in 2 times faster computational time of Delft FM model when compared to Delft 3D model for the River Drava study while preserving the same accuracy and with improving the physics of the flood, time of the rise of the flood wave hydrograph and levee breach simulation.

1. INTRODUCTION

The Delft 3D Flexible Mesh Suite (Delta Shell GUI) is the successor of the structured Delft 3D 4.01 Suite. It consists of different modules that can simulate detailed flows and water levels, waves, sediment transport, morphology storm surges, huricanes, water quality and ecology, etc. and enables interaction between the described processes [1]. The key component of Delft3D FM is the D-Flow Flexible Mesh (in further text Delft-FM) engine for hydrodynamical simulations on unstructured grids in 1D-2D-3D [2,3]. Delft-FM is the result of five years of research funded by Deltares and the Dutch Ministry of Infrastructure and Environment which successed the Delft3D-FLOW and SOBEK-FLOW [1]. Delft-FM uses the curvilinear meshes and the unstructured mesh which can consist of triangles, pentagons (etc.) and 1D channel networks, all in one single mesh. In 2013, Deltares has introduced the concept of Delft-FM pilot cases to provide external users with the possibility to gain experience with the software. The software was tested by pilot users which gave an insight in the performance and accuracy of the software and pushed the developments of the software. As part of Delft Flexible Mesh (FM) pilot cases programme, a case study for the comparison of Delft 3D and Delft FM models was initiated for the pilot case Drava. Delft FM was coupled with a Real time control module which allows simulating complex real-time control of all hydraulic structures.

This paper shows the results and advantages of a new modelling functionalities integrated within the Delft FM. The extents of the numerical model(s) on the River Drava between HPP Formin Dam and HPP Varaždin Dam are shown in Figure 1. The system operates in a way that during low and mean flows the majority of flow is diverted to the powerhouse and through the derivation canal towards the HPP Varaždin system. During high flows the flow is diverted from the HPP Formin dam to the old river channel. The November 2012 flood event on the River Drava caused serious flooding in Slovenia and Croatia. During the 2012 flood event two significant levee breached of the HPP Formin derivation canal occurred, the upstream breach (L1) and the downstream breach (L2), as well as overspilling of the downstream levee Virje Otok – Brezje (L3), see Figure 1. The upstream breach (L1) was 150m wide and it caused extreme sediment deposition (up to 12m high) and 50m bank erosion of the derivation canal. The second breach (L2) was 200m wide and caused sediment deposition of approximately 300,000m^3 in the derivation canal. Due to levee breaches (L1, L2) two new channels were developed that directed part of floodplain flow to the derivation canal. The Virje Otok - Brezje levee (L3) started to overspill at the 4:30hrs on the 6th November 2012 and it consequently breached between 11:00 hours and 13 hours, causing a serious flooding between Otok Virje and Brezje villages. The hydrological analysis [4] showed that the November 2012 flood was between 1% and 0.1% AEP. The complexity of such flow pattern required a 2D hydrodynamic modelling approach and the Delft 3D model was developed [4].

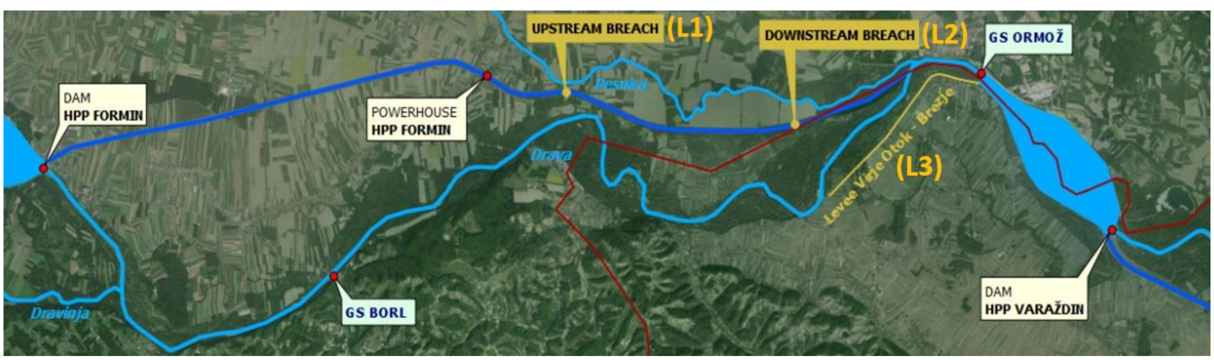

Figure 1: Case Study between the HPP Formin and the HPP Varaždin with locations of levee breaches of the derivation canal (L1 and L2) and “Virje Otok – Brezje” levee breach (L3).

2. METHODOLOGY

A test program has been made to compare the Delft 3D (finite difference) and the Delft FM (finite volume) models. The measured water levels and discharges are compared with (a) existing Delft 3D (D3D) model, (b) Delft-FM (D-FM1) model using existing mesh (Figure 2b), and (c) New Delft-FM (D-FM2) model using unstructured mesh (reducing the number of calculation points), see Figure 2c. The tasks of the pilot study were to:

1. Convert existing Delft 3D model (D3D) into Delft Flexible Mesh model (D-FM1) without changing mesh in Delft-FM. Calibrate and validate D-FM1 model.
2. Set-up of a new Delft-FM grid (D-FM2) and apply the advantages of the new software (Real Time Control and 1D elements). Calibrate and validate D-FM2 model.
3. Compare results (output results and computation time) of all existing models with measured data (discharges and water levels) for three recorded hydrological flood events
4. Test and use the new graphical user interface (RGFGRID + Delta Shell),report and log any bugs

The model inputs are recorded data of hourly water levels and discharges from the available rating curves. The Delft 3D model was calibrated and verified for the two flood events in 2010 and 2011 respectively with satisfied accuracy of ±0.15m when compared to the measured water levels. The Delft-FM models inherited the same bathymetry and bed roughness values from Delft 3D model. The Delft-FM model results for 2010 and 2011 flood event showed ±0.10m differences in water levels when compared to Delft 3D model. Delft-FM2 showed better match with Delft 3D and recorded data than Delft-FM1.

As the calibration and verification results of the new Delft FM model were satisfactory, further analysis was conducted. The major flood event in November 2012 was simulated in which several levee breaches occurred. The modelling of levee breaches in a "realistic way" was a particular challenge. The Delft 3D model does not have special features (such as 1D longitudinal elements) so the levees were modelled as part of bathymetry. No changes in geometry over time applied in D3D model. The levee breaches in D3D model were simulated by extracting discharge from the floodplains and adding the estimated discharges in the HPP Formin derivation canal (simulation A). Unlike in the Delft 3D, the levees within the Delft FM are represented by using 1D longitudinal elements, allowing simulation of levee breaches in a more realistic way with the utilization of a Real Time Control (simulation "dike breach"). An explanation of simulations A, B together with the "dike breach" simulation and the model set-up are given in the following chapter.

3. MODEL SET-UP

The numerical models comprised the River Drava natural channel and floodplans, the derivation canal of the HPP Formin (parallel to the natural channel), the levees of the natural river channel and of the derivation canal and the reservoir of the HPP Varaždin (Figure 1 and Figure 2a). In simulation "A" the levee breaches of the HPP outlet canal (L1+L2) was simulated by their effect on discharge distribution between the main river channel and the outlet canal. The discharge at the HPP Formin Powerhouse (upstream boundary condition) Q is a sum of flow through powerhouse $Q_{Powerhouse}$ and the extracted discharge from the main channel Q_e ($Q = Q_{Powerhouse} + Q_e$), see Figure 1. In simulations "A" it is assumed that the HPP Formin Powerhous was working with its full capacity ($Q_{Powerhouse} = 500m^3/s$), although the official data indicate that the discharge from the Power house was $0m^3/s$ after 6^{th} November 2012 2:00 hours. In simulations "B" the levee breaches were not simulated and recordings were used as the model upstream/downstream boundary condition. Simulation "dike breach" is using Real Time Control for changes of levee elevation at the sections of recorded breaches. Similar as in simulations "A", it was assumed that the HPP Formin Powerhouse was working with its full capacity ($Q_{Powerhouse} = 500m^3/s$). The modelled change of levee still heights over time is shown in Figure 4. The Virje Otok – Brezje levee (L3) started to overspill on 6^{th} Nov 2012 at 4:30 and the breach occurred between 11:00 and 13:00 hours (Figure 1).

A comparison of applied model set-ups is shown in Table 2. The main difference is geometry set-up: mesh type (structured or unstructured), number of computational points, utilisation of 1D elements (thin dams/weirs). In all Delft 3D and Delft-FM simulations, the four upstream boundary conditions were defined as flow boundaries with recorded hourly discharges at: HPP Formin Dam (UBC1); HPP Formin Power House (UBC2); Dravinja - the right tributary (UBC3); and Pesnica - the left tributary (UBC4). The downstream boundary condition is defined as the upper water level of HPP Varaždin dam (DBC). The bathymetry and bed roughness values were ovetaken from the Delft 3D model. The full description of the Delft 3D model set-up and the results for the November 2012 flood event is explained in [4]. The hourly water level recordings from two hydrometric stations (HS Borl and HS Ormož) were used as control points for simulations. The timing of the outlet canal breaches (L1 and L2) were confirmed in the models. The timing of the breach (L1) is the 6th Nov 2012 at 02:00 and time of breach (L2) is the 6th Nov 2012 at 04:00, see Figure 4. Modelling of the breaches included testing of simulations "A", "B" and "dike breach". In the simulations "A", part of the discharge Q_e is extracted from main channel and diverted into the outlet canal. To model discharge extraction the sink element was used in Delft 3D (D3D) and the pump element in Delft FM (D-FM).

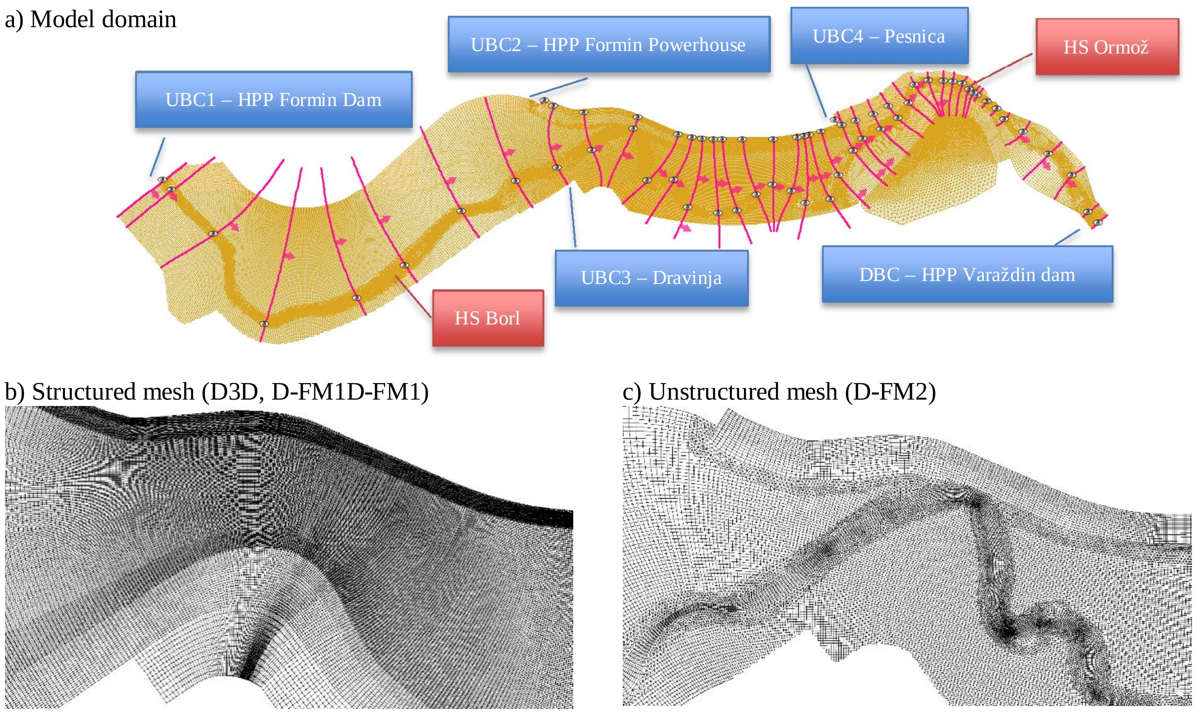

Figure 2: Model extents and mesh: a) Model domain with bathymetry; b) Close view of structured mesh used for D3D (finite difference) and D-FM1 (finite volume) models; and c) Close view of unstructured mesh used for D-FM2 model (finite volume).

Model	D3D	D-FM1	D-FM2
Method	Finite differences	Finite volumes	Finite volumes
Grid type	Structured	Unstructured	Unstructured
Noumber of net nodes	331,082	331,082	84,300
Number of net links	660,523	660,523	177,659
Use of 1D elements (Thin dams/weirs, pumps, etc.)	No	No	Yes
Maximum orthogonality	0.35 (poor)	0.35 (poor)	0.014 (good)
General smoothness	1 (good)	1 (good)	1 (good)
Maximum local smoothness	8 (poor)	8 (poor)	10 (poor)
Time Control	No	No	Yes
Roughness	Same distribution		
Simulation start (day month year hour)	4th Nov 2012 0:00	4th Nov 2012 0:00	4th Nov 2012 0:00
Simulation time (hours)	50	50	50
Courant	-	0.7	0.7
Time step, Δt (s)	7.5	Restricted by Courant	
Simulation type	A, B	A	A, B, dike breach

Table 1: Comparison of model set-up.

3.1 New functionalities of Delta Shell

New Delta Shell GUI simplified and improved model set-up (boundary conditions, roughness, bathymetry and definition of levees and groynes). It is possible to make changes of bathymetry and roughness directly from the model, see Figure 3. Existing values for roughness (Manning) and bathymetry elevations can be overridden by changing values in a single cell or by defining the polygons with constant or gradiant values. Polygons can overlap and the order of the polygons dictates which polygon is used as input. The model takes the value from the last defined polygon (the bottom one) for the calculations, see Figure 3. This way of modifying of the input data directly from the model calibration and verification process is more user friendly. It saves enginners time and allows to focus more on the improvement of the input data instead on techniques how to drag the input data intop the model.

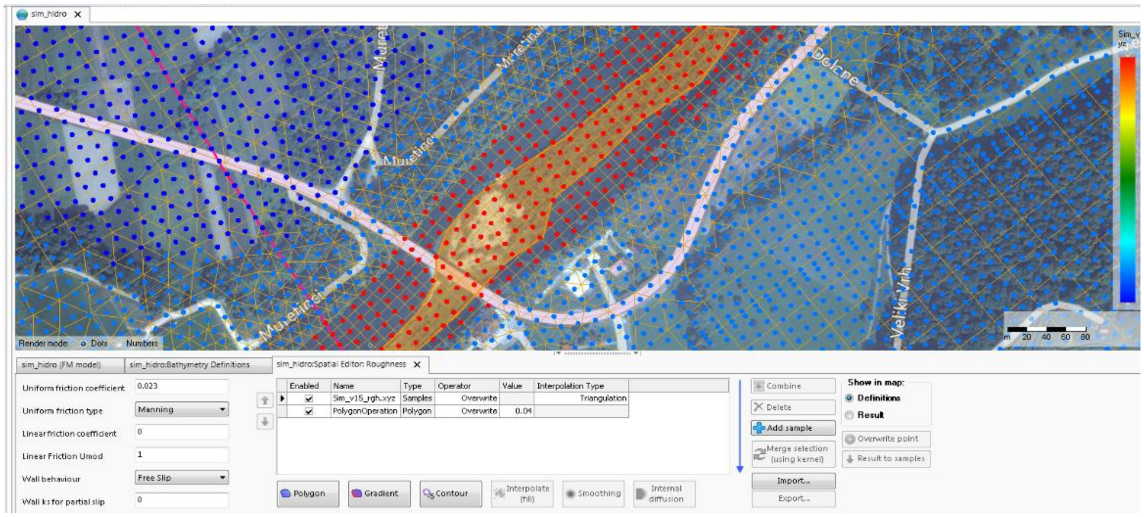

Figure 3: Modifying the local roughness from Delta Shell GUI.

Furthermore, levees, groynes and weirs can now be modelled using 1D elements called "weirs". In this way number of computational points can be significantly reduced while the levee definition remains detailed. The levee geometry (elevations) can be manipulated using Real Time Control within the simulation, enabling simulation of levee breach. The weirs are defined as polylines with defined sill heights. The best modelling practice suggests splitting the single line of a levee into part that is supposed to be lowered, e.g. will breach during the simulation and parts for which levee sill heights are unchanged during the simulation. The sill height is changed only at the breach location. Real Time Control of the sill heights requires definition of two ASCII files which are shown in Table 1. The first file ("breach1.pli") provides coordinates of a polyline near the defined line of breached levee. The structure of the file is following: first row gives a name of a polygon, second row gives number of rows "i" and colums "j" respectively. The following "i" number of rows define X and Y coordinates of a polyline. All values are "tab separated". The second file "breach.tim" is a time series of a sill heights. Each row consists of a tme step and corresponding sill height. Time steps are defined in minutes from the reference date and time. All values are "space separated". Figure 4 shows the levee sill heights timeseries used in simulating the levee breaches (L1), (L2) and (L3).

a) Polygon coordinates file: "breach.pli"		b) Time series file: "breach.tim"	
X – coordinate [m]	Y – Coordinate [m]	Time step	Sill heigh [m n.J.m.]
S1		0.0	204.29
5	2	3000.	204.29
5580425.3000	5140007.4400	3005.	199.0
5581168.8428	5140048.0647	999999.	190.0
5581417.7029	5140049.1662		
5581743.5000	5139970.5800		
5582864.7250	5139523.4550		

Table 2: Structure of ASCII files for the Real Time Control of levee sill heights for breach (L1).

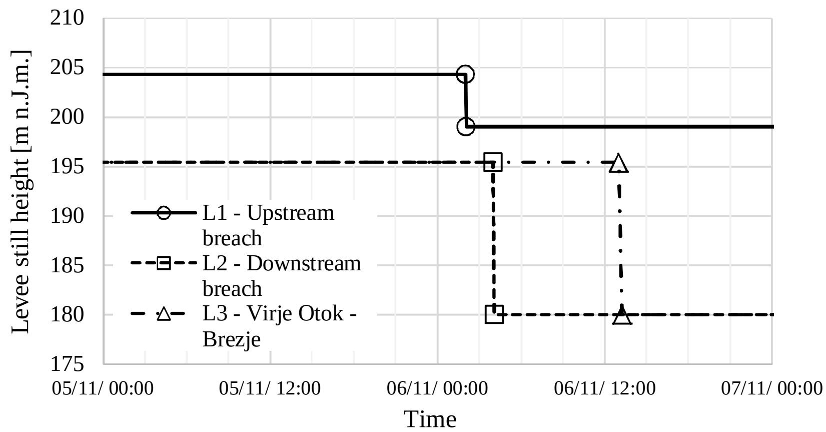

Figure 4: Timeseries of levee sill height in Real Time Control module in simulations "dike breach".

4. RESULTS AND DISCUSSION

Water level results from simulations "A", "B" and "dike breach" for three models D3D, D-FM1 and D-FM2 are shown in Figure 5. Simulations "A" for all three models show the best fit with the recorded water levels at HS Ormož. Simulations "B" indicate that the levee breaches had a significant effect on the particular flood event and that with recorded discharges / water levels it is not possible to compute the recorded water levels at HS Ormož. There is a high difference in peak discharge between in simulations A (3341m^3/s) and simulations B (2580m^3/s), see Figure 5. The difference in the peak discharge is 761m^3/s. Part of the difference can be explained that the power plant was operating at its full capacity $Q_{Powerhouse}$ = 500m^3/s. Excess of the additional 261m^3/s can be explained that the rating curves at the HPP Formin Dam for high water levels are inaccurate due to lack of significant flood events. Secondly, more interesting explanation is that significant accumulation of the volume of water occurred upstream of the location of the breach L1, causing increase of the flow. The above assumptions were tried to replicate using Delft FM functionalities (1D elements and Real Time Control) in the simulations "dike breach". Simulation "dike breach" partially replicated this by: defining the road embankments on the left overbank of the Drava old channel, by lowering the bathymetry upstream of the (L1) breach and simulating the breach of the road embankment. The desired increase of the discharge on HS Ormož was not noted. The simulations showed how Real Time Control for changing the levee elevation successfully improves the rise of the hydrograph. However, even if assuming that the HPP Powerhouse was working with full capacity, the peak flows of 3300m^3/s at HS Ormož cannot be computed. The effect of the accumulation of the water was not simulated successfully and it was not proven within the model. The simulation successfully replicated time of start of over-spilling the Virje Otok – Brezje levee overspill (L3) with a start of the overspill at 6th November 2012 at 4:30 hours. The comparison of measured and computed water levels and along the levee Virje Otok – Brezje at start of overspill is shown in Figure 6.

A comparison of model computational speed (table 3) indicates that for the same number of computational points simulations D-FM1 (finite volumes) are up to 4.0 times slower than D3D (finite differences). By using functionalities of Delft FM it is shown that number of computational points can be significantly reduced. As a result, D-FM2 simulations show that the Delft FM has from 2.3 to 2.5 times faster computational time than Delft 3D. All simulations were conducted on the PC with following configuration: Intel(R) Core (TM) i5-2500 CPU @ 3.30GHz, 4GB RAM and 64-bit Windows 7 OS.

Model type	D3D_A	D-FM1_A	D-FM2_B	D-FM2_dike breach
Simulation time (hours)	50	50	50	50
CPU time (hours)	10.020	36.850	3.983	4.100
CPU compared to D3D	n/a	4.0x slower	**2.5x faster**	**2.3x faster**

Table 3: Comparison of model computational speed.

a) Water levels at HS Ormož b) Discharges at HS Ormož

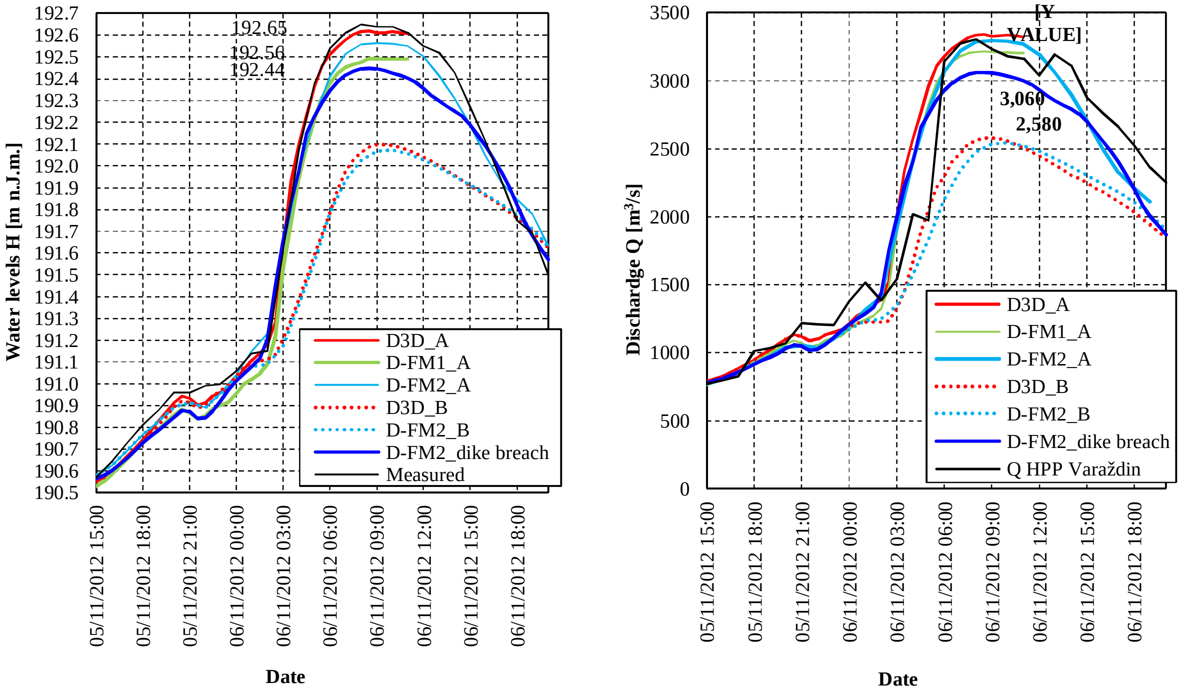

Figure 5: Comparisson of measured and computed water levels and discharges at Ormož for the 5th Nov 2012 flood event. The recorded discharges at b) are recorded discharges downstream of HS Ormož, at the HPP Varaždin dam.

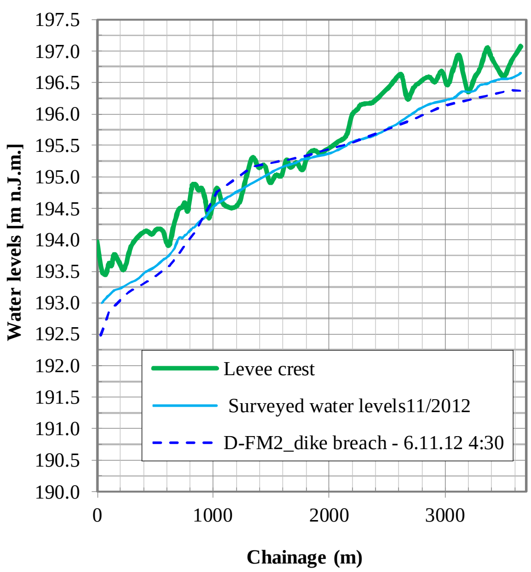

Figure 6: Comparison of measured and computed water levels along the Virje Otok – Brezje levee at the beginning of overspill at 6th Nov 2012 4:30 hours

5. CONCLUSIONS

Two dimensional models Delft 3D and Delft FM were developed to replicate and understand propagation of the November 2012 flood event on the HPP Formin system. The Delft FM and its Delta Shell GUI were in the user testing phase. The utilisation of Delft FM model showed that at HS Ormož rising stage of hydrograph shows good match with the observations and that peak water levels and discharges are closer to the observation. Time of levee breach (L1) (L2) (L3) was replicated satisfactorily using Real Time Control. Start time of levee Virje Otok – Brezje (L3) over-spilling has been replicated very well. A comparison of 2012 flood with breach model reveals reasonable match at Virje Otok – Brezje longitudinal profile (Figure 6). The peak discharge could be reached only if (a) we assume that the HPP Powerhouse was fully opened with discharge over 500 m^3/s (520 m^3/s is the maximum value); (b) we assume that during the 2012 flood, significant volume of water accumulated (clogged) on left floodplain upstream of the breach (L1). This accumulation was the source of additional flow, which rapidly entered into the HPP canal (causing large floodplain erosion and dike breach). This appears to have led to an unexpected rise of the peak in the canal and downstream of the main river channel.

Drava pilot study showed that:

1. Grid flexibility in D-FM allows significant reduction of grid numbers, particularly in case the model domain is complex like in current study.
2. Schematization of weirs with Time Control option allows to simulate levee breach more realistically.
3. Computational time of Delft FM seems to be higher due to local fine grid and high velocities (as the time step is computed in D-FM based on CFL condition).
4. Delft FM is a powerful and user friendly (simple to model) software. New Delta Shell GUI simplified and improved the model set-up (boundary conditions, roughness, bathymetry, etc.)
5. Post processing tool could be improved to allow more output options.

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