Numerical modelling of flash flood event in steep river using Telemac 2D and Sisyphe

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Abstract— **Extreme weather events, natural disasters as well as failure of climate change mitigation and adaptation are the risks with the highest likelihood of occurrence and largest global impact. Historically, the attention has been on floods in the larger, slow responding watercourses. Due to a changing climate, it is both expected and experienced more frequent and more extreme rainfalls, creating violent flash floods in small catchments. In steep rivers, this induces rapid changing discharges and large water forces resulting in erosion and rivers taking new courses, destroying communities and threatening livelihoods and live. Municipalities are responsible for mapping the risks natural hazards induce. When it comes to the risks due to floods in steep rivers, there is still a lack of approach and methodologies to handle their analysis. For mapping of such an event, the identification of critical points where the water can find the way from the river channel due to erosion and sedimentation is important. Therefore, the methodology has to include sediment transport and bed evolution in the river channel and the inundation area of the flood.**

In this study, the flooding of Utvik (western Norway) in July 2017 is reconstructed using TELEMAC – MASCARET numerical simulating software. The longitudinal slope of the river in Utvik is ca. from 3 to 17 %. A 2D numerical model of Utvik was built. The proposed solution consists of hydrodynamic simulation carried out in Telemac 2D and morphodynamic simulation (i.e. including bedload transport and bed evolution) using coupling of Telemac 2D and Sisyphe. Instabilities in bed evolution were observed in the river channel with steep longitudinal slope and steep river banks. To avoid the instabilities, non-erodible bed was set-up in the river channel in the final morphodynamic simulation. The results of the simulations were compared with the documentation of the flood event.

I. INTRODUCTION

The extend and potential consequences of floods in large water courses are in most cases in Norway well mapped [1]. Here the flood risks are related to inundation which have been mapped using hydraulic routing of the floods of different return periods. The risks in small and steep catchment are not that well mapped. Flash floods in such catchments occur due to heavy rainfall and are characterized by fast process (i.e. flooding starts after 6 hours of rainfall) [2]. Therefore, the faster response and the forces due to high water velocities induces another risk dimension that is significantly more challenging to handle. Municipalities in Norway deal with flash flood events caused by heavy rain [3], [4]. Therefore, there is an urgent need to develop methodologies to estimate the risk level and find mitigation measures also in these water courses.

Two-dimensional (2D) numerical simulations are nowadays an important tool for modelling and mapping floods in general. Most of these models consist of the resolution of Shallow Water Equations (SWE) [5]. There are several commercial, free ware and open source software, that could be used to carry out these simulations (e.g. MIKE, HEC-RAS, TELEMAC-MASCARET, Basement, etc.). In order to reconstruct flash flood events similar to the one that took place in Utvik (western Norway) in July 2017, it is important to simulate morphodynamically and to include the effect of erosion and deposition to the flood's study. Morphodynamic simulation consists of a hydrodynamic part as well as sediment transport and river's bed evolution [6]. Coarse sediment, boulders and rocks are located in the river bed and the slope of the river channel in Utvik is considered steep (ca. 3-17%).

There are some studies regarding hydrodynamic simulations of flash floods and flow in steep slopes using SWE. In [7], hydrological and hydraulic simulation of flash flood event in small ungauged steep catchment. Hydraulic simulation adequately reproduced the flood event. However, the domain is in the urban area without any sediment transport included.

Several configurations of 2D DIVAST model were tested on idealized valley with steep slope and on real flash flood event in [8]. The authors recommend to use shock-capturing schemes in the simulations of flow in the longitudinal slopes greater than 1%.

Dam [9] also performed 2D morphodynamic simulation of Utvik's flood event. FINEL2D model was used to carry out hydrodynamic and morphodynamic simulation. The results of bed evolution match well with the documentation of real flood even though notably finer sediment diameters than observed in the area were set-up in the model. Except this study, no application of any SWE model to flash flood in steep river similar to the one in Utvik has been found.

The goal of this study is to examine the critical points in the river channel during this recent flash flood. In this study, critical points are spots where water could find the way out from the river channel, which could be caused by erosion and deposition of sediments. A 2D numerical model of Utvik was built and the flood event was reconstructed. The proposed solution consists of hydrodynamic and morphodynamic simulation (i.e. including sediment transport and river's bed evolution). Results of the simulation were compared with documentation of the event [4], [10], [11].

TELEMAC – MASCARET ("Telemac" hereafter) was selected as a suitable tool to carry out the 2D morphodynamic simulations. However using of Telemac for simulations of sediment transport was validated against laboratory experiments and study cases with gentle slope [12]. Hence, the goal of this study is also to evaluate suitability of the model to simulation of flash flood in steep rivers (i.e. longitudinal slope greater than 3%).

II. STUDY AREA

The study area is located in Utvik in Sogn og Fjordane (western Norway). On 24th July 2017, the most recent flash flood due to highly concentrated heavy rain took place in the municipality of Utvik. The research performed in this study is focused on Storelva river; the catchment of this river is displayed in dark blue color in Figure 1. Area of the catchment is ca. 25 km^2.

As shown in Figure 2, the river made new flow paths due to a combination of rising water levels, water velocities, and the following erosion and bed evolution. During its channel migration, the large amount of wood and coarse sediment as well as rapid water flow, incremented by the steep downhill slope, triggered the breach of key connecting infrastructure (e.g. bridges and roads)) and an increased consequent damage to neighboring property on the river's way to the fjord. Therefore, it is evident that a complementary morphodynamic simulation should be carried out in this case.

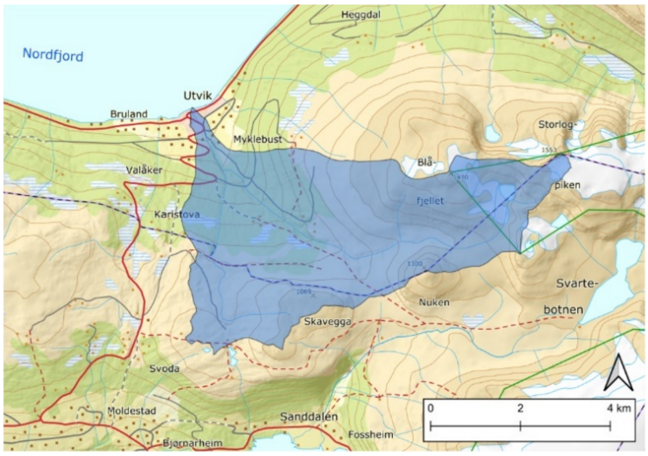

Figure 1 Storelva catchment in Utvik (Geonorge 2018), (NVE 2018a).

Figure 2. Aerial view of Utvik flood event from the fjord [4], with original river thalweg (blue line) and bridges.

III. METHODS

A. *Data for numerical model*

The data used to build the numerical models consist of: pre-flood event Digital Elevation Model (DEM) with grid size 0.5 m [11]; post-flood event DEM created in 2017 with grid size 0.25 m [11]; orthophoto map and geometry of buildings and roads [13]; flow hydrograph [10]; measurement of bridge opening dimensions (measured in the field by O. Bruland); photo and video documentation of flood event in Utvik (taken by O. Bruland); [4].

B. *Model description*

Version v7p3 of Telemac was used to perform the simulations. BlueKenue, FUDAA, HEC-RAS, ParaView and QGIS were used for pre- and post- processing.

In particular, Telemac's 2D module was used to run 2D hydrodynamic simulations in the horizontal plane. The code solves Saint-Venant (shallow water) equations in non-conservative form. The result is the water depth and two velocity components in each point of the computational mesh. Finite element or finite volume method can be chosen as resolution method. In addition, the module includes the solution of flow through structures in the river channel (e.g. bridges, weirs, etc.). Further description of theory can be seen in [14] and [15].

Regarding the morphodynamic simulations (i.e. sediment transport and river's bed evolution; see further description in section D), Sisyphe module was used. The morphodynamic simulation consists of i) hydrodynamic solution (see section C), ii) sediment transport (i.e.bedload and suspended load) and iii) river's bed evolution (see section D for the latter two). This software offers several formulas available for sediment transport and the module solves river's bed evolution with the sediment mass conservation equation (Exner equation). The module is applicable to either uniform/non-uniform, cohesive/non-cohesive sediments. Second currents and effect of bed's slope associated with the influence of gravity can be included. Also, vertical stratification of sediments and non-erodible river's bed is possible to set up in the model [6].

C. Hydrodynamic simulation

Input data of the model are listed in the previous section (see section A). By discretization, the computational domain was divided into mesh elements in BlueKenue (see Figure 3), which uses triangular shapes for these. The mesh elements had a size of 20 m in the fjord, 2 m in the river channel and of 3 m in the rest of the domain. Buildings were set-up as holes in the mesh so there is no flow through them. Roads and river banks were set up as break lines in the mesh (i.e. the edges of mesh elements lie on the break lines). The mesh contains ca. 70,000 elements and 36,000 nodes.

Flow through bridges can be simulated by modification of the terrain (i.e. adding bridge abutments to DEM). But this way does not include overflowed bridges. When flow over the bridge deck is desired, the bridges are treated as couples of points with flow between them. The discharge through the bridge is a function of water level in the points [15], this option was used in the simulations. Mesh size was refined (i.e. 1.0 m, see Figure 3) in the inflow and outflow bridge points, in order to create representative cross sections around the bridges.

A flow hydrograph (Figure 4) of Utvik's flood event was assigned as the inflow open boundary condition. There is no continuous discharge measurement in Storelva in Utvik. The flow hydrograph is reconstructed based on observation carried out during the event and the maximum discharge is estimated based on posterior measurements of flood level over a dam crest [10]. 30 m long artificial reach of the channel with mild slope was created by modification of DEM downstream the inflow boundary condition to avoid supercritical flow on the boundary. Constant water surface elevation 0 m a.s.l. was attached to the outflow open boundary condition. The rest of the boundary is closed (wall). The result of a steady flow simulation with an inflow discharge of 0.5 m^3/s was used as initial condition for subsequent unsteady simulations.

The domain was divided into polygons according to the type of surface, hence, different values of Manning roughness coefficient were assigned: 0.045 for the river channel and the fjord bed, 0.025 for the roads, and 0.100 for the rest of the domain.

Figure 3. Example of the mesh (cell size is 2 m in the river channel and 3 m in the rest of the domain). Buildings are cropped out of the mesh.

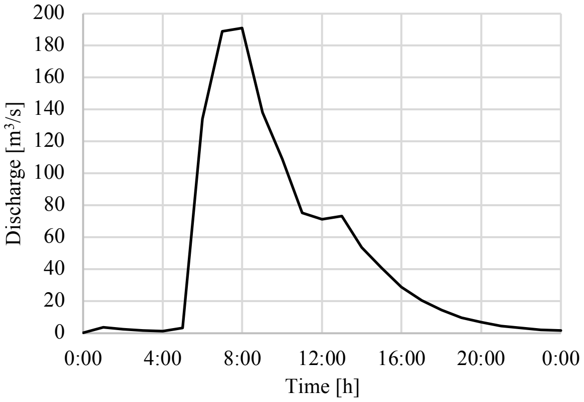

Figure 4. Flow hydrograph of Utvik's flood [10]

Time step was computed according to the value of Courant number (Cu = 1.0). Duration of the simulation was 23 hours.

Finite elements and finite volumes methods were tested for resolution of the governing equations. It is possible to use HLLC (Harten Lax Leer-Contact) shock-capturing scheme within finite volumes method [16]. Eventually, finite elements method was used for all the simulations, due to the equivalent results of both methods and shorter execution time.

Constant viscosity turbulent model was assumed.

D. Morphodynamic simulation

Once hydrodynamic simulation is fully developed, Telemac 2D could be coupled with Sisyphe to carry out the morphodynamic simulation. Sisyphe was fully coupled with Telemac 2D. For initial simulation set-up, mesh size 20 m in fjord and 1 m in the river channel and the rest of the domain was set-up. Uniform sediment diameter 0.01 m were assumed in the whole computational domain. Bedload transport was simulated using Meyer-Peter and Müller formula, no suspended load was taken into account. No solid discharge was attached to the inflow boundary condition. It was assumed an active layer thickness of sediment and the thickness of erodible layer 100 m (i.e. the layer of material that can be transported and eroded). The effect of the local bed slope on the magnitude and direction of bedload was modelled with Koch and Flokstra formula [6].

Instabilities in the bed evolution were observed in the reaches with the steepest slope and steep river banks. Figure 5 shows the example of the instabilities in results of the initial simulation. The example in Figure 5 is located in the river reach with longitudinal slope ca. 17 % and presented results of bed evolution are in the peak of the hydrograph (i.e. 8:00, Figure 4. Longitudinal profile of the river channel with the results from the initial simulation set-up can be seen in Figure 6. Cross sections of the river channel are presented in Figure 7, Figure 8 and Figure 9. Instabilities in the whole wide of the channel are observed in Figure 8 and also some in the riverbanks (Figure 7, Figure 9). In order to avoid the instabilities, several combinations of sediment parameters, bedload transport formulas, mesh size, active layer and erodible layer thickness, excluding bridge structures and numerical set-up were tested to find out the best match with the flow paths observed during the flood event. However, no model configuration without appearance of the instabilities was found.

In order to simulate Utvik flood event, an assumption of non-erodible bed in the river channel and the fjord was accepted for the final simulation set-up. Mesh size was 20 m in the fjord, 2 m in the river channel and 3 m in the rest of the domain. The values of sediment diameters and an erodible layer in the rest of the domain were modified, unless the best match with the flow paths observed during the flood event was reached. In this final set-up, an erodible layer 2.5 m was assumed in the rest of the domain and sediment diameter in the inundation area was set up 0.5 mm. Otherwise the set-up was the same as in initial simulation. Tab. 1 presents the summary of the morphodynamic simulations.

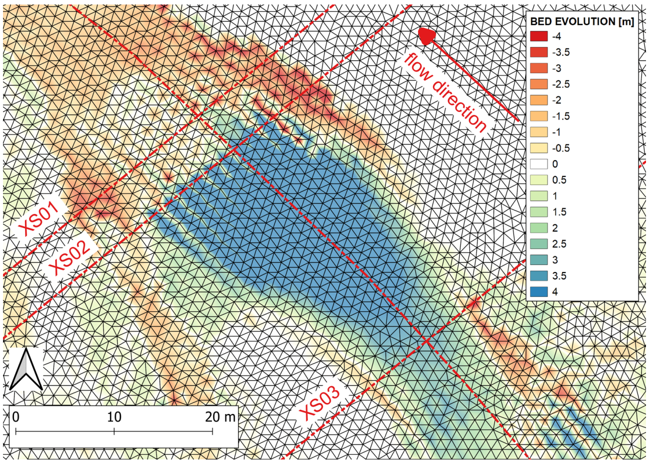

Figure 5. Results of morphodynamic simulation in Utvik. Displayed variable is bed evolution in the peak of the hydrograph (i.e. 8:00).

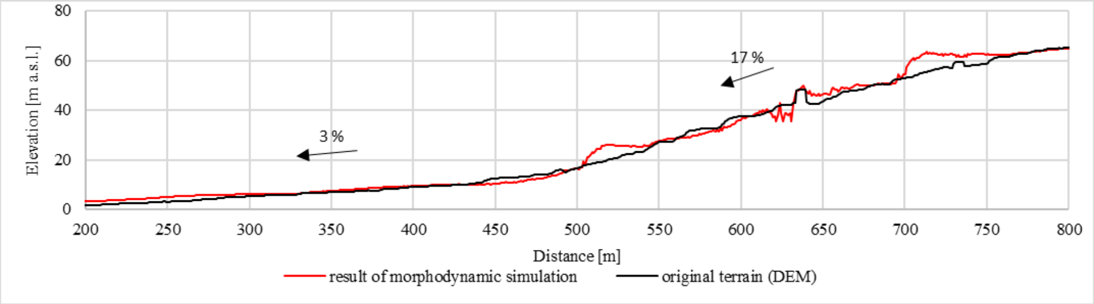

Figure 6. Longitudinal profile of the river channel. Black line represents the original river bed, red line represents river bed obtained from morphodynamic simulation with the initial set-up.

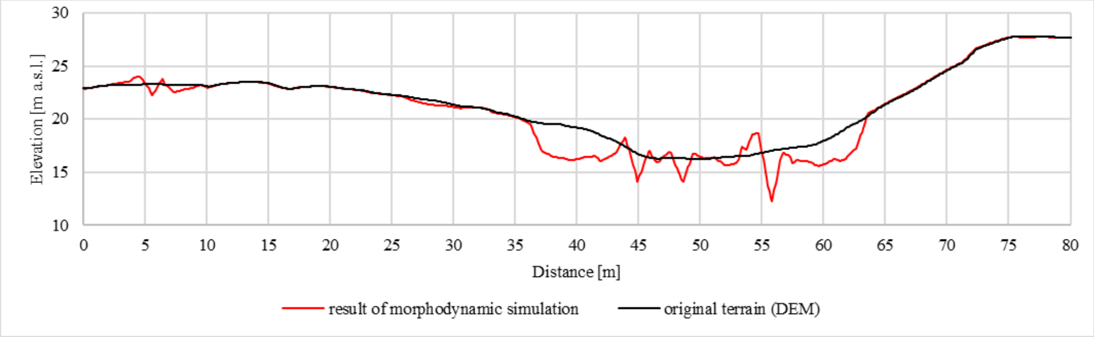

Figure 7. Cross-section XS01 of the river channel. Black line represents the original river bed, red line represents river bed obtained from morphodynamic simulation with the initial set-up.

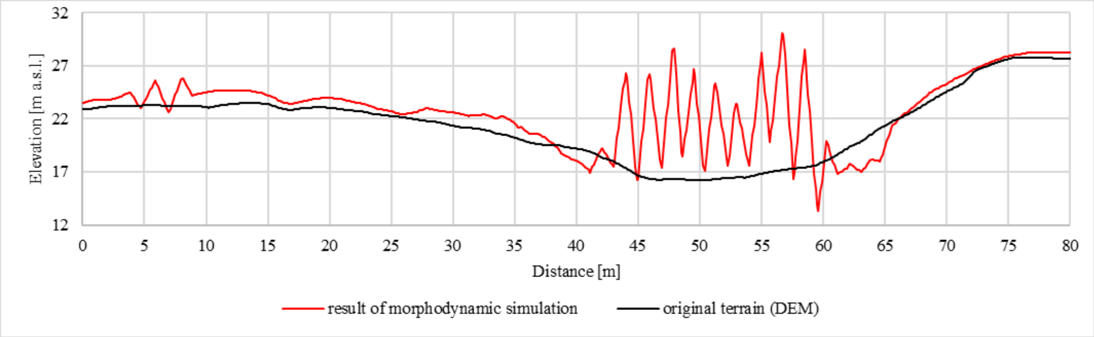

Figure 8 Cross-section XS02 of the river channel. Black line represents the original river bed, red line represents river bed obtained from morphodynamic simulation with the initial set-up.

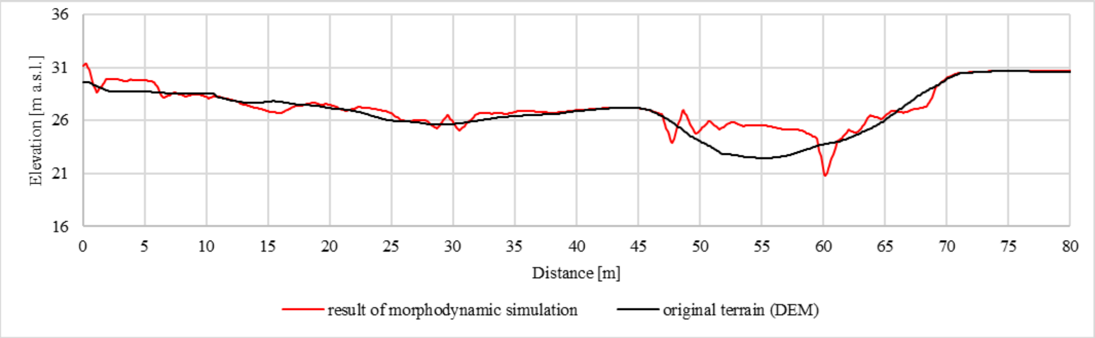

Figure 9. Cross-section XS03 of the river channel. Black line represents the original river bed, red line represents river bed obtained from morphodynamic simulation with the initial set-up

TABLE 1 SUMMARY OF THE MORPHODYNAMIC SIMULATIONS

		Initial morphodynamic simulation	Final morphodynamic simulation
Mesh size [m]	Fjord	20	20
	River channel	1	2
	Rest of the domain	1	3
Sediment diameter [mm]	Fjord	10	non-erodible
	River channel	10	non-erodible
	Rest of the domain	10	0.5
Active layer thickness and erodible layer [m]		100	2.5

IV. RESULTS AND DISCUSSION

Figure 10 shows results of hydrodynamic and the final morphodynamic simulations. Displayed variable is maximum water depth (m). Figure 11 represents results of maximum shear stress (Pa) from hydrodynamic simulation (left), results of the bed evolution (m) from morphodynamic simulation (center) and the bed evolution (m) obtained from pre and post flood event DEM [11] (right). In the figures, black dashed lines represent the original river channel; red circles represent the critical points and purple lines represent flow paths during flood event. The critical points and flow paths were identified according to bed evolution obtained from pre and post flood event DEM [11] and photo and vide documentation of the flood [4]; (taken by O. Bruland).

There are not any available data for calibration the model in Utvik. The results were compared with the flow paths and bed evolution obtained from documentation of the flood event [4] and the post flood DEM (in 2017; [13]). From the results is clear that in the hydrodynamic simulation (Figure 10, left), the main flow path is located in the river channel and the other paths matches quite well with the paths from the real flood.

As for the final morphodynamic simulation (i.e. non-erodible bed in the river channel), results show that the water found new flow path on the left side of the bridge 02 (Figure 10, right), which is the most critical point in the domain. But the inundation area is similar as in the hydrodynamic simulation and the other critical points were not found according the results. From Figure 11 (center) is clear that the water found the new path from the river channel due to erosion of the road embankment. As can be seen in Figure 11 (left), the results of shear stress from hydrodynamic simulation are also suitable to find the critical point besides bridge 02 due to the high values of the shear stress in this area (i.e. erosion would be expected). Hence, there is not much of a difference between the results of hydrodynamic simulation and morphodynamic simulation with non-erodible bed in the river channel.

In both types of simulation, all bridges were overflowed. There were also no data for calibration a flow through the bridges opening.

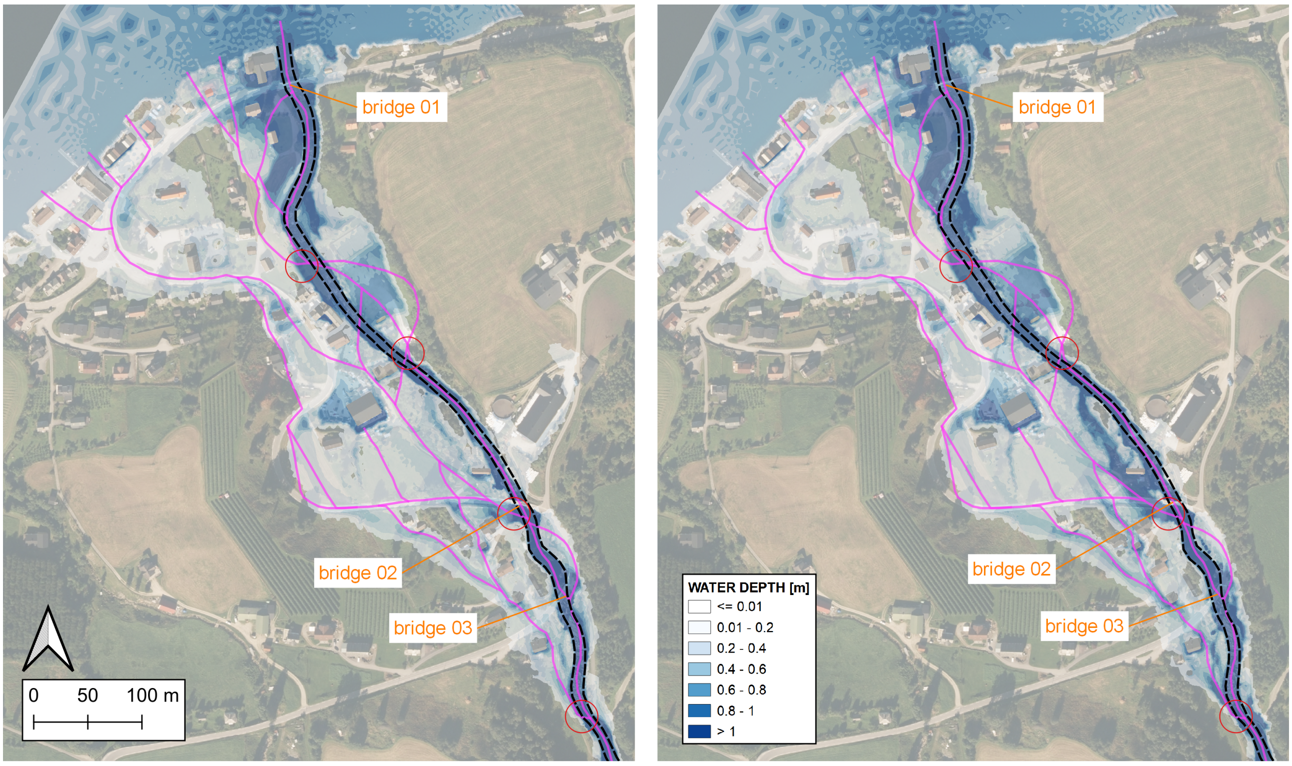

Figure 10. Results of hydrodynamic (left) and final morphodynamic (right) simulations in Utvik. Displayed variable is maximum water depth; black dashed line represents the original river channel; red circles represent the critical points; purple lines represent flow paths during flood event.

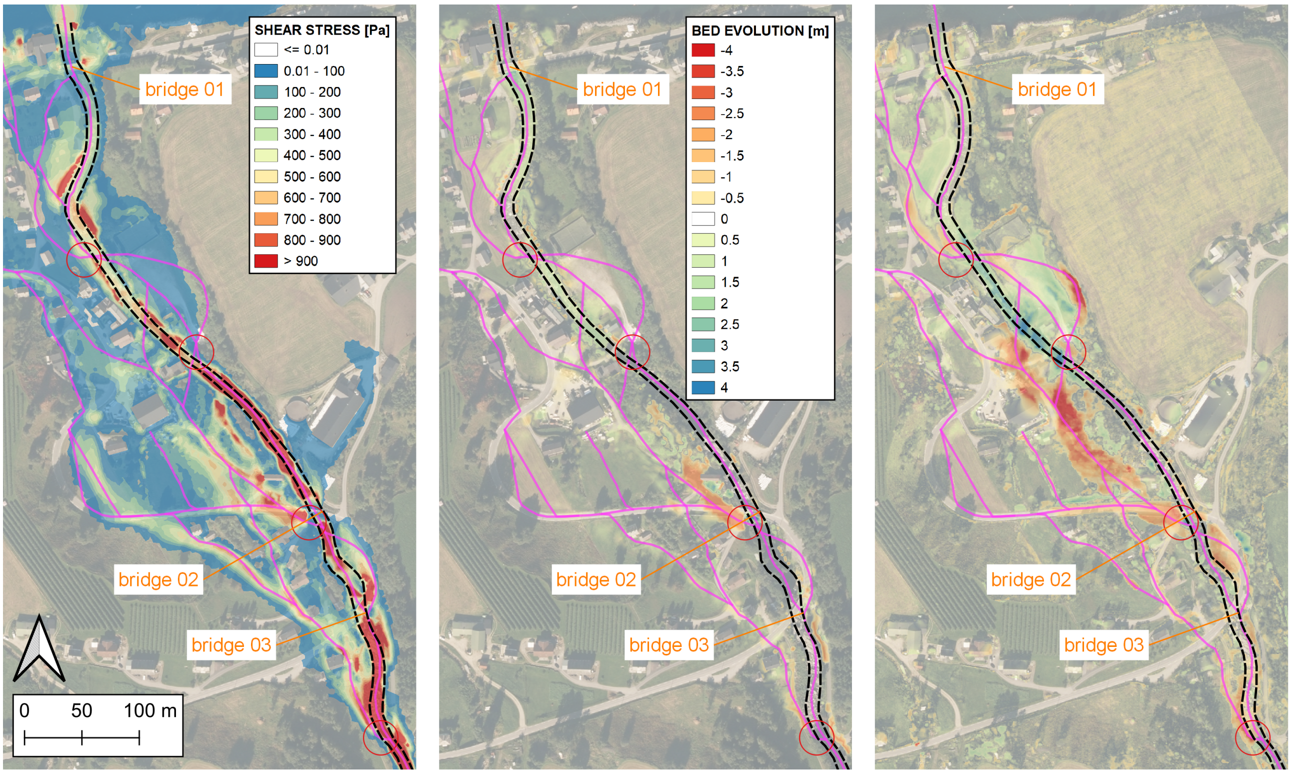

Figure 11. Results of hydrodynamic simulation in Utvik (left, maximum shear stress), final morphodynamic simulation (center, bed evolution in the end of simulation) and bed evolution measured after real flood event (right, bed evolution [11]); black dashed line represents the original river channel; red circles represent the critical points; purple lines represent flow paths during flood event

V. CONCLUSIONS

Hydrodynamic and morphodynamic simulations were carried out in Utvik study area. Instabilities in the river bed evolution were observed in the morphodynamic simulations. Due to the instabilities, non-erodible bed in the river channel was assumed for final morphodynamic simulation.

The results presented in this paper showed that the hydrodynamic simulation could be used to determine the capacity of the river channel and finding the critical points due to the shear stress. However, it does not take into account the creation of the new flow paths due to erosion and deposition processes, so the critical points do not have to be clearly identified.

Regarding the morphodynamic simulation, the inundation area in both types of simulations is not much different. The results of the current morphodynamic simulation present a non-erodible bed, thus, a negligible volume of transported sediment in the river channel. So, the assumption of non-erodible river channel is a significant simplification and further research should be focused on improving the configuration of the model in order to find the suitable set-up for morphodynamic simulation in steep rivers. Therefore, the configuration should be tested and improved on the simpler cases with steep longitudinal slope covering an erodible bed in the river channel to investigate the source of the instabilities. Erosion and sedimentation processes are important to determine the critical points during flash floods, hence, the phenomena of bedload transport in steep terrains needs to be investigated further.

According to the results of both types of simulations, capacities of bridges openings are insufficiently dimensioned to deal with the peak discharge in the river's channel. The conclusion is that the capacity of bridges is an important parameter determining flash flood extent and it should be further investigated. Impact of clogged bridges due to debris (e.g. wood, sediment, man-made objects, etc.) could be investigated as well.

Further research will focus on numerical modeling of the phenomena. Both 2D and 3D numerical models will be tested in order to find suitable model for bedload transport in steep slopes. Therefore, simulations of laboratory experiments and cases with field measurements will be carried out for validation and adaptation/development of the numerical model. Initially Telemac and REEF3D (includes the solution of non-hydrostatic SWE) models will be tested.

Bedload transport formulas implemented in Telemac are developed for certain limitations regarding longitudinal slope and sediment diameter. Hence, further research will be also focused on implementation of bedload transport formula for steep rivers, e.g. Smart formula [17].

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