

# Using TELEMAC-2D for Hydrodynamic Modeling of Rainfall-Runoff

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**Abstract**—TELEMAC-2D is a well known and established hydrodynamic model solving the shallow water equations. Since 2013, the SCS-CN-method has been implemented in TELEMAC-2D. With this supplement, the runoff generation is linked to overland flow and TELEMAC-2D could be extended to a Hydrodynamic Rainfall-Runoff Model (HDRRM). Thus the most important requisites are fulfilled to simulate heavy rainfall and flash flood events. However, changes to the code were necessary concerning spatially distributed rainfall, time-dependent roughness and, the wet/dry boundary. The quality of the resulting method is demonstrated using the flash flood event in the district Rottal-Inn in Bavaria on June 1<sup>st</sup> in 2016. In the first step, the simulation is calibrated using a gauging station in the catchment Simbach a. Inn. After this, validation follows by applying the same methodology to the adjacent catchment Triftern. The results gained in both catchments showed good agreement with the event data. Using the new spacial rainfall module and changing the wet/dry boundary worked properly. A HPC-Scaling test showed a good scalability with the introduced methods. Therefore, the enhanced TELEMAC-2D model proved to be an accurate, efficient and versatile tool for the simulation of flash floods.

## I. INTRODUCTION

The cooperation project ‚Hinweiskarte Oberflächenabfluss und Sturzflut‘ (Indicator Map for Surface Runoff and Flash Floods) abbreviated HiOS is funded by the Bavarian State Ministry of the Environment and Consumer Protection (StMUV) and supervised by the Bavarian Environment Agency. The goals of HiOS are:

- Development of a method to evaluate and classify the risk due to surface runoff and flash floods using a GIS application.
- Refined study on 80 towns and municipalities in Bavaria using coupled hydrological and hydrodynamic simulations.
- Generation of a surface runoff and flash flood indicator map for Bavaria indicating different hazard zones for each of the more than 2000 Bavarian municipalities.

During the first project phase, four hydrodynamic models were tested to explore, which models are suitable for flash flood simulation. Although basic tests showed similar results for all four models, TELEMAC-2D has advantages due to its open-source license (adaptability) and code parallelization (high performance). Furthermore, the capability of TELEMAC-2D to include rainfall using a hydrological method had been a critical assessment criterion.

This paper reports recent developments in hydrodynamic rainfall-runoff modeling using TELEMAC-2D.

## II. IMPLEMENTATION

### A. Spatially distributed rainfall

The Soil Conservation Service Curve Number method (SCS-CN) [1] is a widely used calculation method to derive effective rainfall formation based on precipitation and area-specific runoff factors. The Curve Number (CN value) represents the respective input parameter, which can be easily determined by land use, soil group and, antecedent moisture conditions. A comprehensive dataset of the hydrological soil group (A, B, C and D) is available for Bavaria. The SCS unit hydrograph model, often used in combination with the CN values to simulate runoff concentration, is substituted by hydrodynamic simulation in this study. The same applies to the routing process. The SCS-CN method has been implemented in TELEMAC-2D in 2013 [2][3]. However, this implementation does not support spatially distributed rainfall. Because this feature is essential for the analysis of flash floods caused by convective rainfall events, an enhancement of the code was necessary.

We used rainfall radar data to match the spatial distribution of rainfall. The data is read by the new subroutine radarmap.f as x-y-P-pointset per time level  $t$ , where  $x$  and  $y$  are coordinates in [m] and  $P$  is the accumulated rainfall in [mm] for the actual time range  $dt$ . The parameter  $np$  is the number of following lines with x-y-P-pointsets until the next sections of t-dt-np-dataset occurs. The example in Table I demonstrates the data structure, Figure 1 represents the result for a 100 x 100 m domain.

TABLE I. DATA STRUCTURE READ BY THE SUBROUTINE RADARMAP.F FOR SPATIAL RAINFALL.

1	# Radar data
2	# comment line marked by #
3	# Row <t,dt,np>; t, dt in [s]; np in [-]
4	# Block with np-rows containing <x,y,P>; x,y in [m] ; P in [mm]
5	0. 300. 4
6	25. 25. 1.
7	75. 25. 2.
8	25. 75. 3.
9	75. 75. 4.
10	300. 300. 4
11	25. 25. 1.
12	75. 25. 2.
13	25. 75. 3.
14	75. 75. 4.

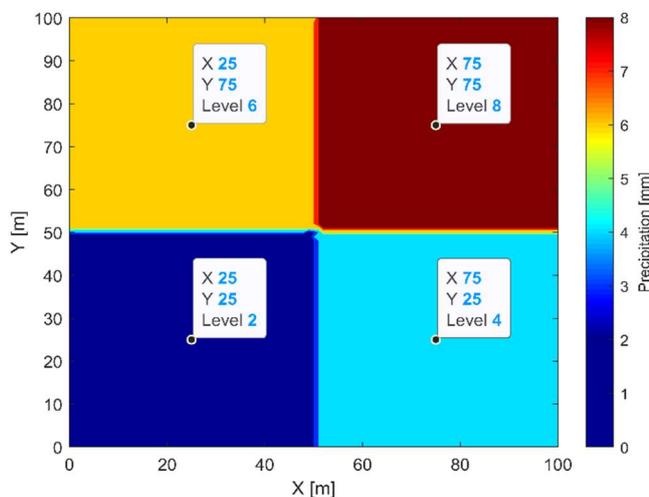


Figure 1. Accumulated precipitation [mm] after 600 s simulation time for the spatial rainfall example given in Table I.

The rainfall data is mapped to the computational mesh using the nearest neighbour interpolation method. Due to design problems, this calculation is repeated after each time step  $dt$ . A more efficient implementation could accelerate the computation.

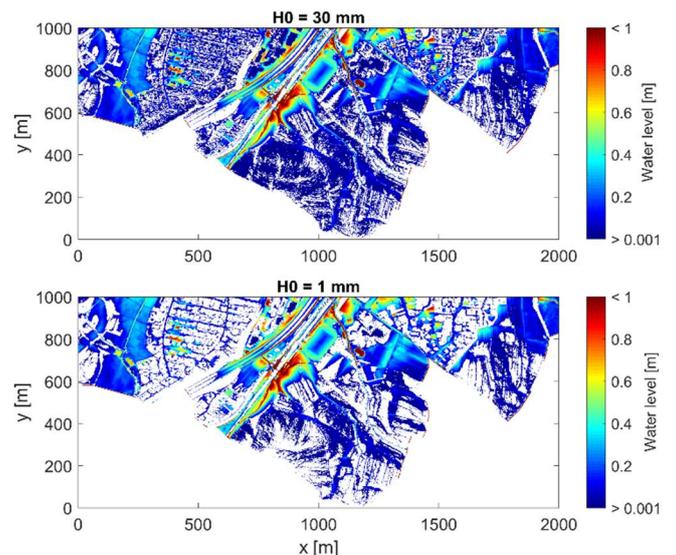
The name of the radar data file can be specified in the cas-file using the keyword FORMATTED DATA FILE 1. The list of subroutines changed is given in Table II.

TABLE II. LIST OF SUBROUTINES CHANGED.

	Subroutine	Description
1	declarations telemac2d.f	Declarations
2	condin.f	Initial condition
3	runoff scs_cn.f	Rainfall-runoff
4	nomvar telemac2d.f	Name declaration
5	radarmap.f (New)	Reads rainfall radar data
6	fasp.f	Nearest neighbour interpolation

### B. Wet/dry boundary

Although the SCS-CN-method, at first sight, operated correctly, a deeper analysis revealed inaccuracies related to the wet/dry strategy of TELEMAC-2D. For water depth lower than 3 cm a change to viscous flow seems to happen. A thin water layer of about 1 to 3 cm remained temporary on the plane ground when using the FE-solver. Such a relatively thick water layer is not applicable for rainfall-runoff simulation, because the total amount of rainfall often is within the range of millimeters. The FV-solver in comparison simulated a plausible sheet flow but doubled the computational effort due to the explicit Courant criterion. Consulting the source code, the hard-coded parameter  $H0$  in fricti.f was found. This "Hidden Parameter"  $H0$  has a significant influence on the propagation of overland flow caused by rainfall for the FE-scheme. Figure 2 shows a comparison of max. water depths for  $H0 = 3$  cm (standard) and  $H0 = 1$  mm for flooding caused by heavy rainfall using the FE-model. The inundated area for  $H0 = 3$  cm is significantly larger than for  $H0 = 1$  mm. The solution of the FE-solver with  $H0 = 1$  mm is much closer to the FV-results. All results gained with  $H0 = 1$  mm are reasonable and the simulation runs smoothly without delay. Side effects in using a smaller  $H0$  were not observed. For the simulations in chapter III Calibration and Validation the FE-solver was applied with  $H0 = 1$  mm.

Figure 2. Inundated town area for calculation with TELEMAC-2D v7p3r1  $H0 = 30$  mm (Standard) and  $H0 = 1$  mm, cut-off = 1 mm.

### C. New roughness approaches

The Strickler roughness approach is widely used in shallow water equation simulations. However, its validity is not proven for flash flood simulations yet. For the hydrodynamic modeling of surface-runoff the proper representation of sheet flow is important. Otherwise, deviations in wave propagation time and water depth can be expected throughout the computational domain. Different alternatives to the Strickler roughness are already implemented in TELEMAC-2D. However, formulae

respecting both the influence of bottom structure and vegetation are not supported. This gap shall be filled implementing and analyzing new roughness formulae.

The scientific goal of this analysis is to find out, whether the Manning/Strickler law is appropriate for flash flood modeling or new approaches offer a better solution in terms of accuracy and efficiency.

The following three new roughness approaches were implemented [10]:

- Lawrence [5]
- Machiels [6]
- DWA [7]

The existing Lindner [8] roughness approach in TELEMAC-2D is used in a modified version from the Bundesanstalt für Wasserbau BAW (communication R. Kopmann).

Initial test-runs showed feasible results, but also the need for adaption. The observed computational effort for the new time-dependent roughness increased drastically due to the higher complexity of the new approaches.

### III. CALIBRATION AND VALIDATION

The extreme flash flood event on May 31<sup>st</sup> and June 1<sup>st</sup>, 2016 near Simbach a. Inn, Bavaria, is well documented [11]. The catchment of Simbach a. Inn has a size of 45.9 km<sup>2</sup>. The area of the adjacent catchment Triftern is 90.1 km<sup>2</sup> [11]. The basic digital elevation model DEM has a resolution of 1 m x 1 m. The standard look-up-table, which links the Strickler roughness values to the land usage, is given. As input for rainfall, radar data product RADOLAN YW by DWD [4] is available in 5 min temporal and 1 km<sup>2</sup> spatial resolution (see Figure 3 and Figure 4).

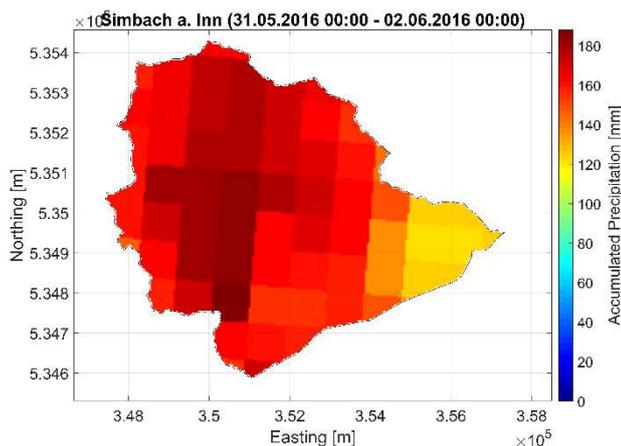


Figure 3. Accumulated precipitation from RADOLAN-YW Data for the heavy rainfall event in Simbach a. Inn in 2016. This data is used in TELEMAC-2D with the spacial rainfall module.

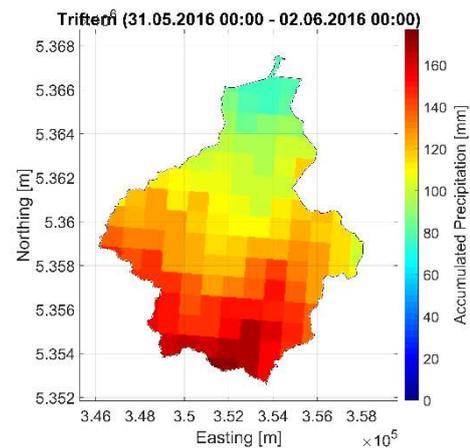


Figure 4. Accumulated precipitation from RADOLAN-YW Data for the heavy rainfall event in Triftern in 2016. This data is used in TELEMAC-2D with the spacial rainfall module.

All necessary data are available in good quality. Furthermore, both relevant catchments in Simbach a. Inn and Triftern are controlled by gauging stations (Figure 5). This situation that two adjacent catchments have reliable gauging stations and are hit by the same convective rainfall event is special. It offers the opportunity to calibrate the simulation method on one catchment and validate the procedure at the second catchment.

Here the data is first prepared for Simbach a. Inn. The optimal setup with respect to the reconstructed discharge at the gauging station Simbach a. Inn was chosen for calibration. The reconstructed discharge curve was taken from Hübl [11]. He derived the discharge upstream of the dam-break location fitting the result of a hydrological model to observed values. For better comparison with this result, the effect of a dam-break was not taken into consideration (Figure 6). It turned out, that the standard values for Strickler-roughness and CN - Values could be applied without changes. The steep slope correction SSC has some relevant impact on the results [2]. The initial abstraction ratio is set to 0.05 (default value 0.2) [2].

Afterward, the validation for the Triftern catchment can be tested following the same procedure for setting up the data and the same steering parameters for running the simulation.

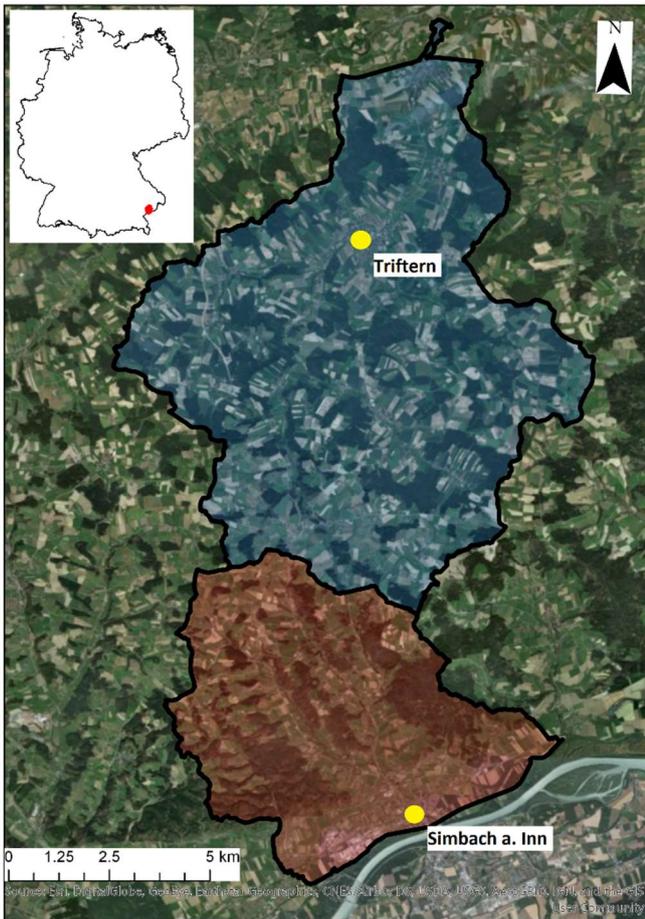


Figure 5. Catchments of Simbach a. Inn and Triftern (yellow point marks the location of gauging station).

The data were prepared and analyzed by Wencker [9]. Both simulations were run on an HPC cluster system with a spatial and temporal resolution of 5 m resp. 1 s.

The results for the calibration are represented in Figure 6, Figure 7 and Table III.

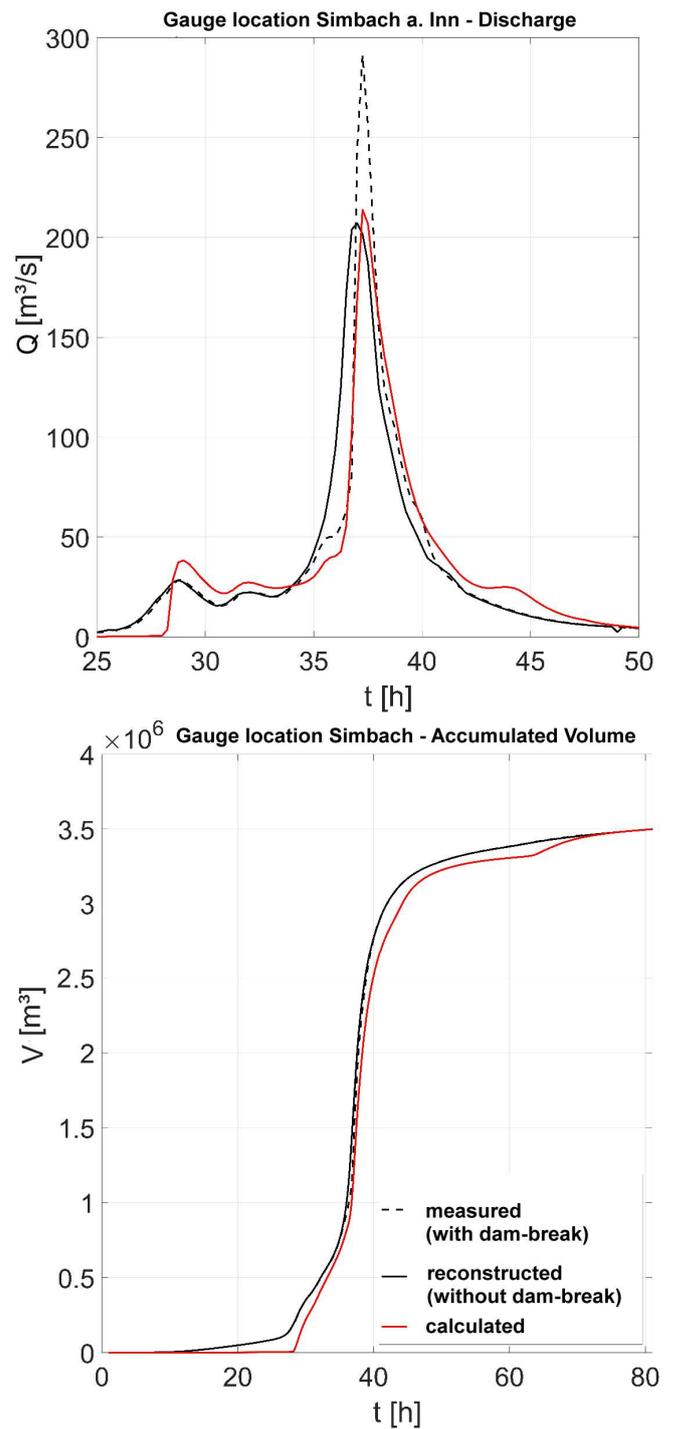


Figure 6. Calibration Simbach a. Inn, Comparison of calculated vs. reconstructed discharge (a) and accumulated volume (b), starting time 31.5.2016 0:00 UTC.

TABLE III. CALIBRATION SIMBACH A. INN, COMPARISON OF CALCULATED VS. RE-CONSTRUCTED DISCHARGE AND ACCUMULATED VOLUME.

	Reconstructed	Calculated	Deviation
Peak	207.3 m <sup>3</sup> /s	213.9 m <sup>3</sup> /s	+ 3.2 %
Time to Peak	37 h	37.25 h	+ 15 min
Final Volume	3.5*10 <sup>6</sup> m <sup>3</sup>	3.49*10 <sup>6</sup> m <sup>3</sup>	- 0.03 %

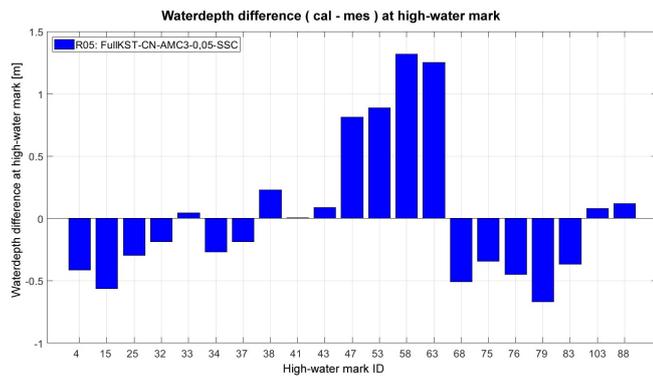


Figure 7. Calibration Simbach a. Inn, Difference of calculated and observed water depth at high water marks.

The deviation of measured and calculated discharge for the Simbach a. Inn calibration test case is below 5 % for peak discharge and well below 1 % for the accumulated volume. The deviations of observed and calculated water depth have much larger scatter (Figure 7). The simulation mostly underestimated the water levels by 20 – 70 cm. Within some polder area, an overestimation of more than 1 m occurred which is partly caused by insufficient information on outlets or pumps.

The procedure and the parameters gained by calibration in Simbach a. Inn is partially validated in Triftern. The characteristic of the discharge curve in Figure 8 is reproduced well. The deviation of the two maximum peaks is in the same magnitude as in the Simbach test case (Table IV). The deviation of accumulated volume again is almost zero. The accuracy of the water depths in comparison to high water marks is even better (Figure 9). This might be caused by the more mildly sloped terrain in Triftern.

TABLE IV. VALIDATION TRIFTERN, COMPARISON OF CALCULATED VS. MEASURED DISCHARGE AND ACCUMULATED VOLUME

	Measured	Calculated	Deviation
Peak 1	120.3 m <sup>3</sup> /s	121.8 m <sup>3</sup> /s	+ 1.3 %
Peak 2	125.5 m <sup>3</sup> /s	133.2 m <sup>3</sup> /s	+ 6.1 %
Time to Peak 1	36 h	35.25 h	- 45 min
Time to Peak 1	37.75 h	38.25 h	+ 30 min
Final Volume	4.93*10 <sup>6</sup> m <sup>3</sup>	4.93*10 <sup>6</sup> m <sup>3</sup>	- 0.02 %

Generally, high water marks tend to overestimate the real mean water elevation. Nevertheless the observed water level in Triftern and Simbach a. Inn is clearly underestimated by the simulation. The new roughness approaches described in Chap. IIC might help to improve the quality of simulated water depth.

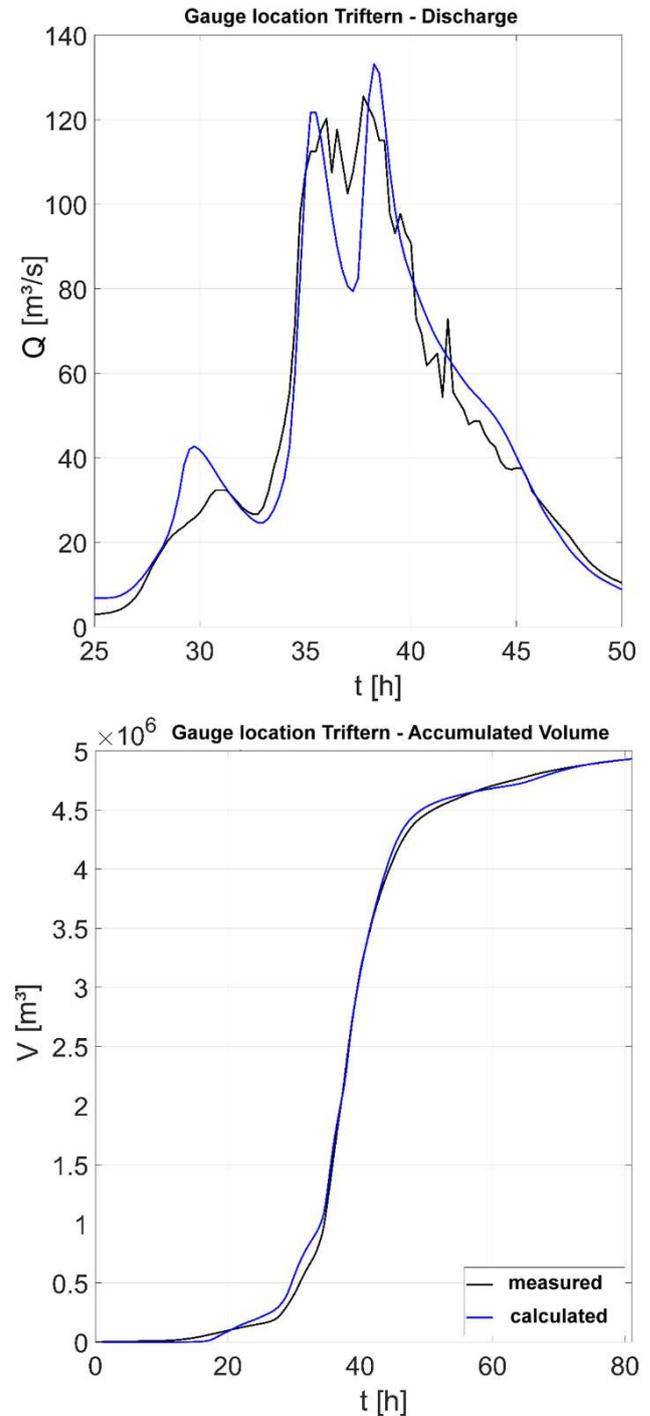


Figure 8. Validation Triftern, Comparison of calculated vs. measured discharge (a) and accumulated volume (b), starting time 31.5.2016 0:00 UTC.

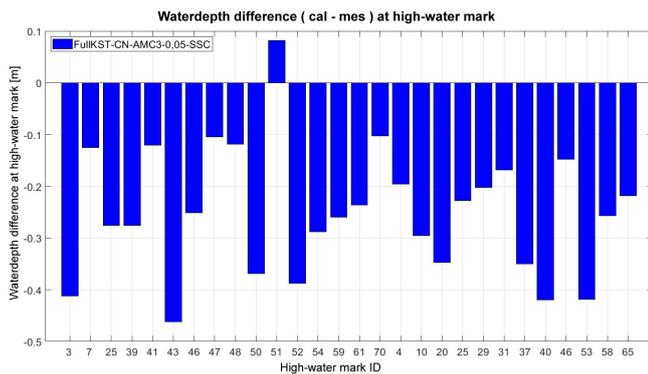


Figure 9. Validation of Triftern, Difference of calculated and observed water depth at high watermarks.

#### IV. HPC-SCALING TEST

Strong-scaling tests were carried out on the HPC cluster at LRZ. TELEMAC-2D v7p3r1 with extensions for spatially distributed rainfall was compiled using the Intel-MPI-Compiler 2017. TELEMAC-2D is configured for usage on the LRZ-SLURM load-leveler. The template for this configuration file was kindly provided by TU Wien.

The test case Simbach a. Inn described in the previous chapter was simulated using 2, 4, 8, 16 and 32 nodes, each node containing 28 cores. The wall time for the reference 1-node-run  $t_1$  and the parallel runs with more nodes  $t_N$  were recorded and the speed-up =  $t_1 / t_N$  plotted against the number of nodes (Figure 10).

The program has very good HPC-performance. The speed-up is almost linear and even above the ideal line. This unusual behavior probably is caused by a different cache mode for the 1-node reference calculation. All the other simulations occupied less memory (because of the smaller sub-catchment for each core) and therefore could run inside the fast low-level cache. Simulations were repeated three times for 2, 4, 8, 16 and 32 nodes. The variation of the three identical sets is relatively small besides two calculations plotted in red. This difference probably is caused by the changing load of the HPC-system.

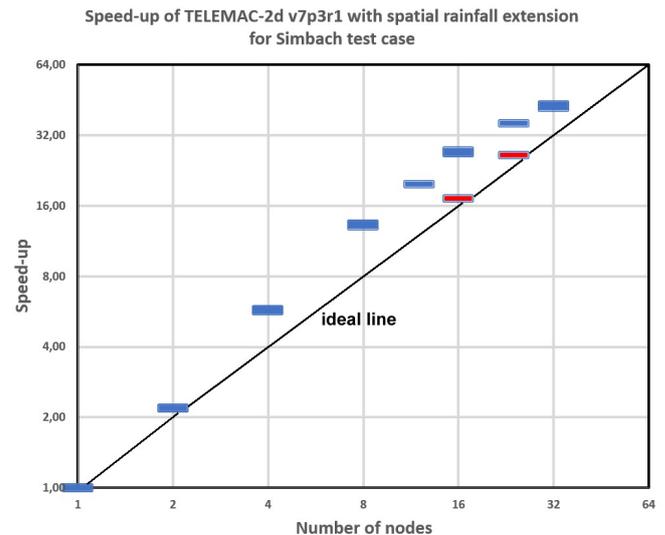


Figure 10. Strong scaling, speed-up Telemac-2D for Simbach-test case. Every node contains 28 cores. Outliers highlighted in red.

#### V. SUMMARY AND CONCLUSION

A general procedure for the simulation of flash floods using the TELEMAC-2D-FE-solver with an enhanced rainfall module extension was developed and validated. A good agreement of simulated and observed discharges was achieved for the study areas Simbach a. Inn and Triftern. Improvements concerning the accuracy of the simulated water depths for flash floods are still needed. Therefore different new roughness approaches are implemented. The hidden parameter  $H_0$  in subroutine `fricti.f` has to be reduced for all rainfall-runoff simulations using the FE-solver. The HPC-performance is good, but memory-bound weak-scaling still has to be tested.

In the next step, the derived method will be applied to 14 sites in Bavaria which experienced a flash flood. At each of these sites, discharge measurements are available for a more robust evaluation of the modeling setup.

#### ACKNOWLEDGMENT

The cooperation project HiOS analyses surface runoff and flash floods in various aspects. HiOS started in 2017 and will last until 2020. It consists of three teams working on GIS, hydrologic and hydrodynamic modeling. Technical University of Munich TUM, Ludwig-Maximilians-Universität LMU and the Leibniz-Supercomputing Centre LRZ are partners in this project. HiOS is funded by the Bavarian State Ministry of the Environment and Consumer Protection (StMUV) and supervised by the Bavarian Environment Agency.

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