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EXTENSION AND TESTING OF A 2D HYDRODYNAMIC MODEL FOR DIRECT RAINFALL RUNOFF SIMULATION

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While the simulation of flood risks originating from the overtopping of river banks is well covered within continuously evaluated programs to improve flood protection measures, flash flooding is not. Flash floods are triggered by short, local thunderstorm cells with high precipitation intensities. Small catchments have short response times and flow paths and convective thunder cells may result in potential flooding of endangered settlements.
Assessing local flooding and pathways of flash floods requires a detailed hydraulic simulation of the surface runoff. Hydrological models usually do not incorporate surface runoff as a part of runoff concentration at this detailedness but rather empirical equations are applied for runoff detention. In return 2D hydrodynamic models usually do not allow distributed rainfall as input nor are any types of soil/surface interaction implemented as in hydrological models. Considering several cases of local flash flooding during the last years the issue emerged for practical reasons but as well as research topics to closing the model gap between distributed rainfall and distributed runoff formation. Therefore, a 2D hydrodynamic model, depth-averaged flow equations using the finite volume discretization, was extended to accept direct rainfall enabling to simulate the associated runoff formation. The model itself is used as numerical engine. Rainfall is introduced via the modification of water levels at fixed time intervals. This work mainly deals with the general application of the software and includes a first study case to proof the method and to test the numerical stability.

METHODS

Numerical model

Hydro_GS-2D (Nujic [1]) was applied for all numerical simulations. This software consists of a flow module and bed load transport module which can be switched on optionally. To solve the shallow water equations a two dimensional Finite Volume code is used. A three layer multi fraction approach is used to describe morphological changes and bed-load transport. Mass balance is calculated between a top mixing layer, an intermediate subsurface layer and a bottom layer. The grain size distributions in the mixing and subsurface layers are determined ac-cording to Hirano [2]. Bed load transport is calculated with a multi fraction application of the Meyer-Peter & Müller equation [3] coupled with a hiding function as introduced by Hunziker [4] and Hunziker et al. [5]. For all test simulations in this work the bed load transport module is switched off. Still, using this model allows a later coupling of local flash flooding with associated bed load transport processes.

Distributed rainfall and temporal decomposition

As outlined before, the applied method is based on altering the given water levels at discrete time steps. From a numerical point of view, the introduction of nodal discharge time series would be a more sound solution, as the additional discharge term in the differential equation would be part of the numerical solution. Still, depending on the type of runoff formation and associated losses, the altering of water levels has substantial advantages. When losses linked to soil states (e.g. as function of soil moisture) are introduced, simultaneous simulation of soil conditions and surface runoff is required. Although the procedure of altering water levels is realized, the so far implemented loss models are simple, allowing the application of initial loss and continuous loss definitions. The resulting net rainfall is introduced for surface runoff routing with the 2D numerical model. To allow a zonal differentiation of rainfall intensities and durations, the nodes can be grouped to “rainfall-zones” where all nodes face the same precipitation. Additionally losses can be as well defined for zonal groups of nodes, representing the concept of hydrological response units (HRU’s). To allow the altering of flow depths, the 2D numerical model is stopped and restarted at discrete time steps.

Core idea is to divide the total simulation period into a number of sub-periods. Instead of computing one Hydro_GS-2D model, several sub-period models are set up and calculated sequentially. Figure 1 (a) shows the method for the case of three sub-periods.

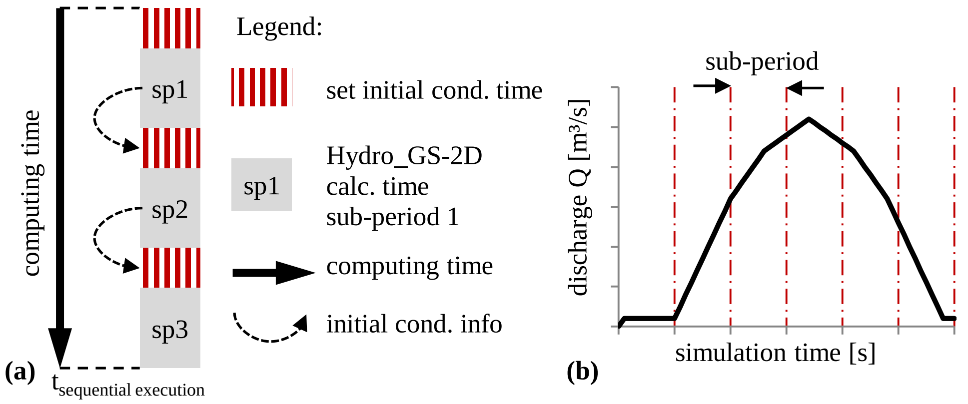

Figure 1. (a) Temporal decomposition approach; (b) exemplary inflow hydrograph with indicated sub-period boundaries

The sequential execution time ($t_{sequential}$) is the total computing time required to simulate all sub-periods, including the overhead times for transferring the initial conditions. The computing time to set-up one sub-period model is referred to as “set initial condition time”. Therein the following tasks are to be covered.

Firstly, all external inflows (sediment and discharge hydrographs from upstream catchments or tributaries) are set (see Figure 1 (b)). This is an optional issue, for cases where the considered catchment is not a headwater catchment.

Secondly, the model state is obtained from the previous model run. This data consists of spatial (nodal) information of the water depth and velocity and – optional for sediment transport modeling cases - the bed elevation and the grading curves of the mixing, subsurface and bottom layer.

The third task is the adaption of the water levels. Currently the introduced net rainfall is added to the previous simulation's water level. In general, this may as well include water level reductions due to extensions such as infiltration processes. The re-running of the

Hydro_GS-2D calculations, the analysis of the results and the parameter adaptions are done in an automatic way by using software tools developed to speedup calculations for very large catchments and long term morphodynamic simulations (Klar et al [6] and Klar et al. [7]).

STUDY CASE AND RESULTS

In order to test the direct rainfall runoff approach, a detailed 2D-numerical model of a catchment around the village of Leonding is used (see Figure 2). The mesh consists of approximately 370 000 elements and 340 000 nodes covering an area of about 3.6 km² with elevations ranging between 279 and 481 masl.

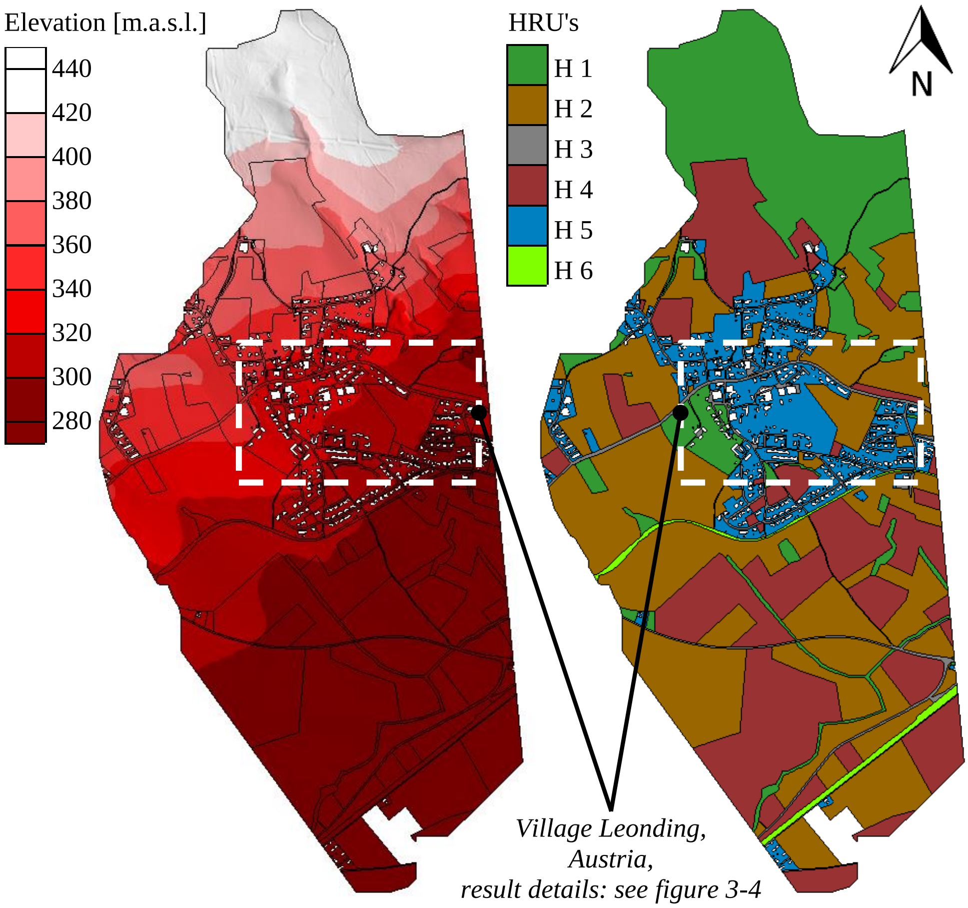

Figure 2. Hydro_GS-2D model; left: elevations; right: hydrological response units (HRU’s)

Roof areas draining into the sewer system are represented by removing these areas from the mesh. The Hydro_GS-2D parameter H_{min}, a depth threshold to distinguish wetted by non-wetted areas, is set to a low value of 0.1 mm. The model area is structured into 6 hydrological response units (HRU’s) with specific parameters as outlined in Table 1 and shown in Figure 2 (right).

Table 1. HRU characteristics: total roughness $k_{St,total}$ according to Strickler, losses and effective rainfall for the test model runs

Hydrological response units (HRU)		Initial loss [mm]	Continuous loss [mm/min]	$k_{St,total}$ [$m^{1/3}/s$]	Effective rainfall/sub-period [mm]			
					Run 1	Run 2	Run 3	Run 4
H1	Forest	15.0	1.80	2.0	0.0	0.0	0.0	0.0
H2	Meadow	5.0	1.10	6.0	2.8	1.4	0.7	0.4
H3	Road	0.0	0.00	40.0	7.2	3.6	1.8	0.9
H4	Acre	1.0	0.25	4.0	6.2	3.1	1.6	0.8
H5	Residential area	5.0	1.10	2.0	2.8	1.4	0.7	0.4
H6	Railway	5.0	1.10	3.0	2.8	1.4	0.7	0.4

As test scenario a constant rain intensity of 0.03 mm/s for the whole area and full simulation period of one hour is selected. In sum 4 runs with varying numbers of sub-periods have been performed. The resulting computation times differs from 5.5 hours for run number 1 with 15 sub-periods to almost 31 hours for the detailed run number 4 with 120 sub-periods and very fine water level modifications (effective rainfall) of less than 1 mm per sub-period and HRU (see Table 1 and 2).

Table 2. Run parameters and results

	Run 1	Run 2	Run 3	Run 4
Number of sub-periods	15	30	60	120
Sub-period time	240	120	60	30
Computation time (ct)	5:27:46	10:41:42	16:07:45	30:42:22
Computation time (ct) [%]	100%	196%	295%	562%
Average ct / sub-period	0:21:51	0:21:23	0:16:08	0:15:21

To show the detailedness of the direct rainfall approach exemplary the local flooding and pathways for run number 1 are presented in Figure 3 and 4.

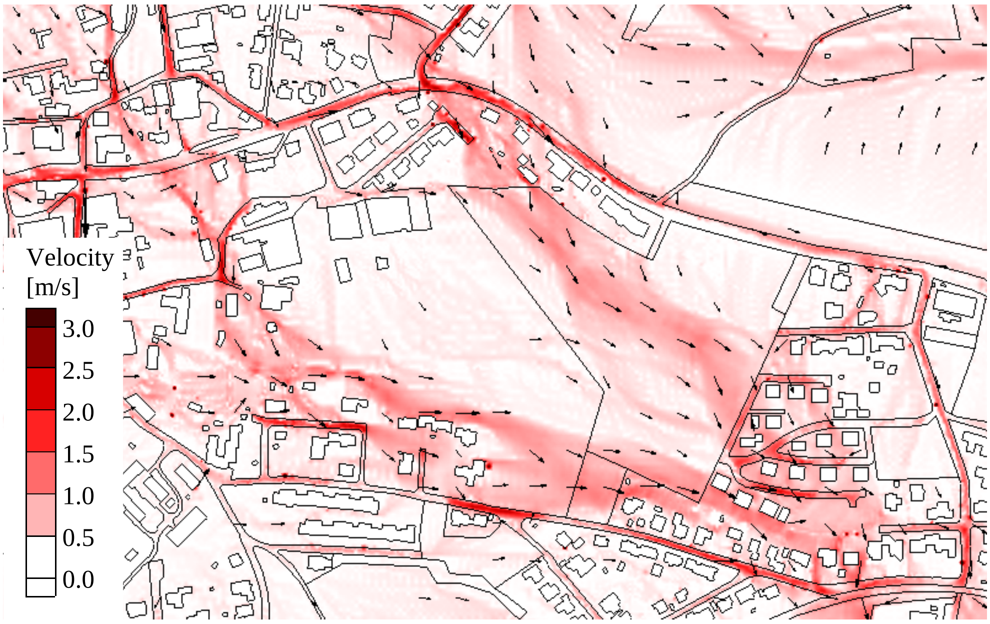

Figure 3. Run 1: flow velocities at the end of the simulation period

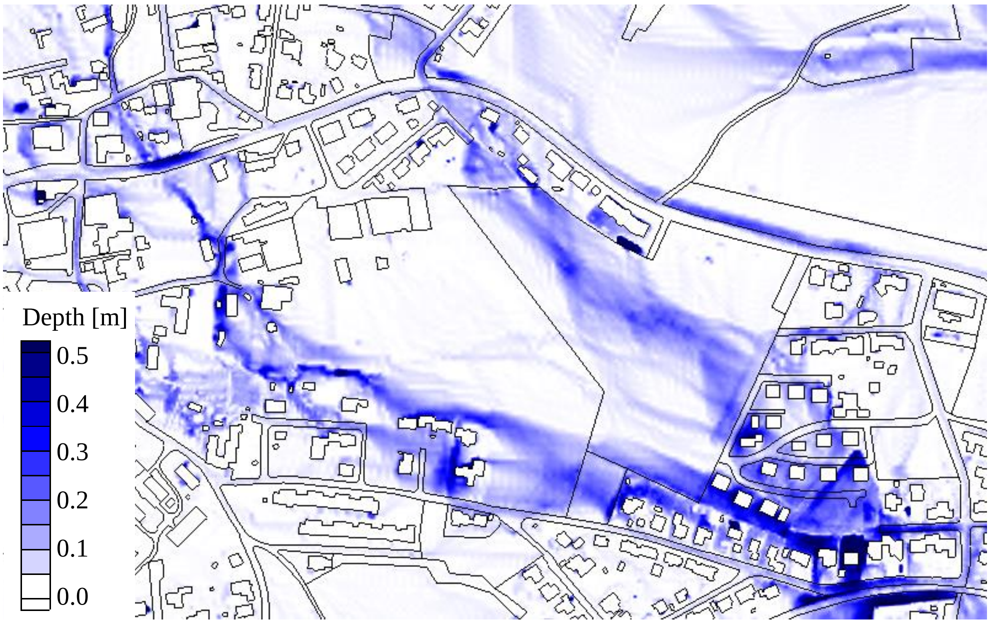

Figure 4. Run 1: water depths at the end of the simulation period

CONCLUSION AND OUTLOOK

The paper not only deals with the general application of the software, but intends to test the numerical stability and reliability of simulation results. All performed runs have been found to be both numerical stable and reliable. The further work is addressing the sensitivity of parameters to the simulation results. The performed tests are made using different artificial as well as measured rainfall series as input. For design purpose, the definition of return intervals and durations used for design rainfalls is crucial. Besides, the used losses but as well the selected roughness are found influencing factors to the results. Where the losses directly impact the magnitude of flooding in terms of water levels, the distribution of surface roughness influence the flow paths and spatial distribution the flooding zone.

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