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Kyoto University
Shallow Water Flow Based Simulation of Flash Floods in Small Catchments
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Keywords: Shallow Water Equations, Urban Flooding, Natural Catchments, Infiltration

Flash floods as a result of heavy rainfalls often cause severe damages to settlements and the environment. In future, the occurrence and intensity of heavy rainfalls might increase due to climate change. The simulation of flash floods is an important tool to analyze flow processes during and after rainfall events and to develop methods to protect settlements and the environment against damages caused by flooding. Generally, rainfall-runoff simulation in catchments is carried out with hydrological models which only ‘roughly’ can take into account the topography, flooding areas and local details of flow processes. To overcome these drawbacks, shallow water based models have been further developed and applied in recent years. The Hydroinformatics Modelling System (HMS) can be used for different applications, as for example rainfall-runoff and flood modelling. HMS is a Java-based framework which is developed at the Chair of Water Resources Management and Modeling of Hydrosystems, Technische Universität Berlin. The two-dimensional depth-averaged shallow water equations are discretized with a cell-centered finite volume method and solved with an explicit MUSCL scheme. Precipitation and infiltration are considered as source/sink terms in the mass balance equation. Different applications of HMS will be presented: (1) the simulation of a dam-break through an idealized city (flooding), (2) rainfall-runoff simulation in a natural catchment and (3) rainfall-runoff simulation considering infiltration with the Green-Ampt model. One future objective is to set up a model of the El Gouna region in HMS. Preliminary studies contain the analysis of different scenarios concerning bottom friction, slope, rainfall, infiltration and additional inflow from upstream for an idealized catchment. By implementing a digital elevation model (DEM) the topography of the natural catchment will be taken into account to simulate the runoff in the region of El Gouna. During the flash flood event on 9 March 2014 data of rainfall and runoff were measured and are published in the doctoral thesis of Hadidi (2016). This event will be simulated with HMS and the numerical results will be compared with the measured data. Later on the model will be applied to investigate different scenarios of structural measures to protect the city of El Gouna against flooding.
Outline

- Motivation
- Modelling framework, physics and numerics
- Applications
- Conclusions and Outlook

Hydrological, hydraulic and environmental problems

- Flooded urban and rural areas
- Interactions
- Sediment transport / morphology
- Contaminant transport
- Urban runoff
- Infiltration

Flash floods

Simulation of flash floods to:
- Analyze structural protection measures
- Develop early warning systems

2D shallow water models:
- Consider complex topographies, flooding areas and local flow processes
- Support high-resolution grids (~1m) to better resolve urban structures
- Include robust numerical methods which enable the modelling of propagating wet-dry fronts
- Deliver results of flow evolution in the whole simulated domain including water depths and flow velocities
Flash floods

- Product of extreme weather conditions
- Cause severe damages
- Storage and usage of fresh water
- Need of mitigation measures

El Gouna, 9th March 2014

- Flooded city of El Gouna

Hurghada, 9th March 2014

- Hurghada airport

Berlin, 27th July 2016

- Parking cars transported by flood
- Flooded city of Berlin

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Highly random occurrence in arid/semi-arid regions as well as in regions with moderate climate
Hydroninformatics Modeling System

- hms is a Java-based object-oriented modeling framework which solves shallow water flow and associated processes using a cell-centered Finite-Volume Method (Simons et al. 2014).
- 'Easy' implementation of extensions, e.g. new conceptual approaches, coupling of processes
- 'Easy' handling of spatial data
- Developed at the Chair of Water Resources Management and Modeling of Hydrosystems

Software design

- Layers contain geometrical information, data, meta-data, methods, ...
- Accessible through generalized interfaces
- Independent of represented information
  - Physically-based model
  - Geospatial database
  - External data sources
  - ...

hms layer concept

Software design

hms core

- Different mesh types
- Geometry library
- Visualization
- Shared-memory parallelization
Shallow water equations

- Two-dimensional shallow water equations:
  \[ q = \begin{bmatrix} \frac{f}{ah} \\ \frac{v h}{vh} \end{bmatrix}, \quad f = \begin{bmatrix} \rho v h + \frac{1}{2} \rho g h^2 - v_i \nabla (u h) \\ \rho v h + \frac{1}{2} \rho g h^2 - v_i \nabla (v h) \end{bmatrix}, \quad s = \begin{bmatrix} \frac{r - \rho g h (h_{Ax} - h_{Ay})}{\Delta x} \\ \frac{r - \rho g h (h_{Ay} - h_{Ax})}{\Delta y} \end{bmatrix} \]

- Mass sink/source term (e.g., rainfall, infiltration)
- Turbulent viscosity
- External forces (e.g., wind, Coriolis)
- Density

- Constant turbulent viscosity or algebraic turbulence model
- Hydrostatic reconstruction for well-balanced results
- Point-implicit solution of friction term

General Finite-Volume solver

- General form of 2D conservation law:
  \[ \frac{\partial q}{\partial t} + \nabla \cdot f = s \]

- General cell-centered Finite-Volume method:
  \[ q_{n+1} = q_n - \frac{\Delta t}{A} \sum_k f^+_k \cdot n_k / \Delta t + \Delta t s^n \]

- Independent of mesh type
- Explicit time discretization

“General” Godunov-type solver

- Using a Riemann solver for flux computation: exact solver, HLL, HLLC, Roe's
- Efficient solution of SWE and any number of other processes which are not influencing the Riemann solution directly
- Second order accuracy in space; avoiding spurious oscillations through TVD methods

Runoff generation / infiltration

- Effective rainfall \( \rightarrow \) runoff generation model
- Infiltration
- Evapotranspiration (planned)

- Conservation law for the soil water content:
  \[ q = \begin{bmatrix} \phi \end{bmatrix}, \quad f = \begin{bmatrix} 0 \end{bmatrix}, \quad s = \begin{bmatrix} \frac{i}{\Delta t} \end{bmatrix} \]

- Infiltration in the unsaturated zone
  \( \rightarrow \) Green-Ampt or Phillips's model
- Coupling with Richard's or two-phase flow model

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Previous studies
### Flash flood in an simplified urban district

**Simons et al. (2013)**

- Simulation of flash flood in a simplified urban district.
- Comparison of simulations and measurements.

### Numerical results of rainfall runoff simulation

**Simons et al. (2013)**

- Comparison of simulations and measurements.
- Runoff simulation.

### Parameter studies on idealized catchment

- Various parameters:
  - Sloped plane
  - Grid resolution: 1m
  - Constant rainfall over the domain
  - Rain duration = 600 s

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<th>Variation</th>
<th>Parameter Description</th>
<th>Reference Case</th>
<th>a (slopes)</th>
<th>b (slopes)</th>
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<tr>
<td>1</td>
<td>Rain intensity (mm/h)</td>
<td>50</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Slope (%)</td>
<td>5</td>
<td>0.01</td>
<td>0.1</td>
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<tr>
<td>3</td>
<td>Friction (m²/s²)</td>
<td>0.03</td>
<td>0.01</td>
<td>0.1</td>
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<tr>
<td>4</td>
<td>Inflow (l/s)</td>
<td>0</td>
<td>100</td>
<td>500</td>
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<tr>
<td>5</td>
<td>Infiltration</td>
<td>No infiltration</td>
<td>Loamy sand</td>
<td>G=0.4</td>
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<tr>
<td>6</td>
<td>Infiltration &amp; Inflow</td>
<td>Loamy sand</td>
<td>G=0.4, G=0.2</td>
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<tr>
<td>7</td>
<td>Buildings</td>
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<td>50</td>
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</tbody>
</table>

### Present study: Flash flood in region of El Gouna

**Presents study:** Flash flood in region of El Gouna.

- Water resources management and modeling of hydrosystems.

### Parameter studies

- Runoff at catchment outlet
- Rain intensity
- Slope

**Lindemayer (2008)**

- Numerical results of rainfall runoff simulation.
Outline
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Conclusions and Outlook
- Idealized Catchment:
  - Most important parameter: inflow
- Model of El Gouna:
  - Water “reaches” the location of TUB Campus after ~ 4.4 hours
  - Infiltration was not considered
  - Constant inflow ≠ real natural condition
  - Next steps:
    - Implementation of measured hydrograph as boundary condition
    - Considering infiltration and comparing results
    - Grid refinement in the city area, resolving buildings and infrastructures
    - Implementation of structural protection measures:
      - Dams, canals, basins, local measures for buildings

References