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Coarse Grid Strategies for Computationally Efficient Flash Flood Simulations
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Flash floods are localized, sudden events characterized by a high rise of the water table in very short time usually caused by localized rainfall events with very high intensity. The short time period and relative small scale of flash flood events rise challenges in flood protection measures as well as the model-based forecasting of these events. Here, the resolution of large-scale weather prediction and hydrological models often is not sufficient to capture these very short and localized rainfall events and their consequences. In recent years, urban flood modeling is carried out with two-dimensional numerical models, which are able to reproduce the effects of buildings and other obstacles in city environment on the flood wave. These models are computationally expensive and real world applications are usually run on supercomputers. The main factor of the computational cost is the high-resolution required to capture the building and topography effects accurately. In this presentation, scaling strategies (sometimes referred to as coarse grid strategies) for the efficient numerical modeling of flash floods are presented. Coarse grid strategies aim to reduce computational effort by not directly discretizing but conceptually accounting for buildings or topography. This allows coarser grids with less cells, therefore reducing the computational cost while obtaining similar accuracy of the results (water levels, flooding areas, arrival time of flood peaks) when compared to fine grid (high-resolution) simulations. Two approaches are shown: (1) friction-law based approach, wherein the unresolved structures are described with an increased roughness coefficient and (2) anisotropic porosity approach where the fraction of the cell available to flow is described via a porosity term. The models are applied in case studies ranging from laboratory experiments to rainfall-runoff in small natural catchments. The presented case studies show that the friction-law based approach is more suitable for numerical rainfall-runoff simulations in small catchments while the anisotropic porosity approach performs better for flood modeling in urban environment. Limitations and capabilities of both approaches are discussed. Both model concepts speed up the calculation significantly, in most cases at least two orders of magnitude.
Coarse grid methods for computationally efficient flash flood simulations

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Introduction

- Shallow water flow processes are influenced at different scales and a large bandwith of scales must be considered, e.g., in urban flooding from pavement edges (~ 10cm) over buildings (~ 10m) to the whole city (~ 10 km) or in a catchment hydrology from microtopography (local depressions, ~ 1m) over a hillslope (~ 1km) to the whole catchment (~100km).
- One possibility to take all scales into account, is to resolve them all leading to high-resolution grids with very small cell sizes.
- Kim et al. (2014) show that the computational cost \( C \) for Godunov based flow solvers is related to the cell size \( L \) as:
\[
C \propto k / L^3
\]
where \( k \) is a factor dependent on the numerical scheme.

Outline

- Introduction
  - Coarse grid methods
  - Hydroinformatics Modeling System
  - Shallow water equations
  - Godunov-type scheme
- Friction law-based upscaling method
  - Governing equations
  - Computational examples
- Anisotropic porosity-based method
  - Governing equations
  - Computational examples
- Conclusions

Processes modeled with shallow water equations

- Flooding (classical)
- Rainfall-runoff (new)
- Robust shallow water models
- Coarse resolution: HPC (Distributed Memory/GPU)
  - Friction law based
  - Porosity based
- Predictions: fast, real time

Conclusion

- Coarse grid methods solve the shallow water equations on a coarse mesh and take the unresolved influences conceptually into account.
- This significantly reduces the computational time, thus allows fast simulations with acceptable accuracy.
- In the last two years, two coarse grid methods for shallow water flow have been developed at the Chair of Water Resources Management and Modeling of Hydrosystems (TU Berlin):
  1. Friction law-based upscaling approach developed by Özgen et al. (2015b, 2015c) and Teuber (2015)
  2. Anisotropic porosity-based upscaling approach developed by Özgen et al. (2015a, nd, a, nd b)
- The approaches have been implemented in the Hydroinformatics Modeling System (HMS).
Hydrological, hydraulic and environmental problems

Hinkelmann et al.

Contaminant transport

Hydrological, hydraulic and environmental problems

Urban runoff

Infiltration

Software design

HMS applications

Layer

Shallow water flow

Transport

Runoff generation

Geo-information

Core

Geometry

Spatial data

Mesh

Numerics

Mapping

Manager

Visualization

Parallelization

Busse et al. (2012), Simone et al. (2014)

Hydroinformatics Modeling System

HMS

Wahynd

- hms is a Java-based object-oriented modeling framework which solves shallow water flow and associated processes using a cell-centered Finite-Volume Method (Simone 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, TU Berlin, Germany

Shallow water equations

- The two-dimensional shallow water equations are a special case of the Navier-Stokes equations and can be written as:

\[
\begin{align*}
\frac{\partial \bar{\mathbf{q}}}{\partial t} + \nabla \cdot \mathbf{f}(\bar{\mathbf{q}}) &= -\nabla \cdot \mathbf{g}, \\
\mathbf{f}(\bar{\mathbf{q}}) &= \begin{bmatrix} 0 \\ \frac{1}{2} q_i q_j + 0.5 g h^2 \end{bmatrix}, \\
\mathbf{g}(\bar{\mathbf{q}}) &= \begin{bmatrix} q_i \varepsilon q_i \\ \frac{q_i}{h} - \frac{1}{2} g h^2 \end{bmatrix}, \\
\end{align*}
\]

where \( \bar{\mathbf{q}} \) denotes the vector of conserved variables, \( \mathbf{f} \) and \( \mathbf{g} \) stand for the flux vectors in x- and y-direction, respectively, and \( s \) is the source term vector.

Godunov-type scheme

- General formulation of cell-centered Finite-Volume method:

\[
\bar{\mathbf{q}}_i^{n+1} = \bar{\mathbf{q}}_i^n - \frac{\Delta t}{2} \sum_k F_k^e n_k l_k + \Delta \mathbf{g}^e
\]

where \( n_k \) is the normal vector of an edge, \( F_k^e \) is the flux vector over the edge, \( \Delta \mathbf{g}^e \) is the new source term at the edge.

- Godunov-type schemes calculate \( F_k^e \) by evaluating the Riemann problem at the edge.
The general structure of the HLLC Riemann solution is as follows:

- It allows efficient solution of SWE and any number of other processes which are not influencing the Riemann solution directly.
- It is second order accuracy in space, spurious oscillations in the solution are avoided by using TVD methods developed by Hou et al. (2013).

Friction law-based upscaling method

Many traditional friction laws relate the friction to the water depth $h$.
- The developed upscaling approach uses a dimensionless variable $\Lambda$, called inundation ratio, instead of the water depth.
- The inundation ratio was initially introduced by Lawrence (1997).

Governing equations

- The inundation ratio $\Lambda$ expresses the relationship between the water depth $h$ and the roughness height $k$.
- In this work, the standard deviation of the microtopography is taken as the roughness height $k$.

\[ \Lambda = \frac{h}{k} \]

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\[ \Lambda = \frac{h}{k} \]
Rainfall-runoff in a small alpine catchment (2)

- The standard deviation of the microtopography is σ = 0.20 m.
- The HR model uses cells with length ∆x = 1 m (DEM resolution).
- All other models use cells with length ∆x = 5 m, which is increased to ∆x = 10 m in a second and to ∆x = 20 m in a third simulation.
- Rain intensity is applied according to a measured time series.

Rainfall-runoff in a small alpine catchment (2)

High-resolution model

Rainfall-runoff in a small alpine catchment (2): Preliminary studies

The standard deviation of the microtopography is σ = 0.20 m.

The HR model uses cells with length ∆x = 1 m (DEM resolution).

All other models use cells with length ∆x = 5 m, which is increased to ∆x = 10 m in a second and to ∆x = 20 m in a third simulation.

Rain intensity is applied according to a measured time series.

Proposed roughness approach
The table below shows the speedups (wall time of coarse model / wall time of high-resolution model).

<table>
<thead>
<tr>
<th>Calc.</th>
<th>Size (HR)</th>
<th>Size (CR)</th>
<th>Nr. (HR)</th>
<th>Nr. (CR)</th>
<th>Ratio</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>2a</td>
<td>1 m</td>
<td>5 m</td>
<td>147 400</td>
<td>5896</td>
<td>25</td>
<td>56</td>
</tr>
<tr>
<td>2b</td>
<td>1 m</td>
<td>10 m</td>
<td>147 400</td>
<td>1474</td>
<td>100</td>
<td>336</td>
</tr>
<tr>
<td>2c</td>
<td>1 m</td>
<td>20 m</td>
<td>147 400</td>
<td>374</td>
<td>424</td>
<td>2520</td>
</tr>
</tbody>
</table>

- Speedup increases with cell ratio!

Friction-based upscaling methods: Concluding remarks and outlook

- The RM approach shows good agreement of discharge at outlet with the high-resolution simulation results and measurements.
- A speedup from about two to three orders of magnitude was achieved.
- An alternative friction law approach with 2 calibration parameters was developed by Teuber (2015), but investigations by Özgür et al. (2016) have found that the 3 parameter approach is a bit more advantageous.
- Calculating the inundation ratio individually in each cell is a bit more advantageous.
- Numerical experiments to further validate the approach and perhaps find upper and lower bounds for the calibration parameters are currently carried out at the Chair of Water Resources Management and Modeling of Hydrosystems.

Anisotropic porosity-based method

- The anisotropic porosity method accounts for the unresolved structures via two types of porosity:
  1. Volumetric porosity: Accounts for obstructions of flow inside the cell
  2. Areal porosity: Accounts for obstructions of flow at the cell edges

- As this method uses two types of porosities, it differs from single porosity methods, e.g. Defina (2000), Guinot & Scares-Frazão (2006), being referred to as isotropic porosity methods. This method is called anisotropic porosity method, cf. Sanders et al. (2008).

- Özgür et al. (2016a) extended the equations of Sanders et al. (2008) to account for full inundation of the computational cells.

Anisotropic porosity-based method

- Microtopography influences the flow in the cell.
- The cell can be considered as a porous medium and the microtopography can be taken into account as a porosity.

Anisotropic porosity-based method

- Volumetric porosity calculation:

  \[
  K_{volumetric} = \left( \frac{1}{n_{volumetric}} \right) 
  \]

  where \( n_{volumetric} \) is the number of pores in the cell.
Anisotropic porosity-based method

- In this figure the blue line illustrates the interface between the fluid and the unresolved blocks inside the cell, whereby the dashed line is the boundary of the cell.

Anisotropic porosity-based method

- Then, porosities are defined as:
  \[
  \phi = \frac{1}{V} \int \left( \delta(z - z_0) \right) dV \\
  \psi = \frac{1}{V} \int \left( \delta(z - z_0) \right) dV
  \]

whereby \( z_0 \) is the zero datum.

- In words, they stand for the ‘ratio of the volume available for the flow to the total volume of the cell’ and the ‘ratio of the area available for the flow to the total area of the cell edge’, respectively.

- Substituting the porosities into the integral shallow water equations gives the flux and source vectors of the shallow water equations with anisotropic porosity and the modified Finite-Volume expression, cf. Özgen et al. (2016a).

### Governing equations

- Multiplying every term (except the source term) of the shallow water equations gives:

\[
\begin{align*}
\eta &= h \\
\tilde{q} &= \left[ \begin{array}{c} q_x \\
q_y \end{array} \right] \\
\tilde{f} &= \left[ \begin{array}{c} f_x \\
f_y \end{array} \right] \\
\tilde{g} &= \left[ \begin{array}{c} g_x \\
g_y \end{array} \right] \\
\tilde{x} &= \left[ \begin{array}{c} -s_x \\
s_x + s_x' \end{array} \right]
\end{align*}
\]

### Governing equations

- The Finite-Volume formulation becomes:

\[
\begin{align*}
\phi \tilde{q} &= \frac{\phi \tilde{q} \tilde{f}}{V} - \frac{\Delta t}{V} \sum A V F \tilde{\eta} j A \Delta x^* + \tilde{\eta} \tilde{F} \tilde{z} dV \\
\tilde{q} &= \left( \begin{array}{c} \tilde{\eta} \tilde{\eta} - z_0 \\
\tilde{\eta} \tilde{\eta} - z_0 \end{array} \right) \\
\tilde{F} &= \left( \begin{array}{c} \tilde{\eta} \tilde{\eta} - z_0 \cr \tilde{\eta} \tilde{\eta} - z_0 \end{array} \right)
\end{align*}
\]

where the bar denotes a ‘volume-averaged’ variable and the circumflex denotes an ‘area-averaged’ variable.

- Porosities are updated every time step depending on the water level changes.
Similiar to the first dam break, the initial conditions are $\eta_0 = 0.03$ m on the left side and dry bed on the right side of the discontinuity. The microtopography of this case is plotted in the figure below (bed varies between 0 and 2 cm):

- A high-resolution model with $\Delta x = 0.01$ m is used as reference, the anisotropic porosity model uses a grid size of $\Delta x = 0.1$ m. Manning’s friction coefficient is $n = 0.016$ s m$^{-1/3}$.

Results at different times (high-resolution left, anisotropic porosity model right):

An overall speedup of about 1000 has been achieved.
Experiment conducted by Soares-Frazao & Zech (2008)

Özgen et al. (2016d)

High-resolution model result (HR) vs experimental data

AP model vs experiment vs averaged HR model

High-resolution model result (HR) vs experimental data

AP model vs experiment vs averaged HR model
### Cell sizes, number of cells, ratios and speedups

<table>
<thead>
<tr>
<th>Calc.</th>
<th>Size (HR)</th>
<th>Nr. (HR)</th>
<th>Size (AP)</th>
<th>Nr. (CR)</th>
<th>Ratio</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.01 m</td>
<td>30 000</td>
<td>0.1 m</td>
<td>300</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>0.01 m</td>
<td>180 000</td>
<td>0.1 m</td>
<td>1800</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>0.02 m</td>
<td>45 000</td>
<td>0.1 m</td>
<td>4500</td>
<td>25</td>
<td>550</td>
</tr>
<tr>
<td>6</td>
<td>0.01 m</td>
<td>28 000</td>
<td>0.1 m</td>
<td>56</td>
<td>500</td>
<td>1140</td>
</tr>
<tr>
<td>7</td>
<td>0.01–0.3 m</td>
<td>96 339</td>
<td>0.25 m</td>
<td>1272</td>
<td>75</td>
<td>750</td>
</tr>
</tbody>
</table>

### Anisotropic porosity-based method: Concluding remarks and outlook

- The anisotropic porosity approach shows good agreement with the high-resolution simulation results for water levels and discharge at outlet, though local details below the coarse grid scale, e.g., discharge in field, can not be resolved.
- Speedups between two and three orders of magnitude were achieved. Coarse grids have been effective when the product of the cell size and the interfacial pressure are too small based on the authors’ experience, the bounds of these product during the calibration should be in the range [0.00 m²].
- Özgen et al. (2016b) show that the stationary part of the interfacial pressure term can be utilized for well-balanced the numerical model.

### Overall conclusions regarding coarse grid methods

- Fast predictions are important for models that try to forecast flash floods.
- Two novel coarse grid methods for the fluvial and pluvial flood modeling have been presented and have been applied to academic test cases, laboratory-scale cases and a “real-world” case.
- The accuracy of water levels and discharge is satisfying for flash flood forecasting considering comparisons with high-resolution grids and measurements.
- Significant speedups of two to three orders of magnitude were achieved. The speedup for both methods (friction-law based and anisotropic porosity-based) is about the same and increases with problem size.
- Local flow details, e.g., discharge in field, can not be reproduced, however this can not be expected from such models but the arrival time of the wave and the average behavior of the flow could be reproduced with satisfactory accuracy.

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**Coarse grid methods for computationally efficient flash flood simulations**

**END**

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References


References