Shallow Water Flow Based Simulation of Flash Floods in Small Catchments

Franziska Tügel[1,*], Ilhan Özgen[1], Ahmed Hadidi[2], Uwe Tröger[3], Reinhard Hinkelmann[1]

[1]Chair of Water Resources Management and Modeling of Hydrosystems, Technische Universität Berlin
[2]Chair for Hydrogeology, Technische Universität Berlin, [3]TU-Berlin, Zentralinstitut El Gouna, Fraunhoferstr. 33-35, 10587 Berlin
[*]Corresponding author

Email: franziska.tuegel@wahyd.tu-berlin.de

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.

International Symposium on Flash Floods in Wadi Systems ISFF

TU berlin CAMPUS EL GOUNA

Shallow water flow based simulation of flash floods in small catchments

F. Tügel, I. Özgen, A. Hadidi, U. Tröger, R. Hinkelmann

Chair of Water Resources Management and Modeling of Hydrosystems, Department of Civil Engineering, Technische Universität Berlin TU-Berlin, Zentralinstitut El Gouna

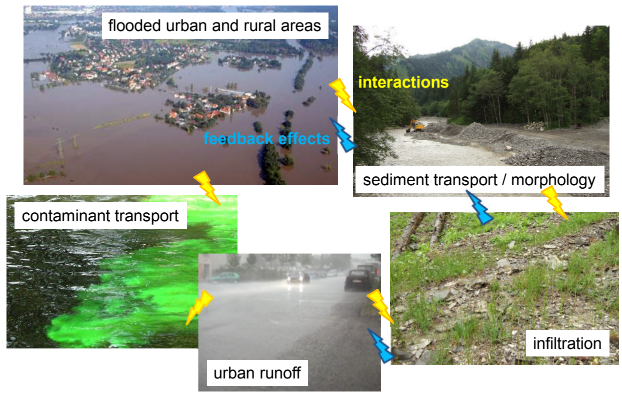
Outline

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

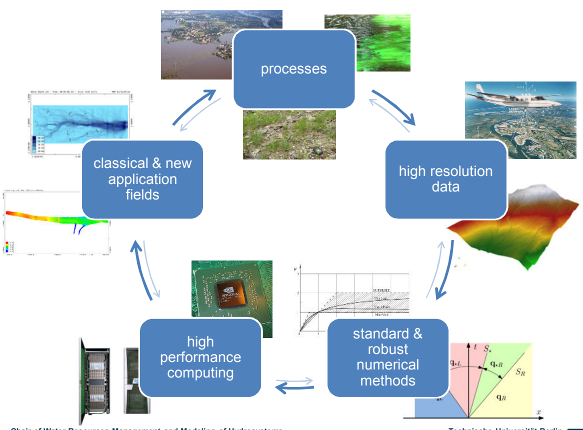
Outline

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

Hydrological, hydraulic and environmental problems



Numerical modeling of hydro- and environmental systems



Flash floods

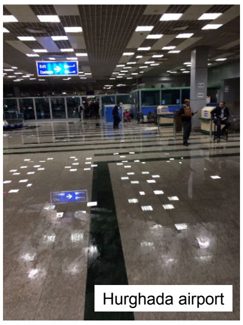
Simulation of flash floods to:
- analyze structural protection measures
- develop early warning systems

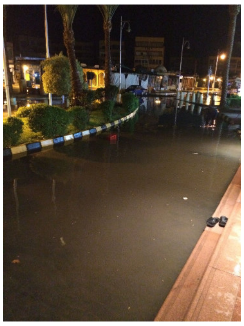
2D shallow water models:
- consider complex topographies, flooding areas and local flow processes
- support high-resolution grids (~1m) to better resolve urban structures
- include robust numerical methods which enable the modelling of propagating wet-dry fronts
- deliver results of flow evolution in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

Flash floods

El Gouna, 9th March 2014

Hurghada 9th March 2014





Berlin, 27th July 2016

Berlin, 27th July 2016

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

Outline

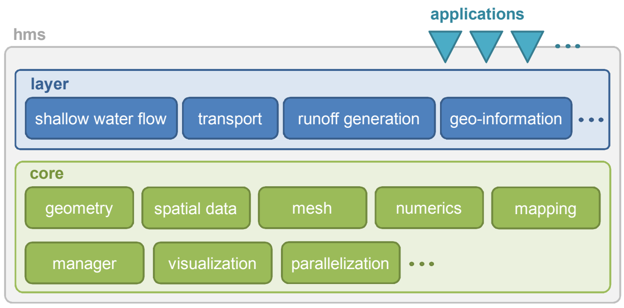
- Motivation
- Modelling framework, physics and numerics
- Applications
- Conclusions and Outlook

Hydroinformatics Modeling System

wahyd hms

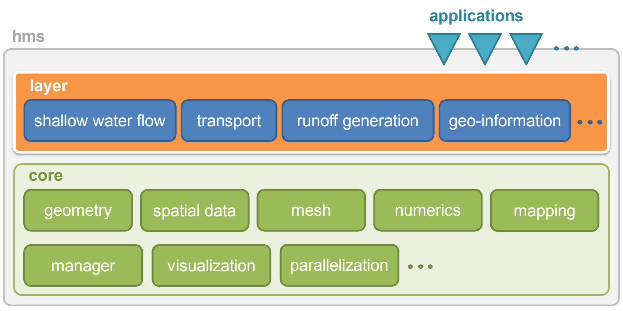
- hms is a Java-based object-oriented modeling framework which solves shallow water flow and associated processes using a cell-centered Finite-Volume Method (Simons *et al.* 2014).
- 'Easy' implementation of extensions, e.g. new conceptual approaches, coupling of processes
- 'Easy' handling of spatial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

Software design



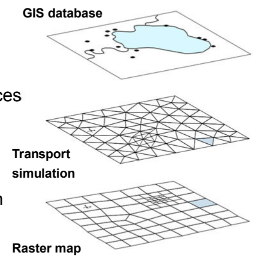
Busse *et al.* (2012), Simons *et al.* (2014)

Software design

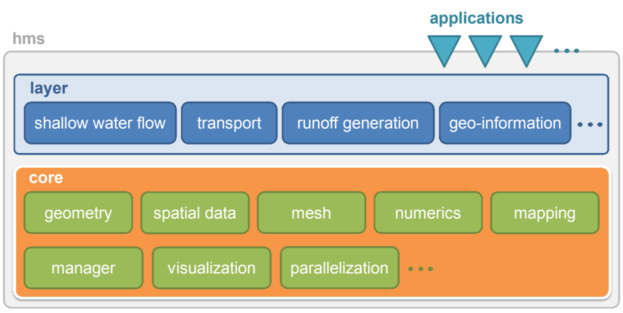


hms layer concept

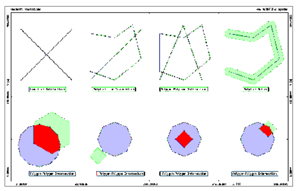
- Layers contain geometrical information, data, meta-data, methods, …
- Accessible through generalized interfaces
- Independent of represented information
  → Physically-based model
  → Geospatial database
  → External data sources
  → …



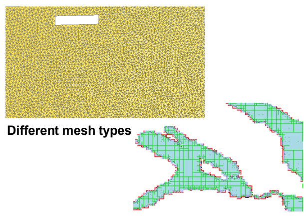
Software design



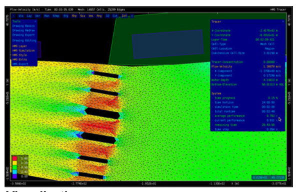
hms core



Geometry library



Different mesh types



Visualization

Shared-memory parallelization

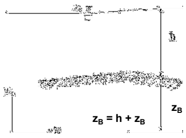
Shallow water equations

- Two-dimensional shallow water equations:

$$\mathbf{q} = \begin{bmatrix} h \\ uh \\ vh \end{bmatrix},\ \mathbf{f} = \begin{bmatrix} \mathbf{v}h \\ \mathbf{v}uh + {}^1\!/_2 gh^2 - \nu_t \nabla(uh) \\ \mathbf{v}vh + {}^1\!/_2 gh^2 - \nu_t \nabla(vh) \end{bmatrix},\ \mathbf{s} = \begin{bmatrix} r \\ -\tau_{Bx}/\rho - gh\,\partial z_B/\partial x - f_x/\rho \\ -\tau_{By}/\rho - gh\,\partial z_B/\partial y - f_y/\rho \end{bmatrix}$$

storage flux source term

r mass sink/source term (e.g. rainfall, infiltration)
ν_t turbulent viscosity
τ_B bottom shear stress
f external forces (e.g. wind, coriolis)
ρ density



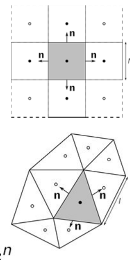
→ Constant turbulent viscosity or algebraic turbulence model
→ Hydrostatic reconstruction for well-balanced results
→ Point-implicit solution of friction term

General Finite-Volume solver

- General form of 2D conservation law:

$$\frac{\partial \mathbf{q}}{\partial t} + \nabla \cdot \mathbf{f} = \mathbf{s}$$

storage flux source term



- General cell-centered Finite-Volume method:

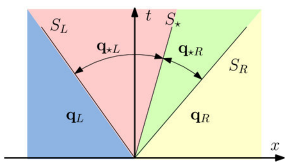
$$\mathbf{q}^{n+1} = \mathbf{q}^n - \frac{\Delta t}{A} \sum_k \mathbf{f}_k^n \cdot \mathbf{n}_k l_k + \Delta t\, \mathbf{s}^n$$

→ independent of mesh type
→ explicit time discretization

Simons et al. (2013)

"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



HLLC solution

Runoff generation / infiltration

- Effective rainfall → runoff generation model

→ Infiltration

→ Evapotranspiration (planned)

- Conservation law for the soil water content:

$$\mathbf{q} = [\theta],\ \mathbf{f} = [0],\ \mathbf{s} = [i]$$

storage flux source term

Infiltration in the unsaturated zone

→ Green-Ampt or Phillip's model

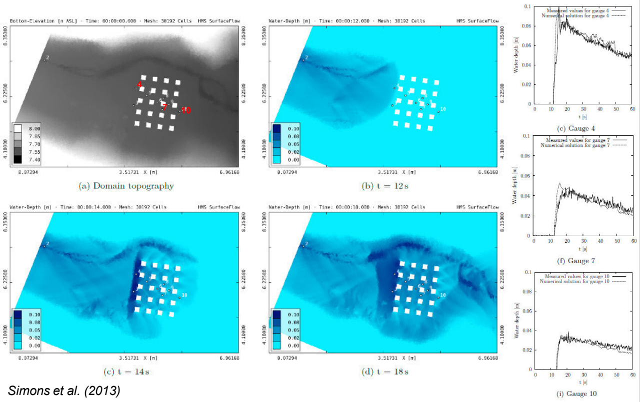
→ Coupling with Richard's or two-phase flow model

Outline

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

Previous studies

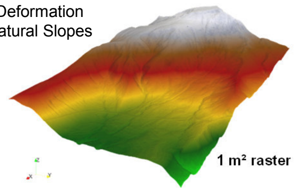
Flash flood in an simplified urban district

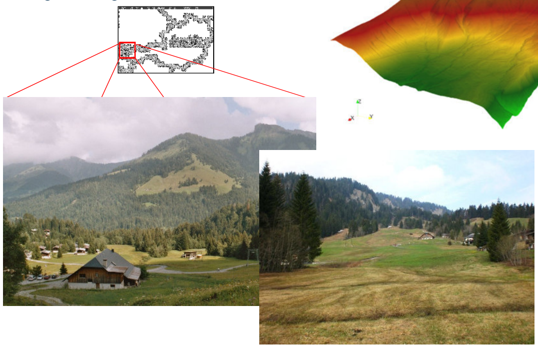


Simons et al. (2013)

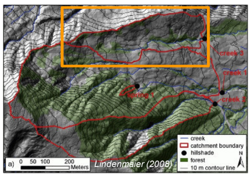
Heumöser slope

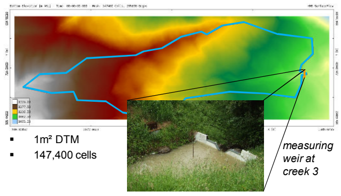
DFG **Research Unit:** Coupling of Flow and Deformation Processes for Modelling the Movement of Natural Slopes
www.grosshang.de



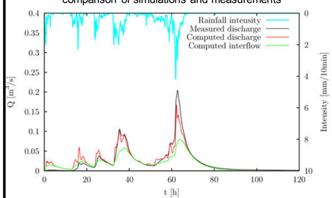


Numerical results of rainfall runoff simulation

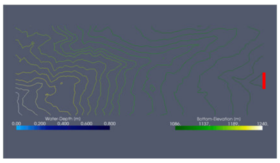




comparison of simulations and measurements



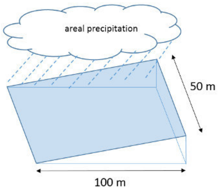
runoff simulation



Simons et al. (2013)

Present study: Flash flood in region of El Gouna

Parameter studies on idealized catchment

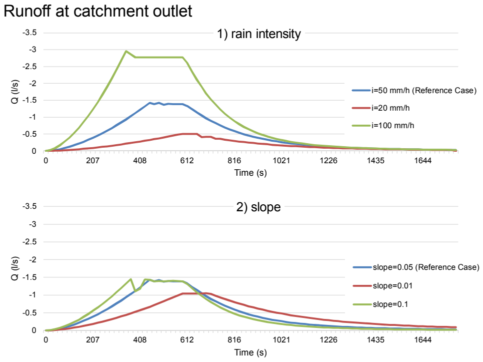


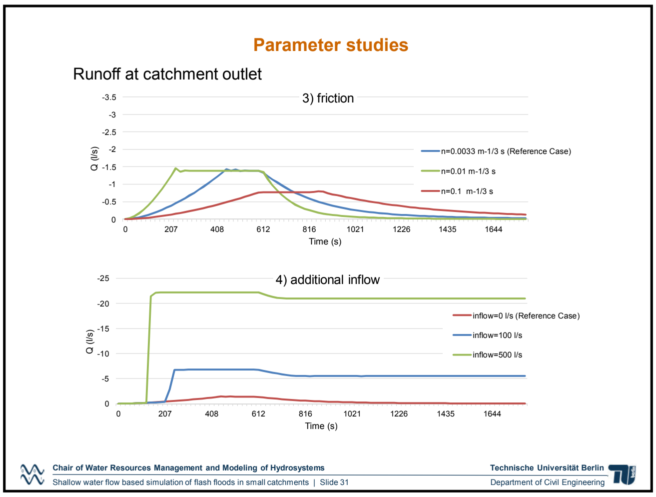
- sloped plane
- grid resolution: 1m
- 5000 cells
- constant rainfall over the domain
- rain duration = 600 s

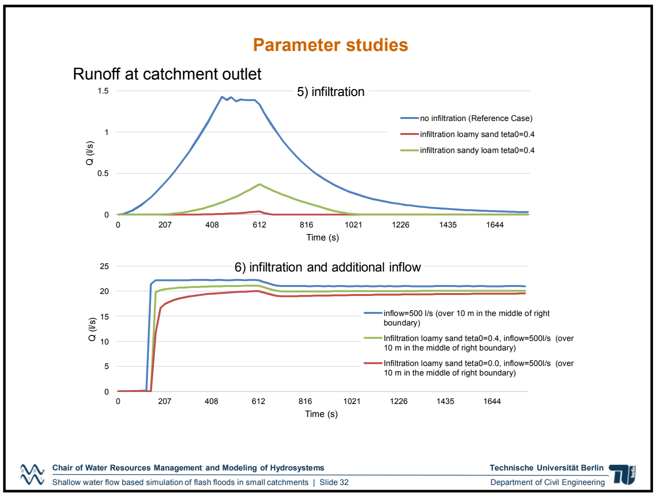
Variation	Parameter	Reference Case	a	b
1	rain intensity (mm/h)	50	20	100
2	slope (%)	5	0.01	0.1
3	friction ($m^{-1/3}s$)	0.033	0.01	0.1
4	inflow (l/s)	0	100	500
5	infiltration	no infiltration	loamy sand, Θi=0.4	sandy loam, Θi=0.4
6	infiltration & inflow	-	loamy sand, Θi=0.4,	loamy sand, Θi=0.0
7	buildings	0	3x3	-

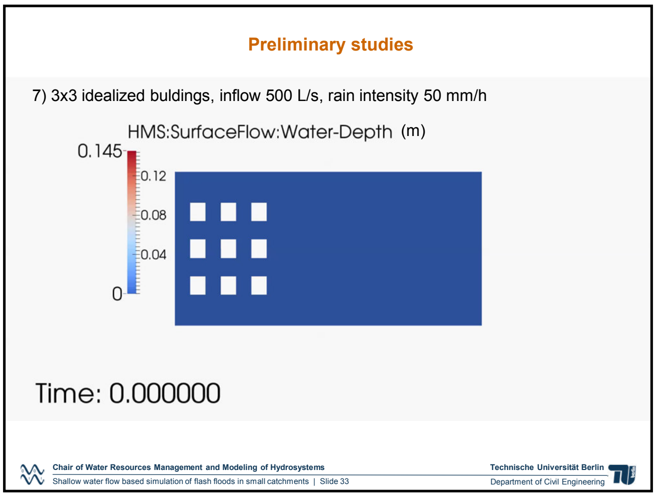
Parameter studies

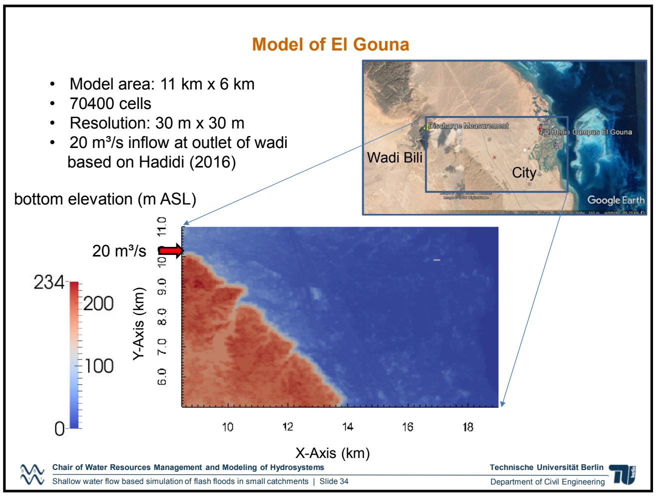
Runoff at catchment outlet

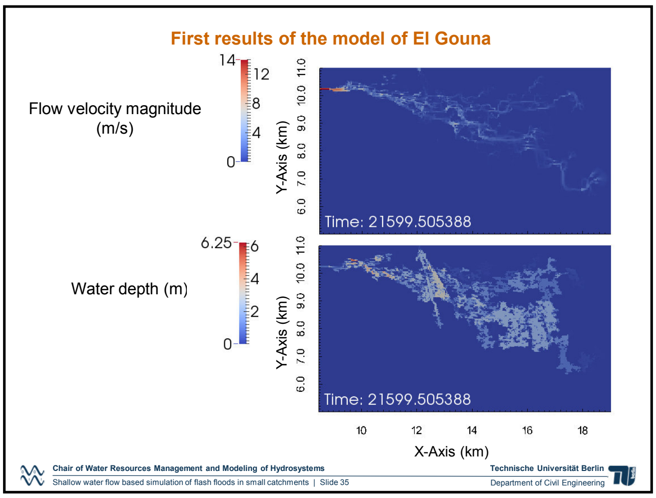


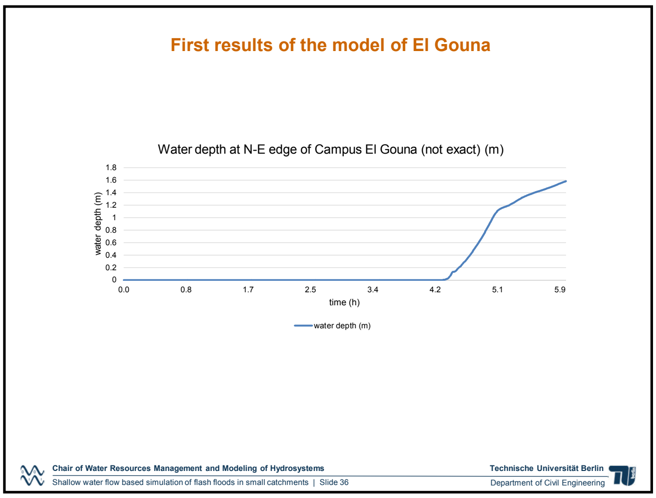

Parameter studies
Runoff at catchment outlet
3) friction
Q (l/s)
Time (s)
n=0.0033 m-1/3 s (Reference Case)
n=0.01 m-1/3 s
n=0.1 m-1/3 s
4) additional inflow
Q (l/s)
Time (s)
inflow=0 l/s (Reference Case)
inflow=100 l/s
inflow=500 l/s
Chair of Water Resources Management and Modeling of Hydrosystems
Shallow water flow based simulation of flash floods in small catchments | Slide 31
Technische Universität Berlin
Department of Civil Engineering


Parameter studies
Runoff at catchment outlet
5) infiltration
Q (l/s)
Time (s)
no infiltration (Reference Case)
infiltration loamy sand teta0=0.4
infiltration sandy loam teta0=0.4
6) infiltration and additional inflow
Q (l/s)
Time (s)
inflow=500 l/s (over 10 m in the middle of right boundary)
Infiltration loamy sand teta0=0.4, inflow=500l/s (over 10 m in the middle of right boundary)
Infiltration loamy sand teta0=0.0, inflow=500l/s (over 10 m in the middle of right boundary)
Chair of Water Resources Management and Modeling of Hydrosystems
Shallow water flow based simulation of flash floods in small catchments | Slide 32
Technische Universität Berlin
Department of Civil Engineering


Preliminary studies
7) 3x3 idealized buldings, inflow 500 L/s, rain intensity 50 mm/h
HMS:SurfaceFlow:Water-Depth (m)
0.145
0.12
0.08
0.04
0
Time: 0.000000
Chair of Water Resources Management and Modeling of Hydrosystems
Shallow water flow based simulation of flash floods in small catchments | Slide 33
Technische Universität Berlin
Department of Civil Engineering


Model of El Gouna
• Model area: 11 km x 6 km
• 70400 cells
• Resolution: 30 m x 30 m
• 20 m³/s inflow at outlet of wadi based on Hadidi (2016)
bottom elevation (m ASL)
Wadi Bili
City
Google Earth
20 m³/s
234
200
100
0
Y-Axis (km)
X-Axis (km)
Chair of Water Resources Management and Modeling of Hydrosystems
Shallow water flow based simulation of flash floods in small catchments | Slide 34
Technische Universität Berlin
Department of Civil Engineering


First results of the model of El Gouna
Flow velocity magnitude (m/s)
14
12
8
4
0
Y-Axis (km)
Time: 21599.505388
Water depth (m)
6.25
6
4
2
0
Y-Axis (km)
Time: 21599.505388
X-Axis (km)
Chair of Water Resources Management and Modeling of Hydrosystems
Shallow water flow based simulation of flash floods in small catchments | Slide 35
Technische Universität Berlin
Department of Civil Engineering

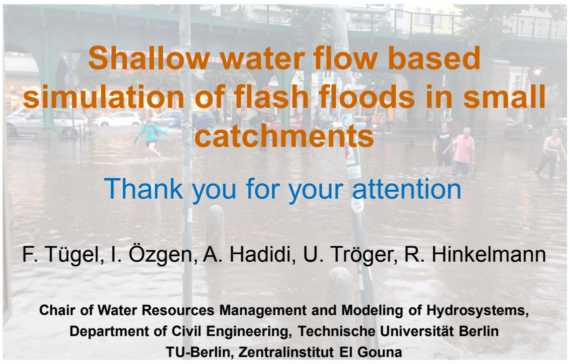

First results of the model of El Gouna
Water depth at N-E edge of Campus El Gouna (not exact) (m)
water depth (m)
time (h)
water depth (m)
Chair of Water Resources Management and Modeling of Hydrosystems
Shallow water flow based simulation of flash floods in small catchments | Slide 36
Technische Universität Berlin
Department of Civil Engineering

Outline

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

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 → not natural
- 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

- Busse, T., Simons, F., Mieth, S., Hinkelmann, R. & Molkenthin, F. (2012): HMS: A generalised software design to enhance the modelling of geospatial referenced flow and transport phenomena. In Proceedings of the 10th International Conference on Hydroinformatics. Hamburg, Germany.
- Cao, Z., Pender, G., Wallis, S. & Carling, P. (2004): Computational dam-break hydraulics over erodible sediment bed. *Journal of hydraulic engineering*, *130*(7), 689-703.
- Hadidi, A. (2016): Wadi Bili Catchment in the Eastern Desert - Flash Floods, Geological Model and Hydrogeology. PhD thesis, TU Berlin, Fak. VI Planen Bauen Umwelt.
- Hou, J., Liang, Q., Simons, F. & Hinkelmann, R. (2013): A 2D well-balanced shallow flow model for unstructured grids with novel slope source term treatment. Advances in Water Resources, 52, 107–131. doi:10.1016/j.advwatres.2012.08.003
- Notay, K. V., Stadler, L., Simons, F., Molkenthin, F., & Hinkelmann, R. (2012): Model Coupling in Hydroinformatics Systems through the use of Autonomous Tensor Objects. In Proceedings of the 10th International Conference on Hydroinformatics. Hamburg, Germany.
- Özgen, I., Seemann, S., Candeias, A. L., Koch, H., Simons, F. & Hinkelmann, R. (2013): Simulation of hydraulic interaction between Icó-Mandantes bay and São Francisco river, Brazil. In G. Gunkel, J. A. A. Silva, & M. C. Sobral (Eds.), Sustainable Management of Water and Land in Semiarid Areas (pp. 28–38). Recife: UFPE.
- Simons, F., Busse, T., Hou, J. & Hinkelmann, R. (2013): A model for overland flow and associated processes within the Hydroinformatics Modelling System. Journal of Hydroinformatics. doi:10.2166/hydro.2013.173.
- Simons, F., Busse, T., Hou, J., Notay, K. V. & Hinkelmann, R. (2011): A Robust and Efficient Solver for the Shallow Water Equations and its Application to a Complex Natural Hydrosystem. In Proceedings of the 34th IAHR Congress (pp. 4276–4283). Brisbane, Australia: Engineers Australia.
- Simons, F., Busse, T., Hou, J., Özgen, I. & Hinkelmann, R. (2012): HMS: Model Concepts and Numerical Methods around Shallow Water Flow within an Extendable Modeling Framework. In Proceedings of the 10th International Conference on Hydroinformatics. Hamburg, Germany.