Investigation of the Green-Ampt infiltration model in rainfall-runoff simulations with a robust 2D shallow water model

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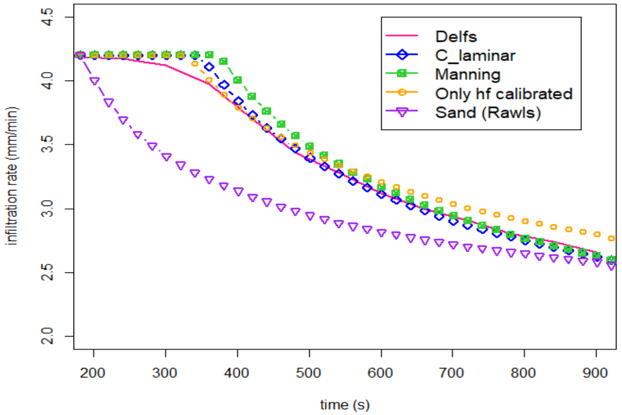
Source: Soliman (2016)

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Outline

- Motivation
- Methods
- Results
- Conclusions & Outlook

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Flash flood modeling

- Flash floods are one of the most dangerous natural hazards, they can occur all over the world and are likely to increase due to climate change
- Numerical models are a useful tool for the risk assessment as well as to investigate different possible mitigation measures
- Due to sudden occurrence and fast flow velocities, flash floods are hardly measureable → lack of data for model calibration
  - ➢ Remote sensing and crowdsourcing can complement classical measurements
  - ➢ Physically-based methods with no need of (many) calibration parameters are preferable
  - ➢ Ideal: robust 2D shallow water model with high-resolution and accurate digital elevation model (DEM) and an appropriate infiltration model, whose parameters could be derived from soil type


Source: Hadidi (2016)

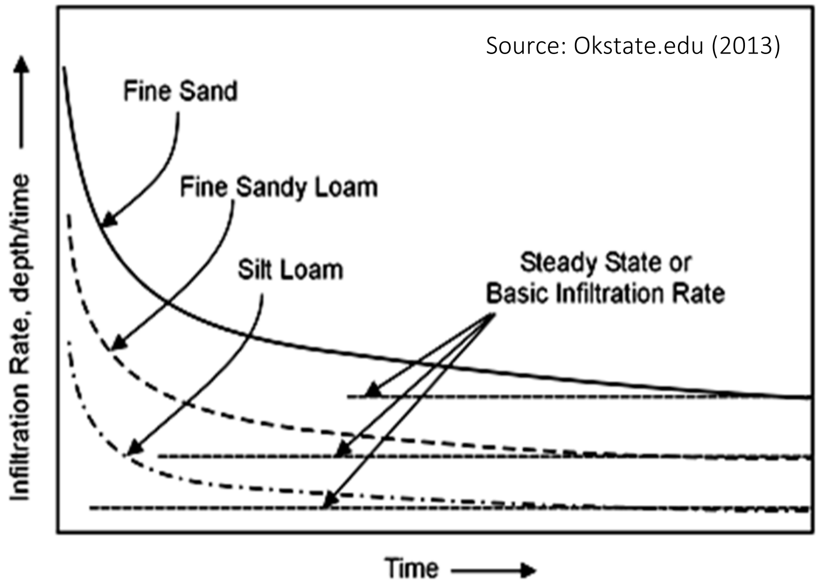
Flash flood in Wadi Bili, El Gouna, Egypt, March 2014


Source: Soliman (2016)

Flash flood in Ras Gharib, Egypt, October 2016

The role of infiltration

- Infiltration: most important water losses during flash floods
- Especially in areas with less sealed surfaces, infiltration cannot be neglected (as for example also urban green infrastructure)
- Good understanding of infiltration is crucial for an appropriate representation of runoff generation & transmission losses during flash floods, as well as for successful solutions of groundwater recharge in arid areas



Infiltration rates over time for different soils

Hydroinformatics Modeling System

wahyd hms

- Flow: 2D shallow water equations (fully dynamic)
- Spatial discretization: cell-centered finite-volume method
- Time discretization: explicit forward Euler method

- Robust solution methods:
  - 2nd order MUSCL scheme, switches to 1st order scheme at wet-dry fronts
  - HLLC Rieman solver to compute fluxes over cell-edges
  - TVD scheme avoids spurious oscilliations
  - Water depth threshold to consider a cell as wet: 10^{-6} m

- For further reading, the PhD thesis of Simons (2020) is recommended

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Green-Ampt model

- One of the most used physically-based infiltration models
- Has been proven to be able to represent infiltration behaviour appropriately
- Simplification: piston-type flow into the soil, sharp wetting front
- Cumulative infiltration F(t): iterative calculation

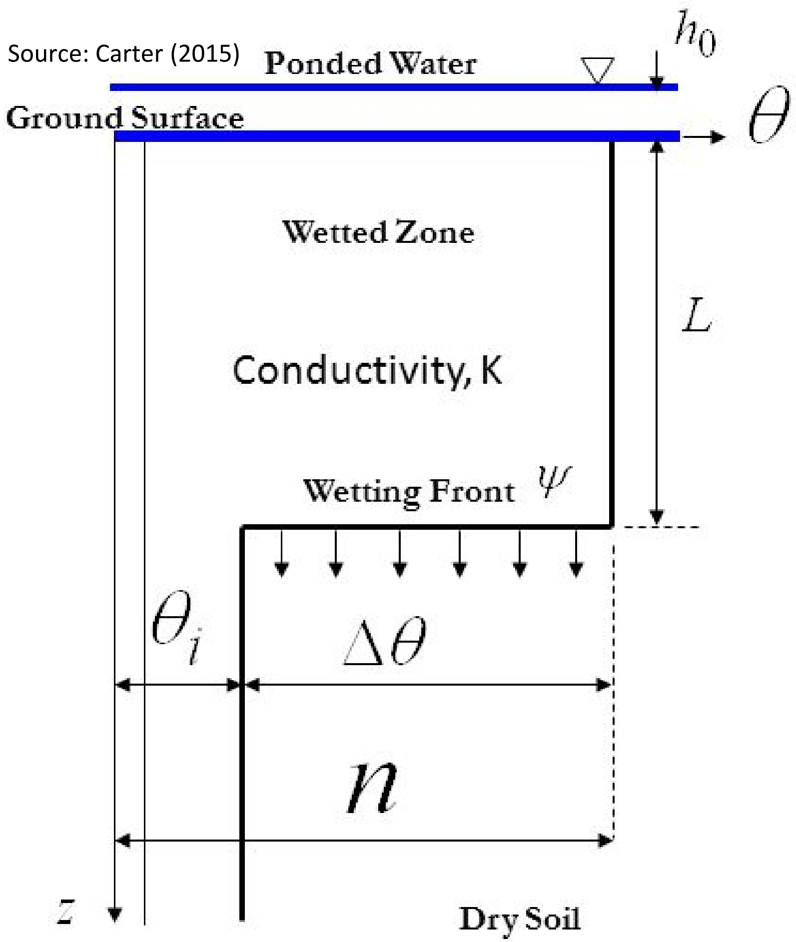
$$F(t) = Kt + \Delta h \Delta\theta \ln\left(1 + \frac{F(t)}{\Delta h \Delta\theta}\right)$$

- Infiltration rate f(t): $$\frac{dF}{dt} = f(t) = K\left(1 + \frac{(h_0 - \psi)\Delta\theta}{F(t)}\right)$$

n: effective porosity (-)
θ_i: initial water content (-)
h_o: ponding water depth at the surface (m)
ψ: soil suction head (m)
K_s: saturated hydraulic conductivity (m/s)

$$\Delta\theta = n - \theta_i$$
$$\Delta h = h_0 - \psi$$
$$K = \frac{K_s}{2}$$

Source: Carter (2015)



Water content profile corresponding to the Green-Ampt infitlration model

Extended Green-Ampt model for crusted surfaces

- Brakensiek & Rawls (1983) proposed to calculate the effective hydraulic conductivity of a two-layer soil - crust and subcrust - by a harmonic mean (Rawls et al. 1990):

$$K_e = K_c \ \ if \ z_f \leq Z_c$$

$$K_e = \frac{z_f}{\frac{z_f - Z_c}{K} + \frac{Z_c}{K_c}} \ \ if \ z_f > Z_c$$

K_e: effective hydraulic conductivity

K_c: crust hydraulic conductivity

Z_c: crust thickness

z_f: wetted depth

- The higher the wetted depth, the higher the effective hydraulic conductivity

Literature values for GA parameters depending on soil texture class

Average values and one standard deviation of the Green-Ampt parameters after Rawls et al. (1983)

Soil texture class	Effective porosity n_{eff} (-)	Soil suction head Ψ (cm)	Hydraulic conductivity K (cm/h)
Sand	0.417 (0.354-0.480)	4.95 (0.97-25.36)	11.78
Loamy sand	0.401 (0.329-0.473)	6.13 (1.35-27.94)	2.99
Loam	0.434 (0.334-0.534)	8.89 (1.33-59.38)	0.34
Sandy clay loam	0.330 (0.235-0.425)	21.85 (4.42-108.0)	0.15

Questions:

- Can the average parameters be taken as acceptable assumptions, if no measurements are available and therefore no calibration is possible?
- Is the modified GA model for crusted soils suitable?

Optimization techniques for automatic calibration

- Optimization techniques can be used to find the best fit between observed and simulated time series if the calibration parameters are given in reasonable ranges
- Simplicial homology global optimization (SHGO) algorithm is used, available in the SciPy package *optimization* (Endres et al. 2018)
- Used objective functions: Nash-Sutcliffe efficiency NSE (Nash & Sutcliffe 1970) and non-parametric Kling-Gupta effeciency R_{NP} (Pool et al. 2018), which are included in the PyPI package *hydroeval* (Hallouin 2019), were used to evaluate the simulated runoffs

$$NSE = 1 - \frac{\sum(Q_{sim} - Q_{obs})^2}{\sum(Q_{obs,mean} - Q_{obs})^2}$$

$$R_{\mathrm{NP}} = 1 - \sqrt{(\beta - 1)^2 + (\alpha_{\mathrm{NP}} - 1)^2 + (r_s - 1)^2}$$

Procedure

- For three test cases with available data for calibration, different simulations were carried out:

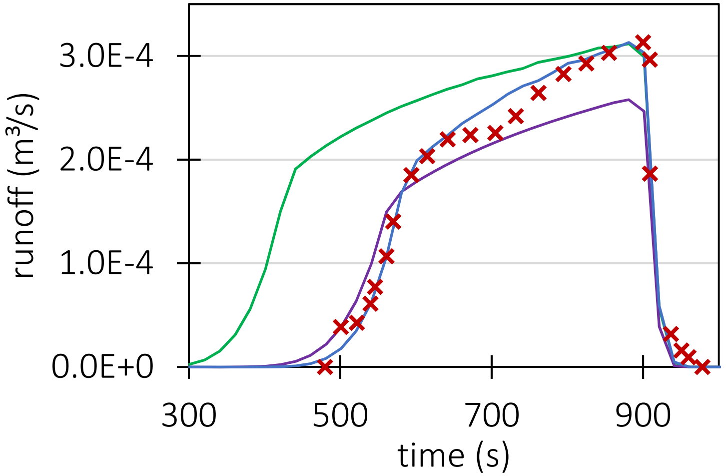
  1. Average values for Green-Ampt parameters for the given soil (after Rawls et al., 1983)
  2. Finding the optimum parameter set within the ranges for the given soil type (after Rawls et al., 1983)
  3. Optional: Find the optimum parameter set in larger ranges (for example the combined range of 2 soil types)
  4. Using parameters given in literature (from measurements or calibration)

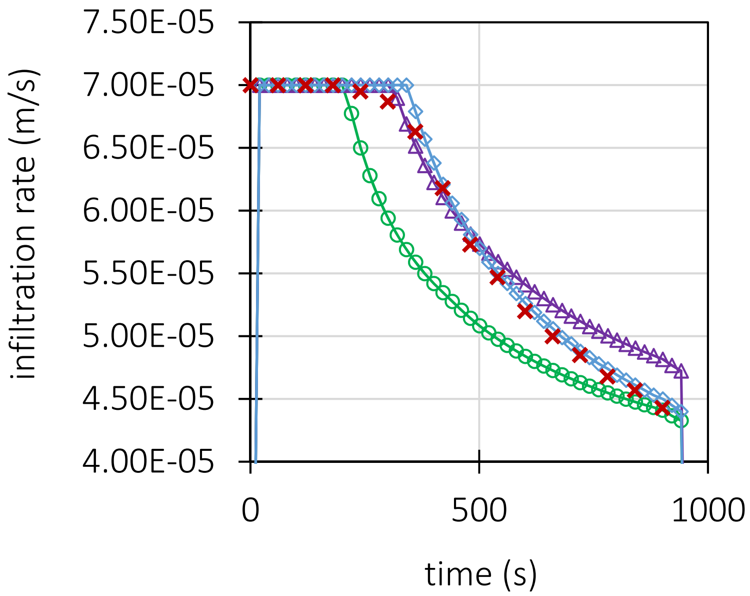
  ➢ Runoff hydrographs from different parameter sets are evaluated through comparison to the observed one

- Finally, a case study with flash flood simulations in Egypt is represented for different infiltration parameters, showing the plausibilty of the results as well as the impact of friction on infiltration processes

Test case 1:

Laboratory experiment after Smith & Woolhiser (1971)
soil type: sand, length: 12.2 m, slope: 1 %



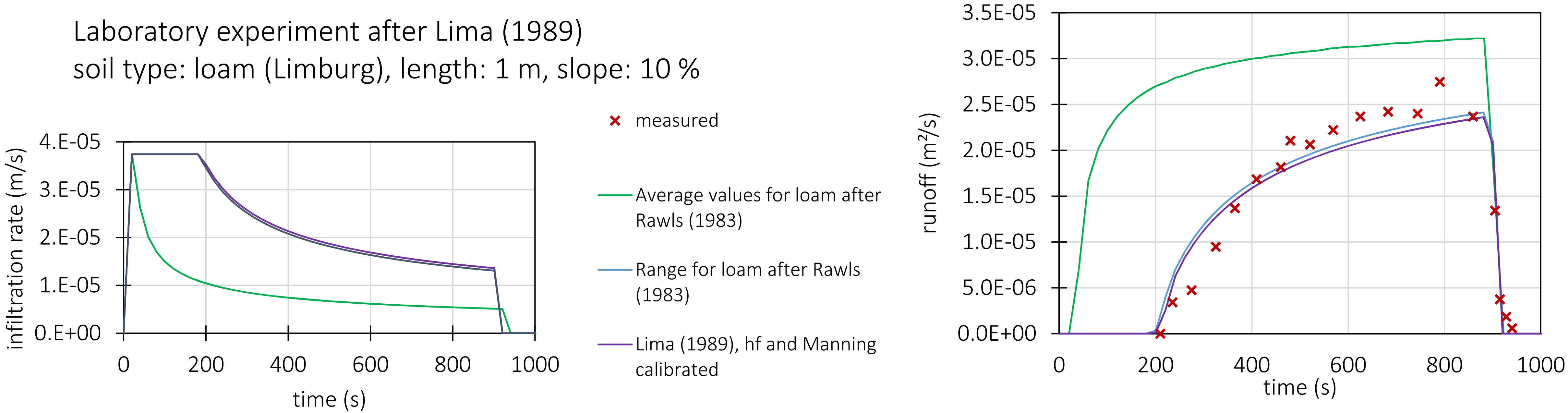


	Initial water content	Green Ampt parameters			Friction	Performance
	θ_i	θ_S	K	h_f	$C_{laminar}$	NSE
	m³/m³	m³/m³	m/s	m	$mm^{-1}min^{-1}$	-
Optimized, range for loamy sand – sand* and calibration of θ_i and $C_{laminar}$	0.123	0.425	2.10E-05	-0.189	79703	0.986
Average values for sand after Rawls (1983)	0.083	0.417	3.27E-05	-0.049	80000	-0.245
Delfs et al. (2009) (different model)	0.084	0.399	2.83E-05	-	80000	0.982
Optimized, range for sand*	0.080	0.397	3.27E-05	-0.078	80000	0.871

$C_{laminar}$: Chezy friction coefficient for laminar flow as explained in Delfs et al. (2009)
* After Rawls et al. (1983)

Test case 2:

Laboratory experiment after Lima (1989)
soil type: loam (Limburg), length: 1 m, slope: 10 %

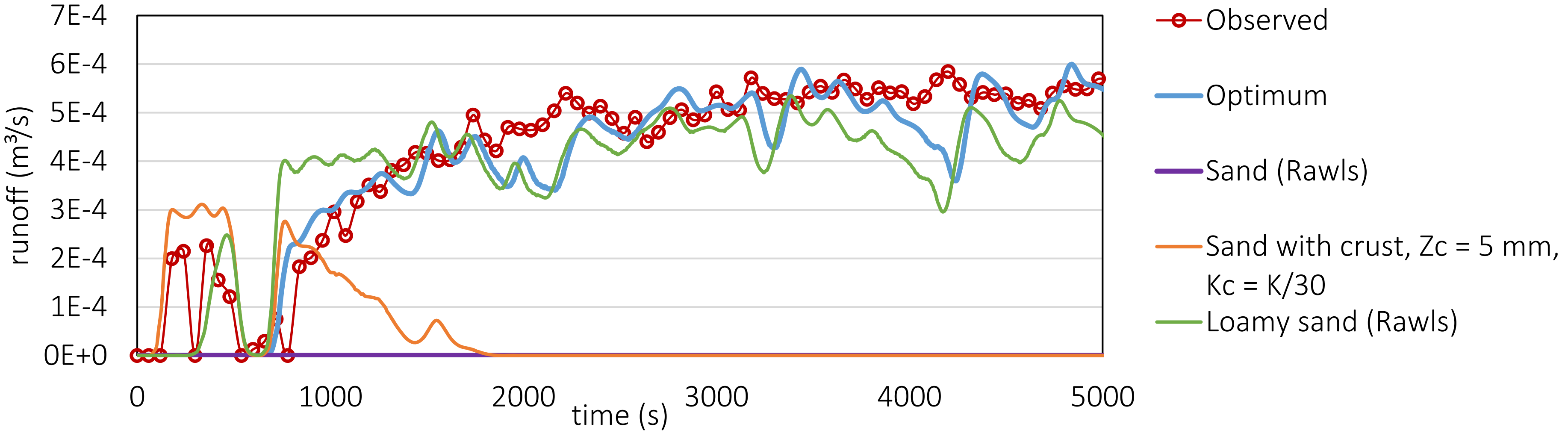


	Initial water content	Green Ampt parameters			Friction	Performance	
	θ_i	θ_S	K	h_f	Manning	NSE	KGEnp
	m³/m³	m³/m³	m/s	m	s/m$^{1/3}$	-	-
Range for loam after Rawls (1983)	0.0107	0.503	9.45E-7	-0.5393	0.021	0.928	0.924
Lima (1989), hf and Manning calibrated*	0.0107	0.506	1.67E-6	-0.3035	0.021	0.930	0.927
Average values for loam after Rawls (1983)	0.0107	0.434	9.45E-7	-0.0889	0.020	-1.186	0.200

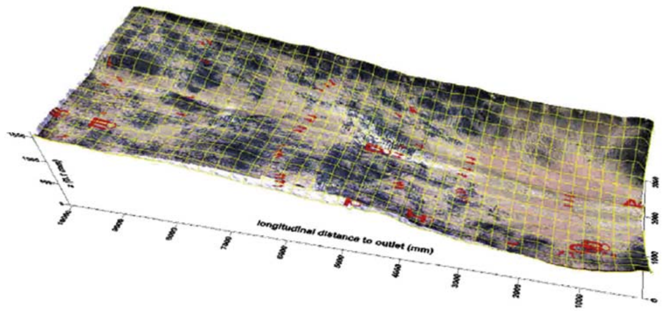
*bounds hf for loam after Rawls (1983), bounds for Manning: 0.01-0.033, for bare sand – bare clay-loam after Engman (1986)

Test case 3:

Surface runoff experiment in Thiès catchment, Senegal (Tatard et al. 2008)
soil type: sand, length: 10 m, width: 4 m, slope: 1 %



Location of plot in Senegal



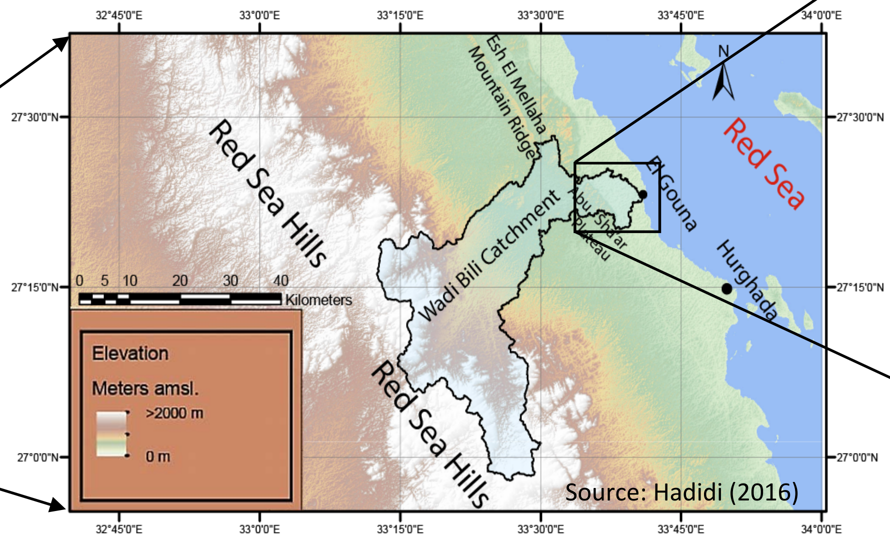
View of the plot (Mügler et al., 2011)

	Initial water content	Green Ampt parameters			Performance
	θ_i	θ_s	K	h_f	NSE
	m³/m³	m³/m³	m/s	m	-
Optimum, range for sand, but lower K value from calibration after Simons (2020)	0.20	0.378	4.50E-06	-0.192	0.807
Sand (average values after Rawls)	0.20	0.417	3.27E-05	-0.0495	-5.052
Sand with crust, Zc = 5 mm, Kc = 1.09E-06	0.260	0.417	3.27E-05	-0.0495	-0.843
Loamy sand (average values after Rawls)	0.260	0.401	8.31E-06	-0.0613	0.605

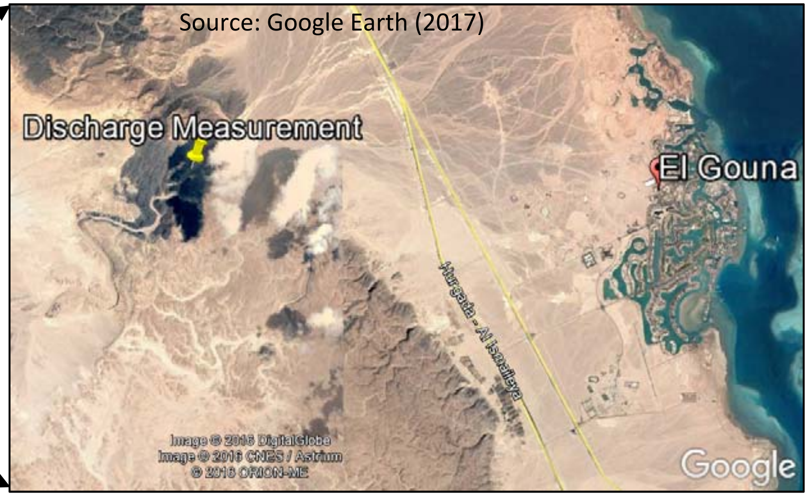
Case study in region of El Gouna, Egypt

- El Gouna is a touristic town at the Red Sea coast 25 km north of Hurghada
- The main wadi affecting the city is Wadi Bili with approx. 880 km² catchment area
- Several flash floods occurred in the last years, and might become more often due to climate change
- During the flash flood event in March 2014 Ahmed Hadidi carried out runoff measurements at Wadi Bili

Location of Wadi Bili in Egypt



Wadi Bili catchment area ~880 km²



El Gouna and position of runoff measurements in March 2014

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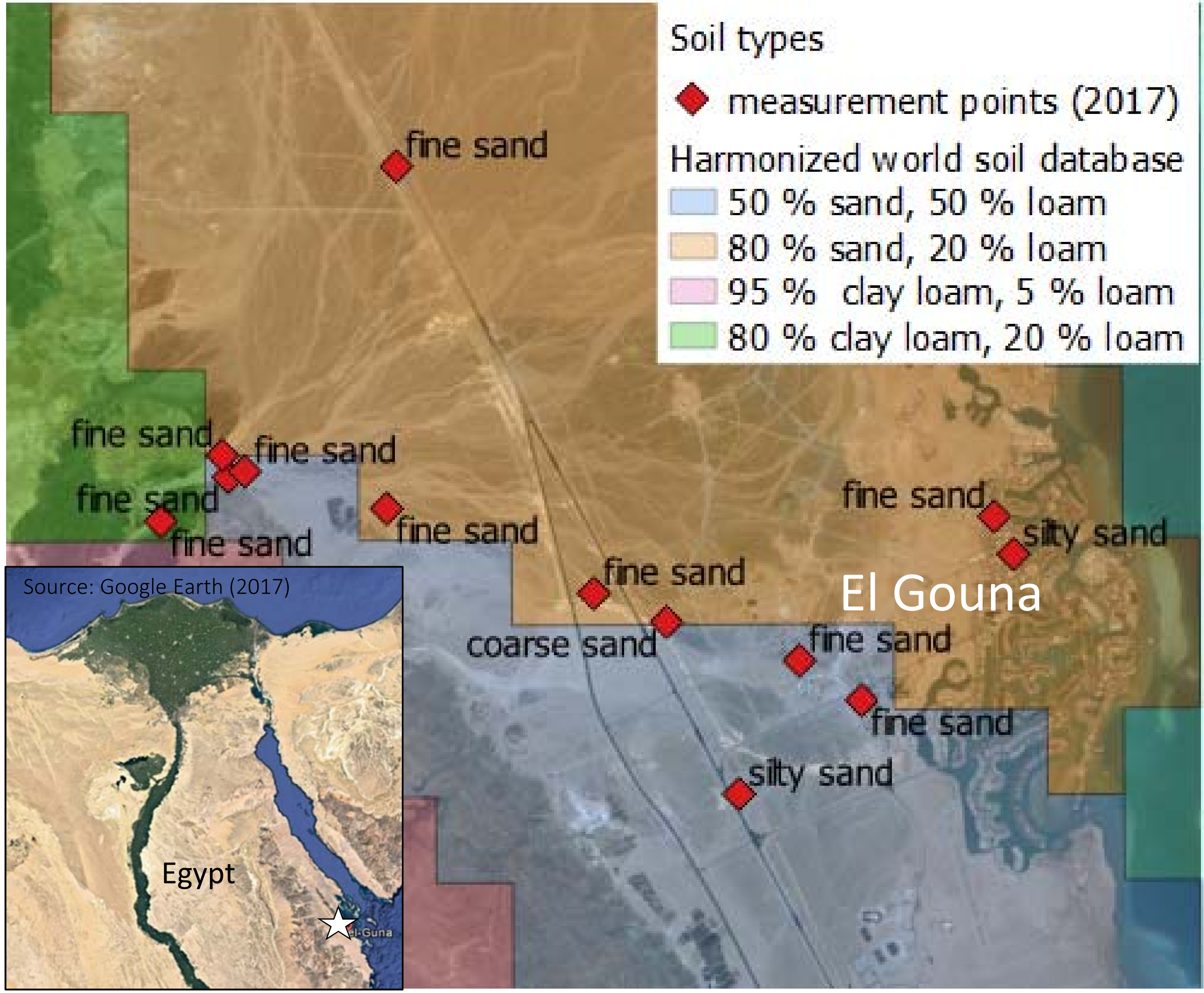
Soils and infiltration rates in region of El Gouna

Result from double ring infiltration tests and sieving curves:

- Dominant soil type: fine sand
- Arithmetic mean of infiltration rates is by a factor of 33 higher than average rainfall intensity on 9 March 2014
  - Infiltration: 140 mm/h, rainfall: 4.25 mm/h
  - **But: strong overland flow and flooding areas were observed** (even in areas that were not inside one of the streams coming from the bigger wadi catchment)

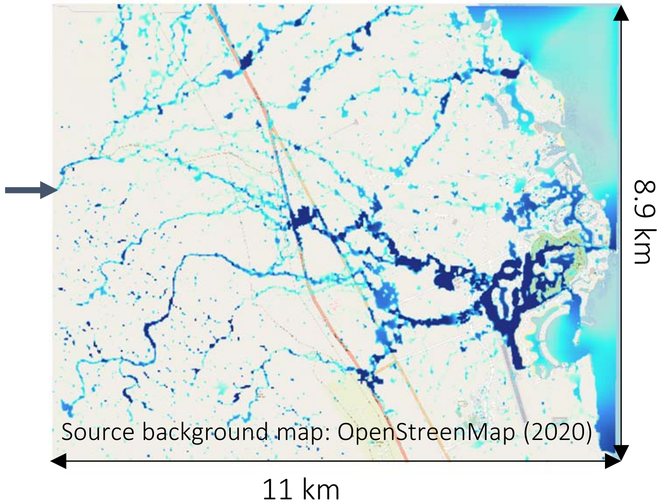
Infiltration test with doublering infiltrometer at TU Berlin Campus El Gouna



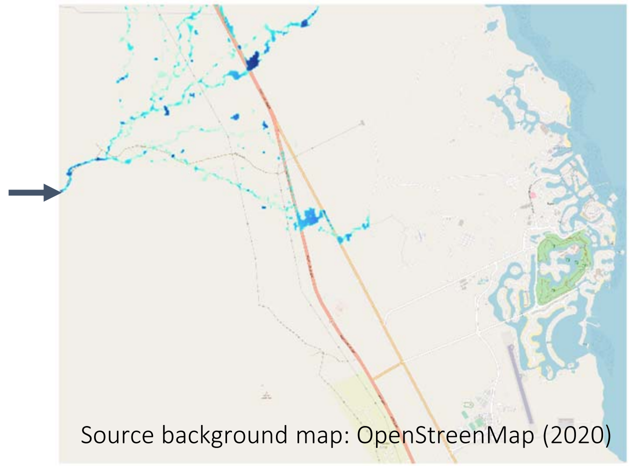
Soil types from doublering tests and Harmonized World Soil Database

Investigation of infiltration & impact of friction

Manning‘s n = 0.025 $m^{-1/3}s$, no infiltration



Manning‘s n = 0.025 $m^{-1/3}s$, loam



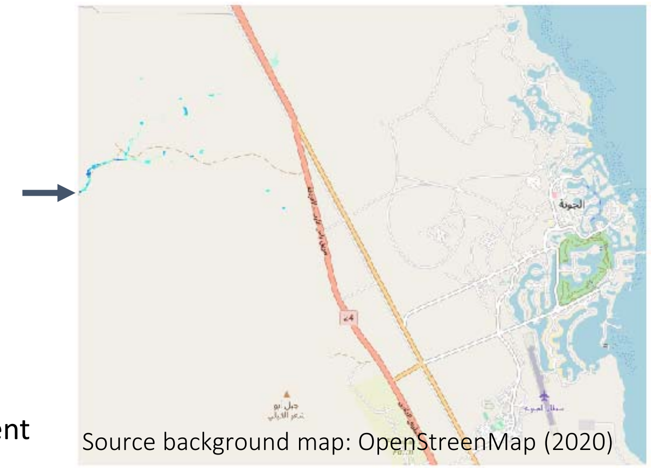
after 9 hours
Water depth (m)

- 0
- 0.075
- 0.15
- 0.225
- 0.3

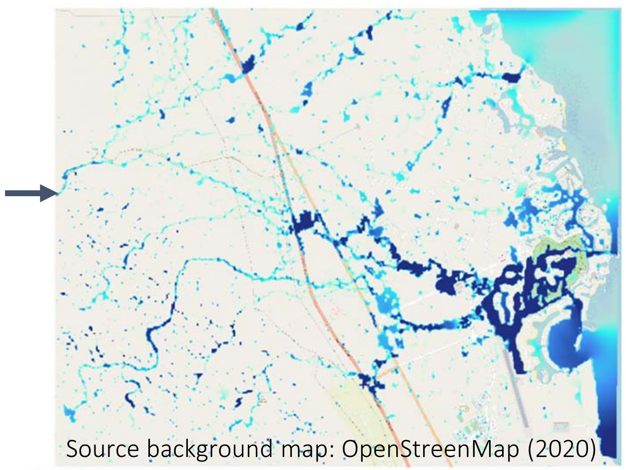
Inflow from wadi catchment

Location of max. water depth

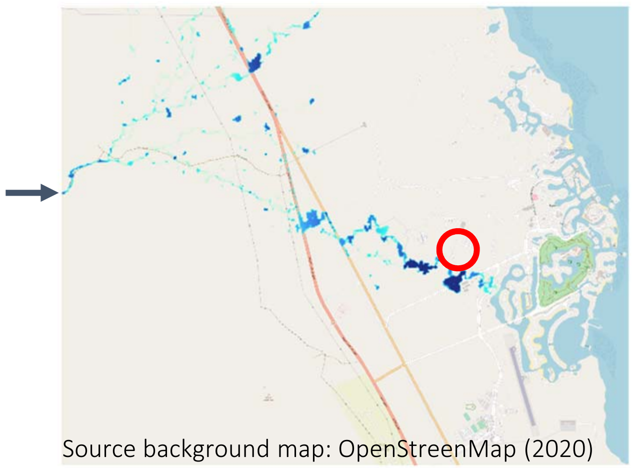
Manning‘s n = 0.01 $m^{-1/3}s$, loamy sand



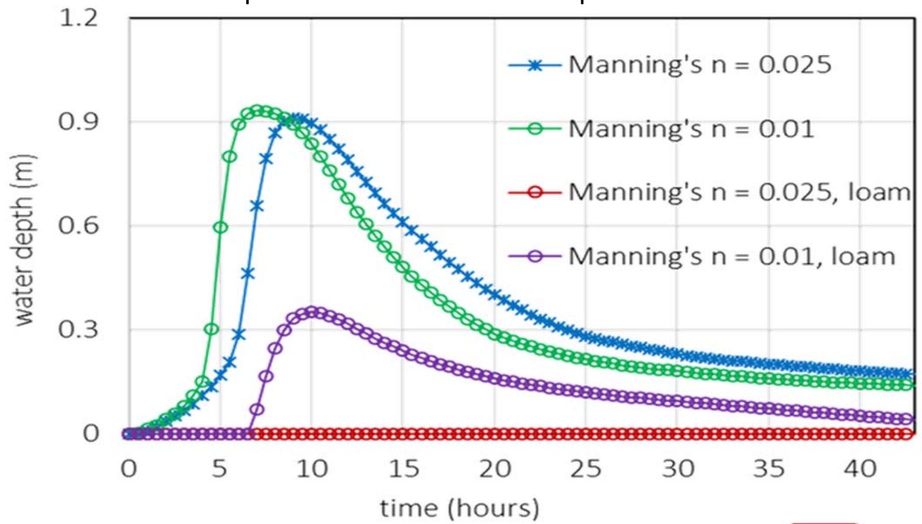
Manning‘s n = 0.01 $m^{-1/3}s$, no infiltration



Manning‘s n = 0.01 $m^{-1/3}s$, loam



Comparison of water depths over time



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Conclusions & Outlook

- Laboratory experiments: averages values for GA parameters after Rawls lead to underestimation of infiltration
- Study areas in the field (El Gouna and Thiès): average GA parameters lead to strong overestimation of infiltration
- Thiès: GA model with crust better captured the first (small) peaks, but overestimated infiltration to later times; GA parameters for loamy sand generated much better results than for sand
- Friction has a significant impact on infiltration behavior in El Gouna

Next steps/possibly ongoing work:

- Case study El Gouna: conducting field experiments with a rainfall simulator measuring surface runoff, soil moisture and sediment rates, and recording digital photos of the plot area to create a high-resolution DEM using photogrammetry
- Simulation of the field experiments to find suitable Green-Ampt parameters (how about the impact of different scales?)
- **Study the effects of surface clogging, friction, micro topography, DEM resolution on infiltration in the model**
- Try to define suitable values of Green-Ampt parameters for different cases, what are the most important factors?

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Page 14 & 15: Google Earth (2017): Satellite images from Egypt and El Gouna extracted from Google Earth, details of recording attributes are included in the pictures

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