21st century hydrological modelling for optimizing ancient water harvesting techniques

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water harvesting techniques: often go back to ancient times

jessr, Tunisa

demi lunes, Capo Verde

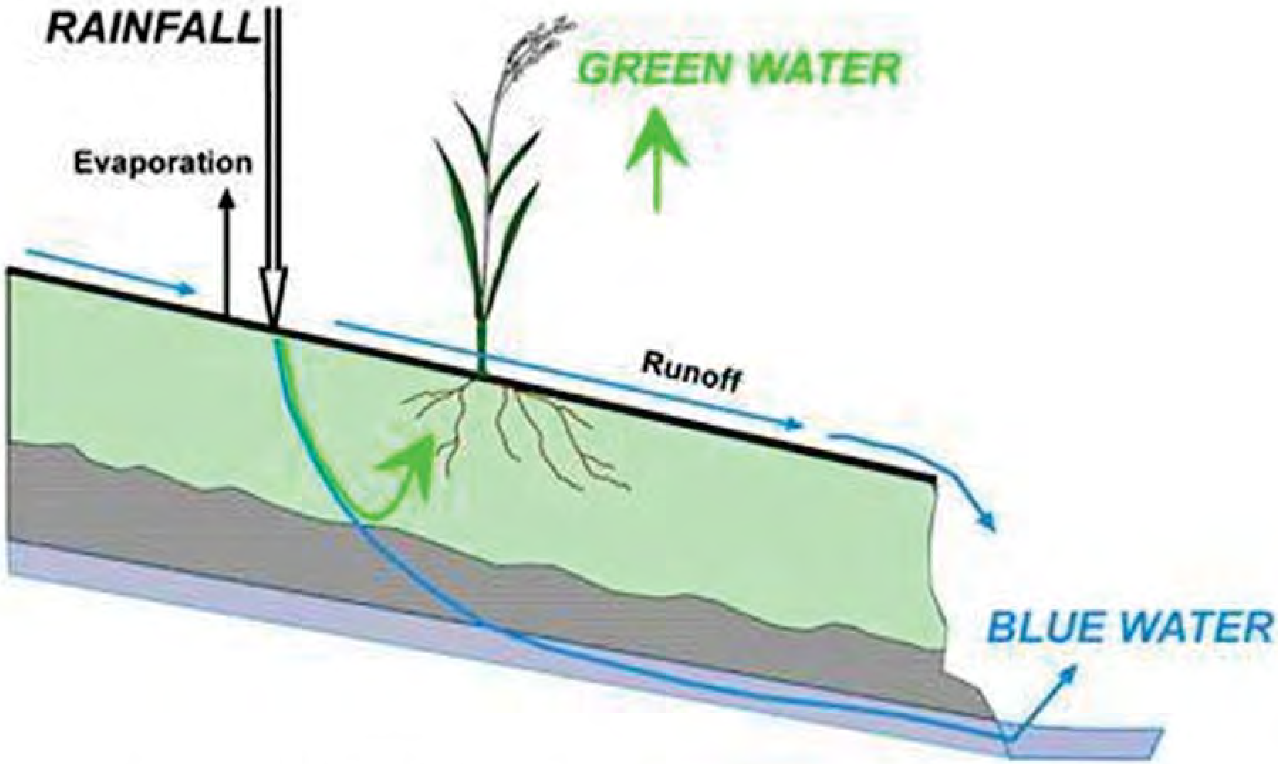

zaï pits, Niger


infiltration trenches, Chile

1. Introduction

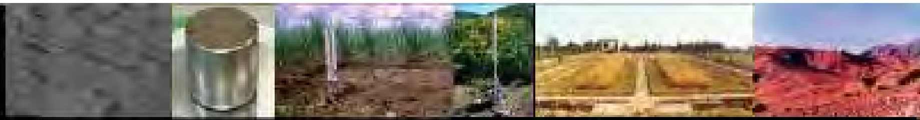
bed and furrows (derdero), Ethiopia


Fanya juu, Kenya ©FAO



Water, stored in the soil and used by plants, equals green water.
Runoff and deep drainage, recharging groundwater and feeding streams, equals blue water.

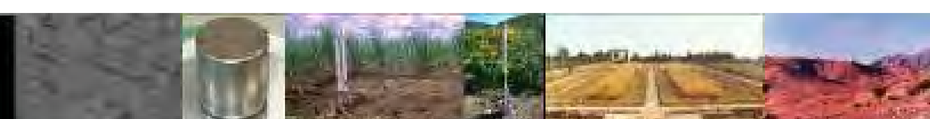
Rockström (1997)



however… WHT often based on trial and error approach or at best on empirical approach

→ often unproductive, not efficient

→ impact on local/catchment hydrology unknown



1. Introduction

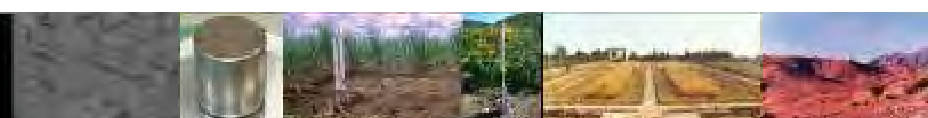
Hydrol. Earth Syst. Sci., 13, 2003–2021, 2009
www.hydrol-earth-syst-sci.net/13/2003/2009/

Hydrology and Earth System Sciences

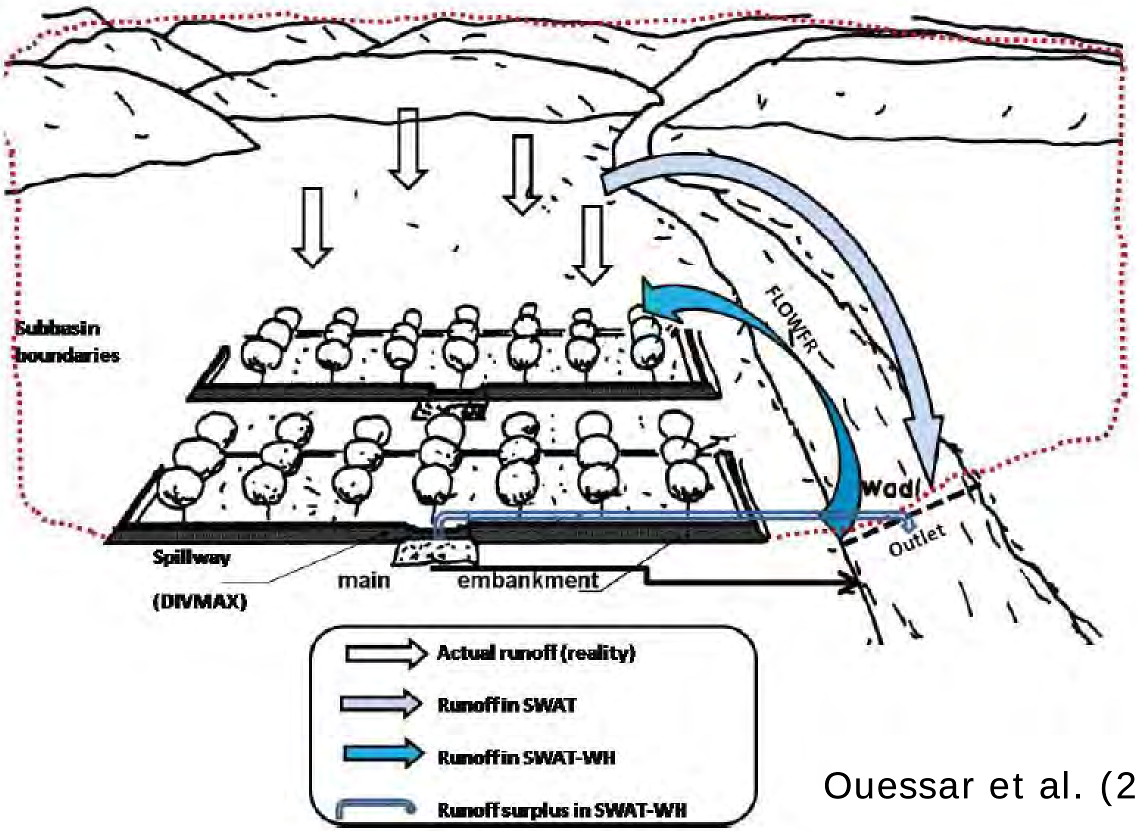
Modelling water-harvesting systems in the arid south of Tunisia using SWAT

M. Ouessar[1], A. Bruggeman[2], F. Abdelli[1], R. H. Mohtar[3], D. Gabriels[4], and W. M. Cornelis[4]

[1]Institut des Régions Arides (IRA), Route de Jorf, 4119 Medenine, Tunisia
[2]International Center for Agricultural Research in the Dry Areas (ICARDA), P.O. Box 5466, Aleppo, Syria
[3]Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA
[4]Department of Soil Management – International Centre for Eremology, Ghent University, Coupure links 653, 9000 Ghent, Belgium



SWAT



Ouessar et al. (2009, HESS)

but…not adapted for optimizing design

Hydrol. Earth Syst. Sci., 13, 1979–1992, 2009
www.hydrol-earth-syst-sci.net/13/1979/2009/

Hydrology and Earth System Sciences

Using an inverse modelling approach to evaluate the water retention in a simple water harvesting technique

K. Verbist[1,2], W. M. Cornelis[1], D. Gabriels[1], K. Alaerts[1], and G. Soto[2]

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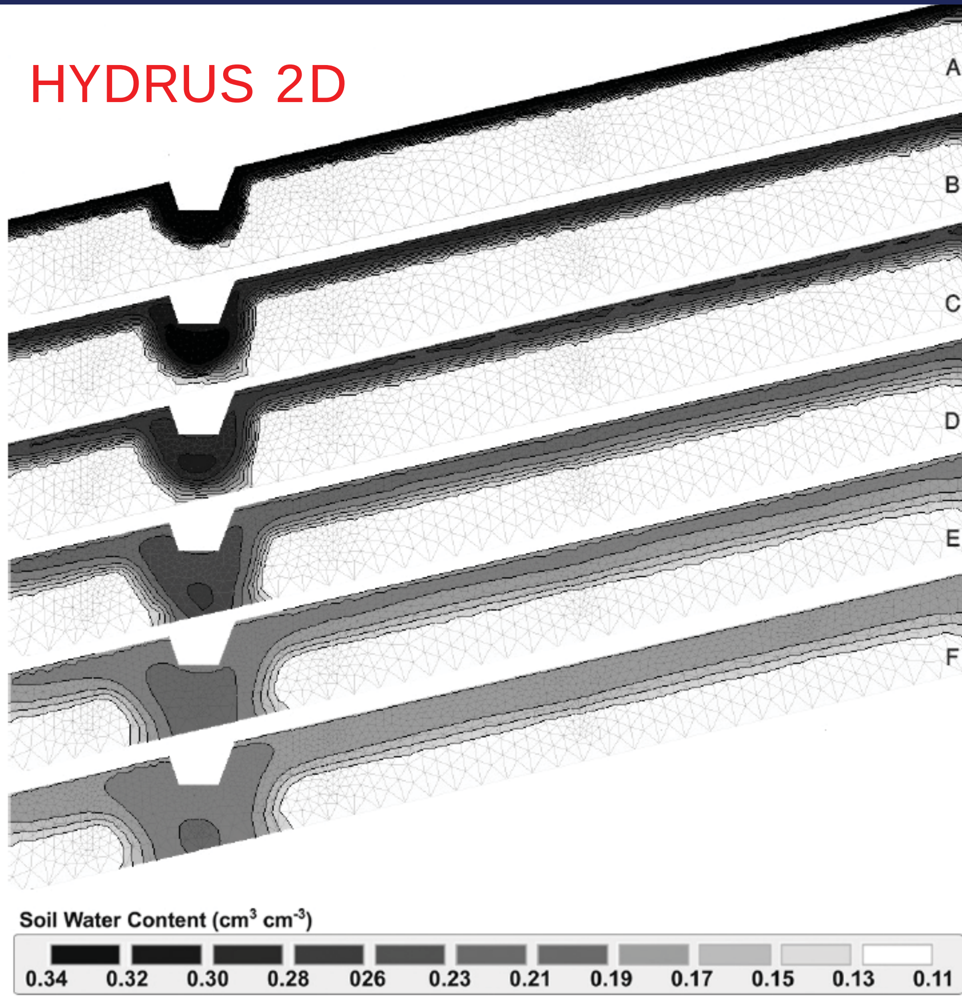
HYDRUS 2D



Verbist et al. (2009, HESS)

but … does not consider overland flow as such

1. Introduction

→ fully coupled surface/subsurface flow model

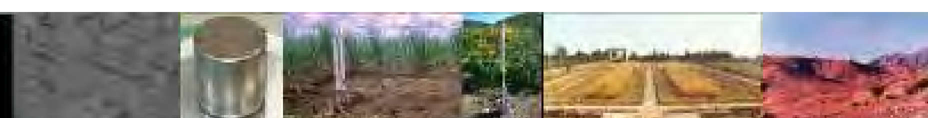
based on blueprint by R.A. Freeze and R.L. Harlan.

"Blueprint for a physically-based digitally simulated, hydrological response model". J. Hydrology 9:237-258, 1969

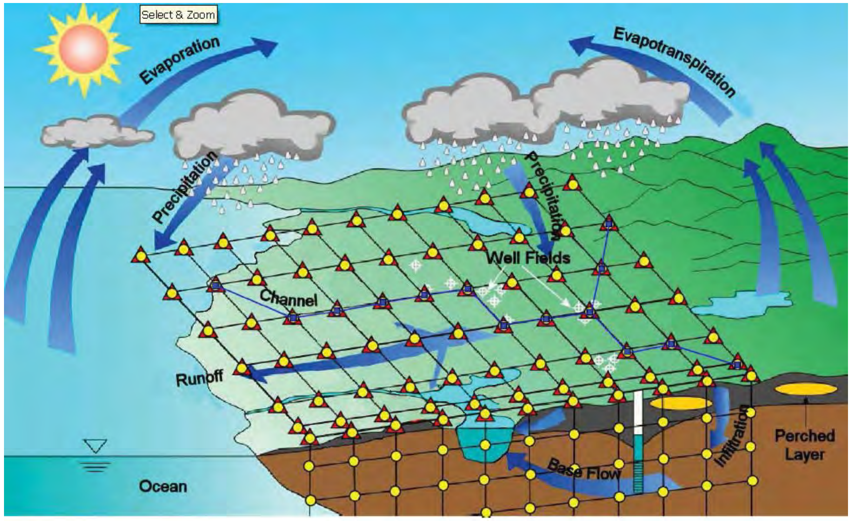
→ HydroGeoSphere (HGS)

2. HydroGeoSphere

- developed for “Simulating Flow and Contaminant Transport in Integrated Surface-Subsurface Flow Systems”
- at the University of Waterloo, Canada (Therrien, McClaren, Sudicky, Panday, 2009)
- first generation code: PhD of Joel VanDerKwaak, 1999, InHM (Integrated Hydrologic Model; U of Waterloo)



- Features:
  - Surface (overland) flow: 2D – Subsurface flow: 3D
  - Coupled Surface-Subsurface
  - Allows any time step
  - Allows any spatial resolution
  - Finite elements



Therrien et al. (2009)

Figure 1.2: Integrated Numerical Simulation of Hydrologic System.

- Governing equations:
  - porous medium: 3D variably-saturated flow

Richards' equation:

$$-\nabla \cdot (w_m \mathbf{q}) + \sum \Gamma_{\text{ex}} \pm Q = w_m \frac{\partial}{\partial t}(\theta_s S_w)$$

Darcy-Buckingham equation:

$$\mathbf{q} = -\mathbf{K} \cdot k_r \nabla(\psi + z)$$

Mualem-van Genuchten

for S_w and k_r

w_m = porous medium vol. fraction
$\mathbf{q}$ = fluid flux
Γ_{ex} = exchange flux
Q = source/sink
θ_s = sat. vol. water content
S_w = degree of saturation
$\mathbf{K}$ = saturated hydraulic conductivity
k_r = relative hydraulic conductivity
ψ = pressure head
z = elevation

- Governing equations:
  - overland/stream: 2D surface flow

diffuse wave approximation of Saint Venant equation:

$$-\nabla \cdot (d_o \mathbf{q_o}) - d_o \Gamma_o \pm Q_o = \frac{\partial \phi_o h_o}{\partial t}$$

flux equation:

$$\mathbf{q_o} = -\mathbf{K_o} \cdot k_{ro} \nabla (d_o + z_o)$$

Manning equation:

$$K_{ox} = \frac{d_o^{2/3}}{n_x} \frac{1}{[\partial h_o / \partial s]^{1/2}}$$

d_o = water depth
$\mathbf{q_o}$ = fluid flux
Γ_o = exchange flux
Q_o = source/sink
ϕ_o = surface flow porosity
h_o = water surface elevation
$\mathbf{K_o}$ = surface conductance
k_{ro} = relative hydraulic cond.
z_o = land surface elevation
n_x = Manning roughness coeff.
s = max. slope

- <u>Governing equations</u>:
  - coupling?

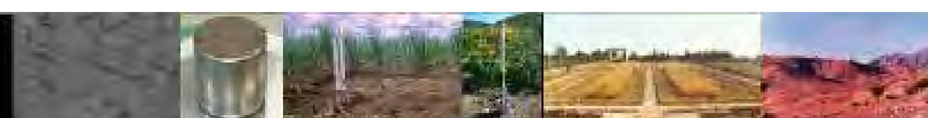
subsurface 3D flow: $$-\nabla \cdot (w_m \mathbf{q}) + \boxed{\sum \Gamma_{\mathrm{ex}}} \pm Q = w_m \frac{\partial}{\partial t}(\theta_s S_w)$$

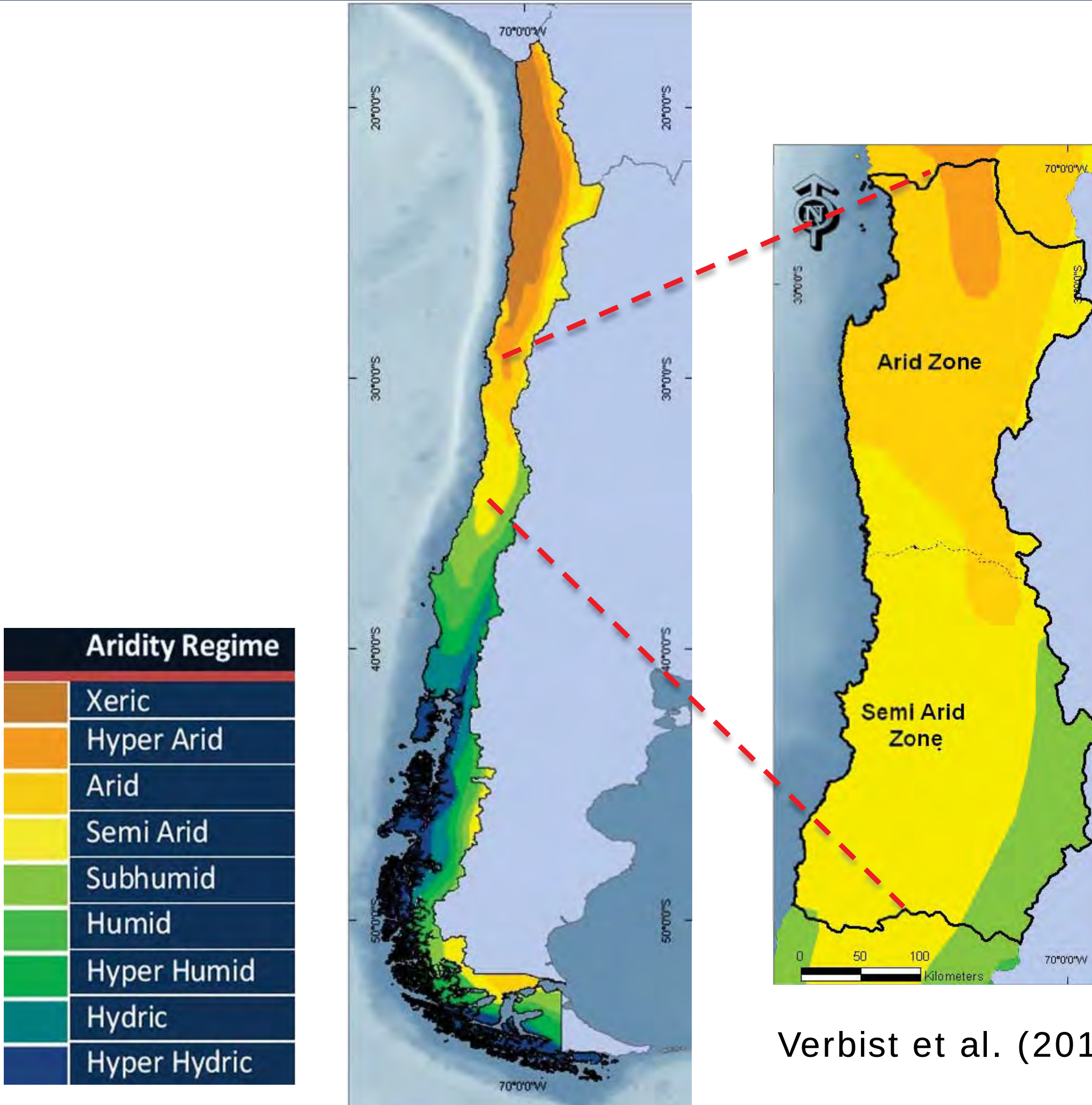
surface 2D flow: $$-\nabla \cdot (d_o \mathbf{q_o}) - \boxed{d_o \Gamma_o} \pm Q_o = \frac{\partial \phi_o h_o}{\partial t}$$

→ first-order exchange:

$$d_o \Gamma_o = \frac{k_r \mathbf{K_{zz}}}{l_{exch}} (h - h_o)$$

k_r = relative hydraulic conductivity of exchange flux
$\mathbf{K_{zz}}$ = sat. hydr. conduct. in vertical dir.
l_{exch} = coupling length

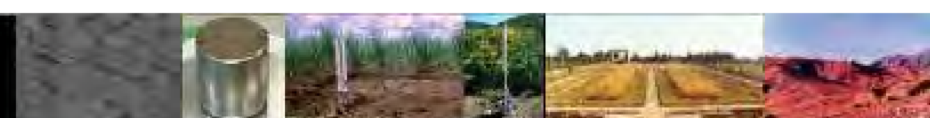




case study 1
small hillslope 6x2m

case study 2
small catchments ~3ha

Verbist et al. (2010)

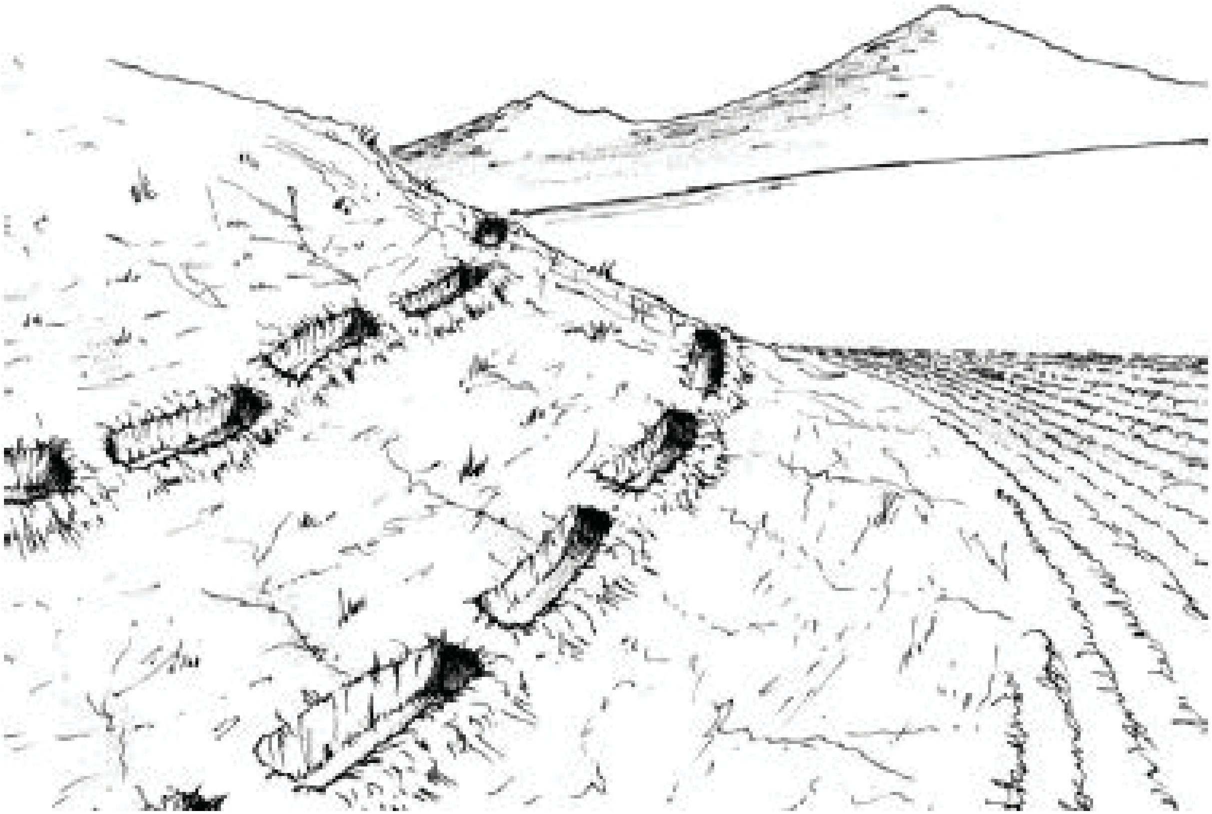


3. Case studies

(1) hillslope study
arid zone
P = 99 mm
ETo = 1500 mm

(2) catchment study
semi-arid zone
P = 560 mm
ETo = 1220 mm

in both cases: infiltration trenches were dug since’90s

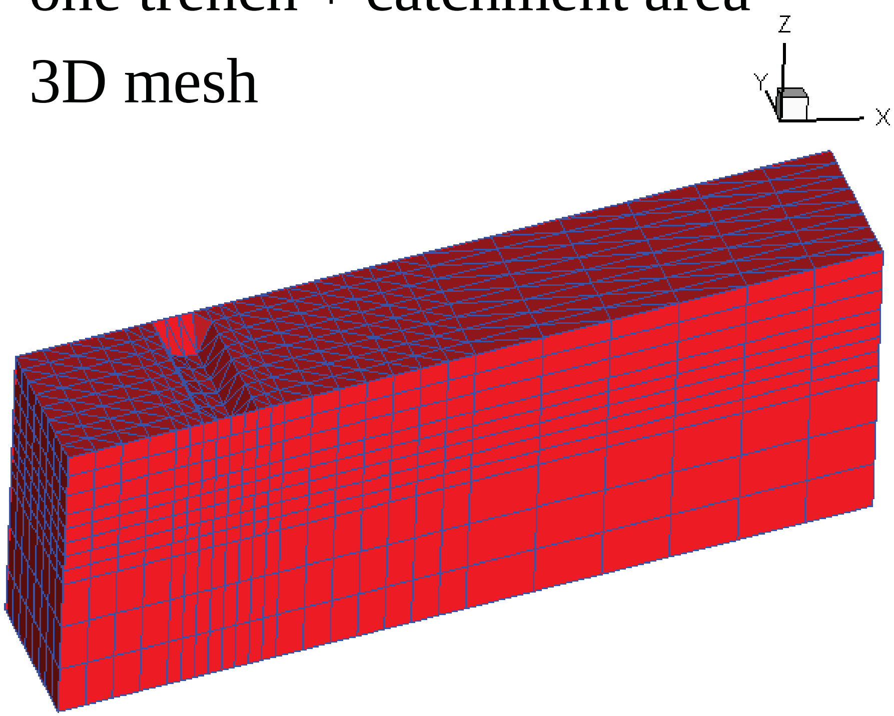


→ to combat desertification: by stimulating

- reforestation (*Eucalyptus*, *Pinus*)
- regeneration of natural vegetation (used by goats)

(1) Flow domain and boundary conditions:

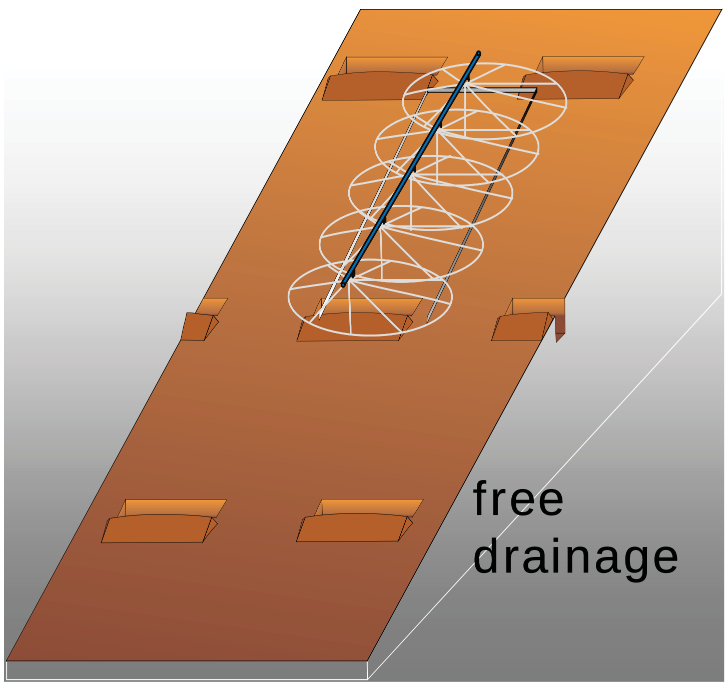
- slope: 23%
- silt loam
- a field plot of 6 x 2 m
- one trench + catchment area
- 3D mesh



3a. Hillslope study

(1) Flow domain and boundary conditions (cont.):

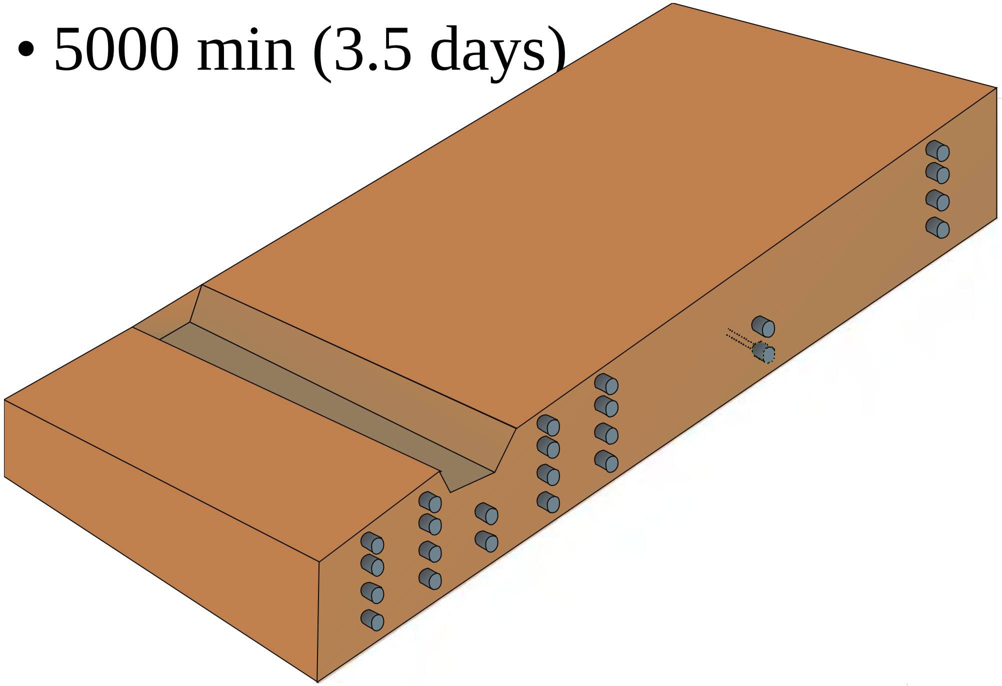
- simulated rain (20 min, 120 mm h^{-1}, 7 nozzles) + evaporation (3.5 days)
- runoff and soil-water content measurements

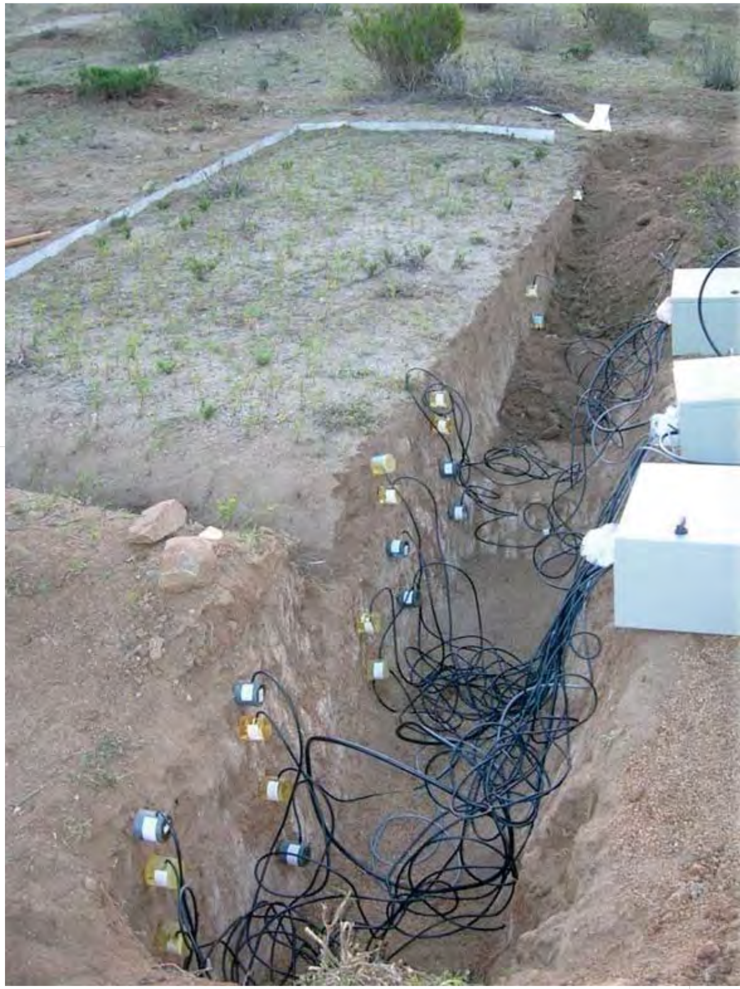


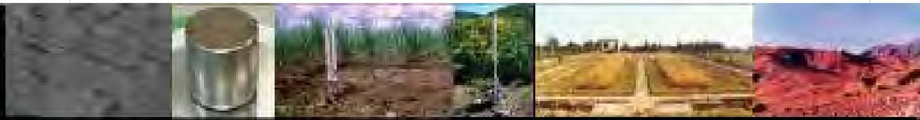
(2) model parameterisation: optimizing the runoff hydrograph
(from 10 independent rainfall simulations)

(2) model parameterisation (cont.): optimizing soil-water content time series

- 22 TDR probes
- probe length: 30 cm
- 5 min interval
- 5000 min (3.5 days)







3a. Hillslope study

(2) model parameterisation (cont.):

- 7 model parameters need to be estimated:
  - K_{fs}: saturated hydraulic conductivity
  - θ_r, θ_s, α, β, λ_p: van Genuchten-Mualem WRC parameters
  - n: Manning coefficient
  - l_{exch} : coupling length (different in catchment area and reception area)

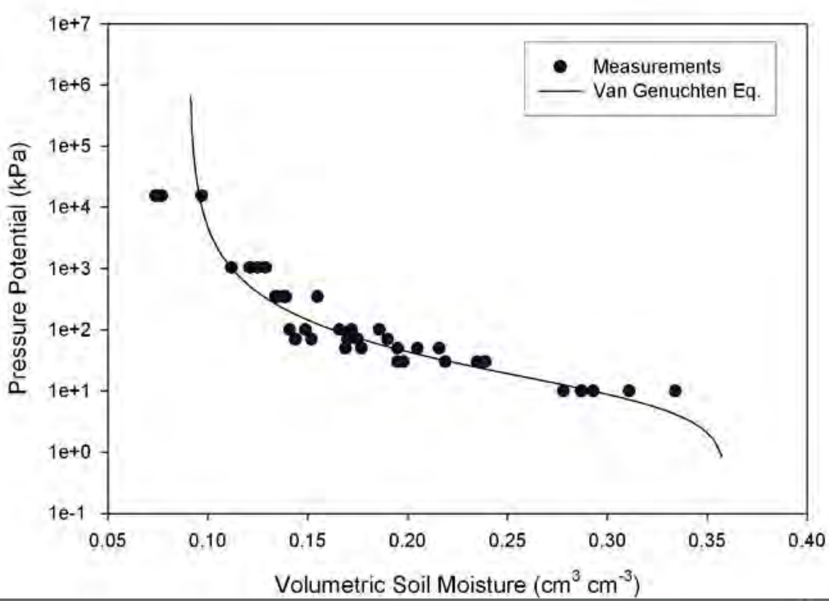
- for some, initial estimates from direct field/lab measurement

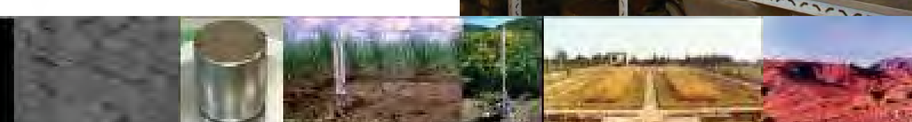
(2) model parameterisation (cont.): measurements of K_{fs} in 10 reps with 6 methods (side study)

Verbist et al. (2009, SSSAJ)
Baetens et al. (2009, WRR)
Verbist et al. (2010, VZJ)

(2) model parameterisation (cont.): water retention curves

- undisturbed soil cores (Kopecky – 100 cm^3)
- tension table (Eijkelkamp Agr. Eq.)
  0-10 kPa
- pressure chambers (Soilmoisture Eq.)
  20-1500 kPa





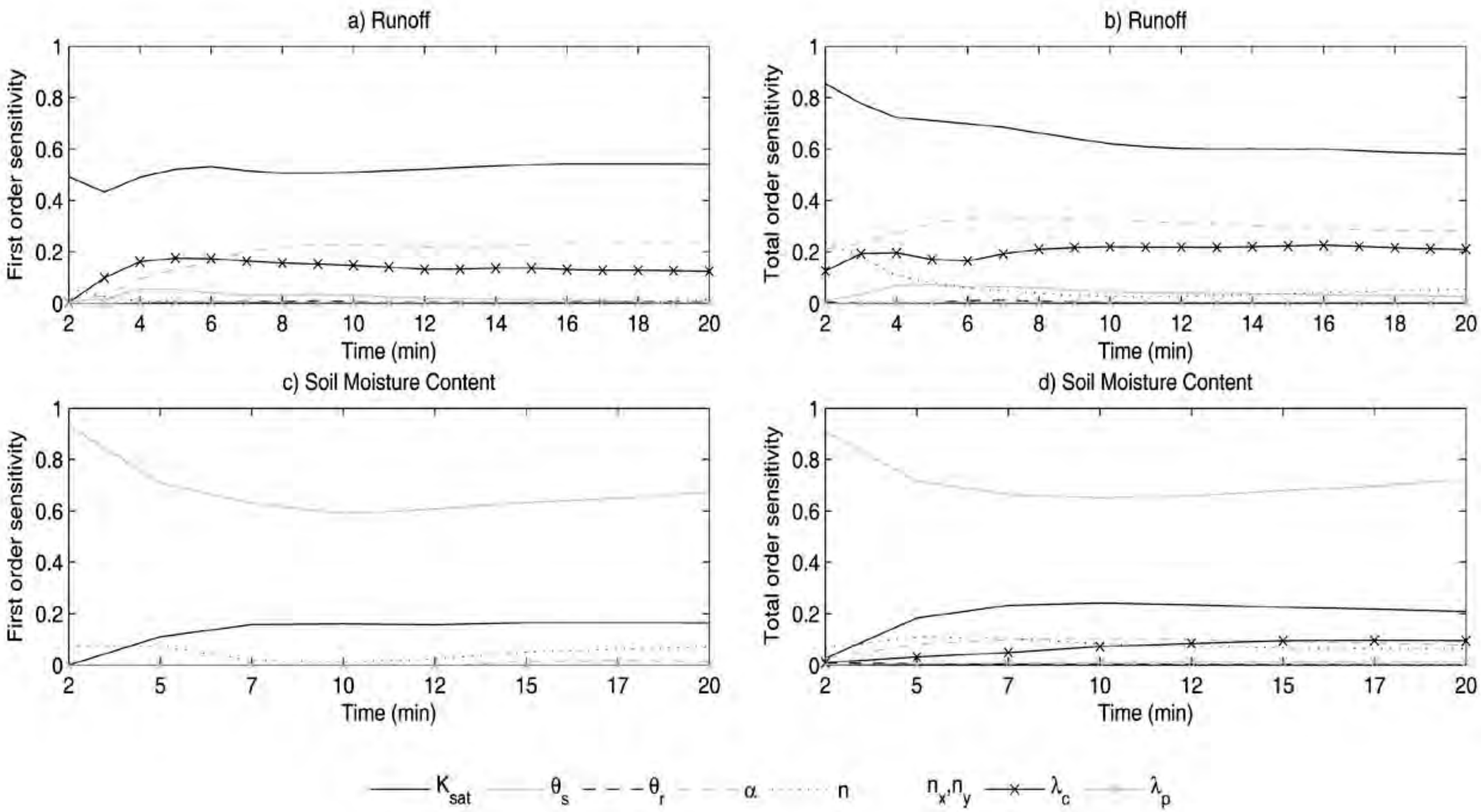
(2) model parameterisation (cont.):

variance-based global sensitivity analysis (GSA) using Jansens' estimator which applies a quasi-random sequence generator

→ 5000 model runs using the parallel HGS version (Park et al., 2010) on 16 computer cores (Intel Xeon L5420 2.5 GHz)

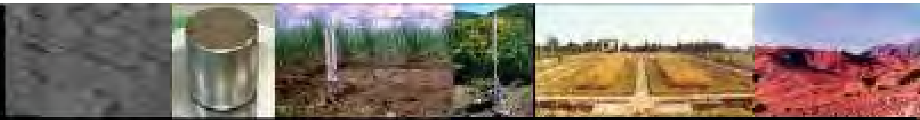
(no local sensitivity analysis or one-at-a-time approach since in non-linear models, parameter interaction might occur)

(2) model parameterisation (cont.):



→ unsensitive for n_x, n_y, λ_p → fixed

Verbist et al. (2012, VZJ)



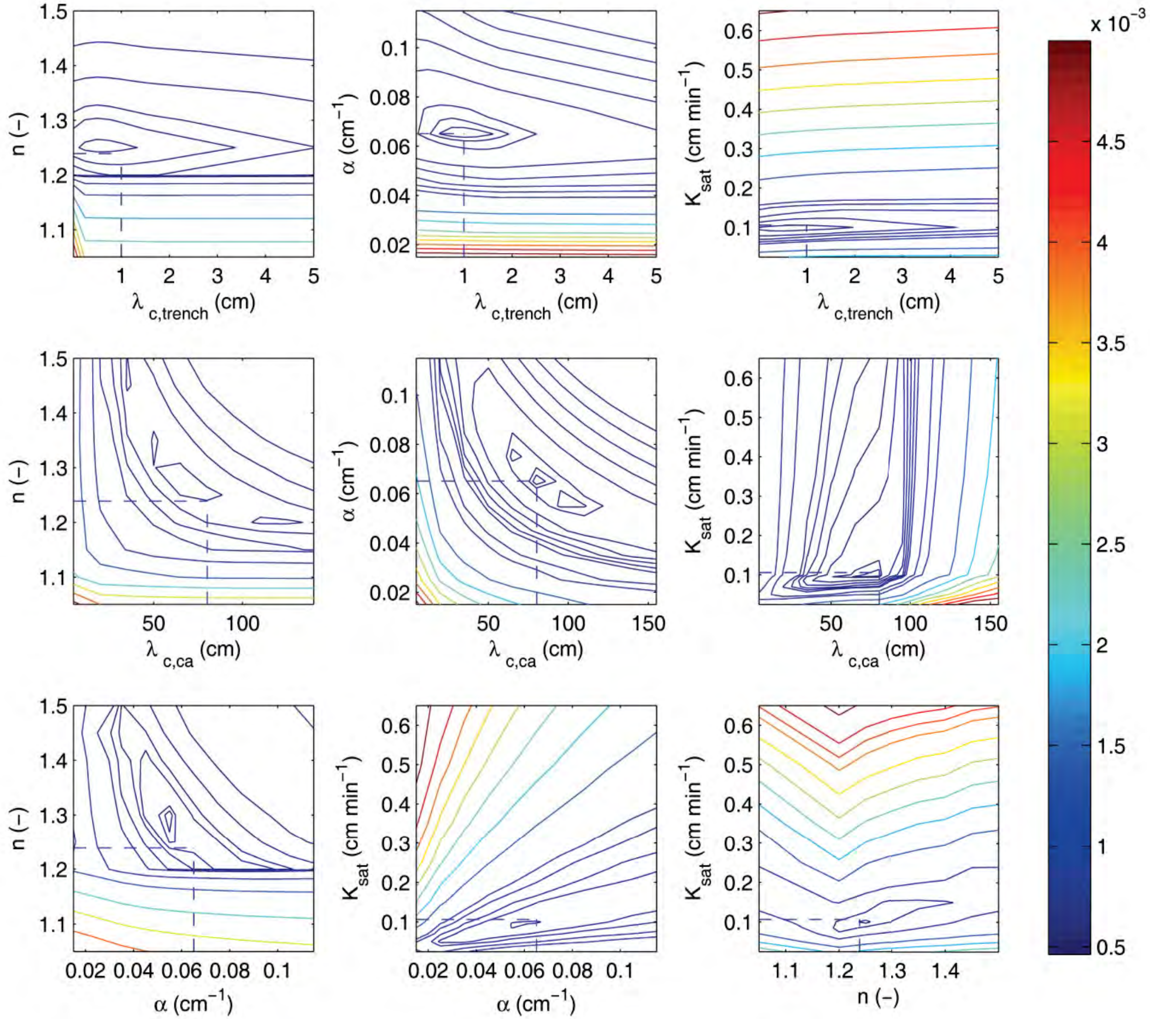
(2) model parameterisation (cont.): parameter estimation

objective function: minimisation-algorithm of Levenberg–Marquardt (1963)

$$\Phi[\Theta(t), R(t)] = \sum_{j=1}^{m}\sum_{i=1}^{n_1} u_i \left[\theta_o(x_j, t_i) - \theta_s(x_j, t_i, \beta)\right]^2 + \sum_{i=1}^{n_2} v_i \left[R_o(t_i) - R_s(t_i, \beta)\right]^2$$

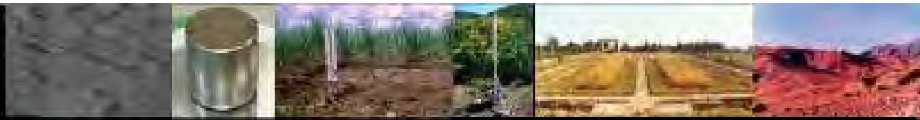
Coupling HydroGeoSphere with PEST (Parameter Estimation Software) (Doherty, 2010)

(DREAM, DiffeRential Evolution Adaptive Metropolis) (Laloy & Vrugt, 2012)

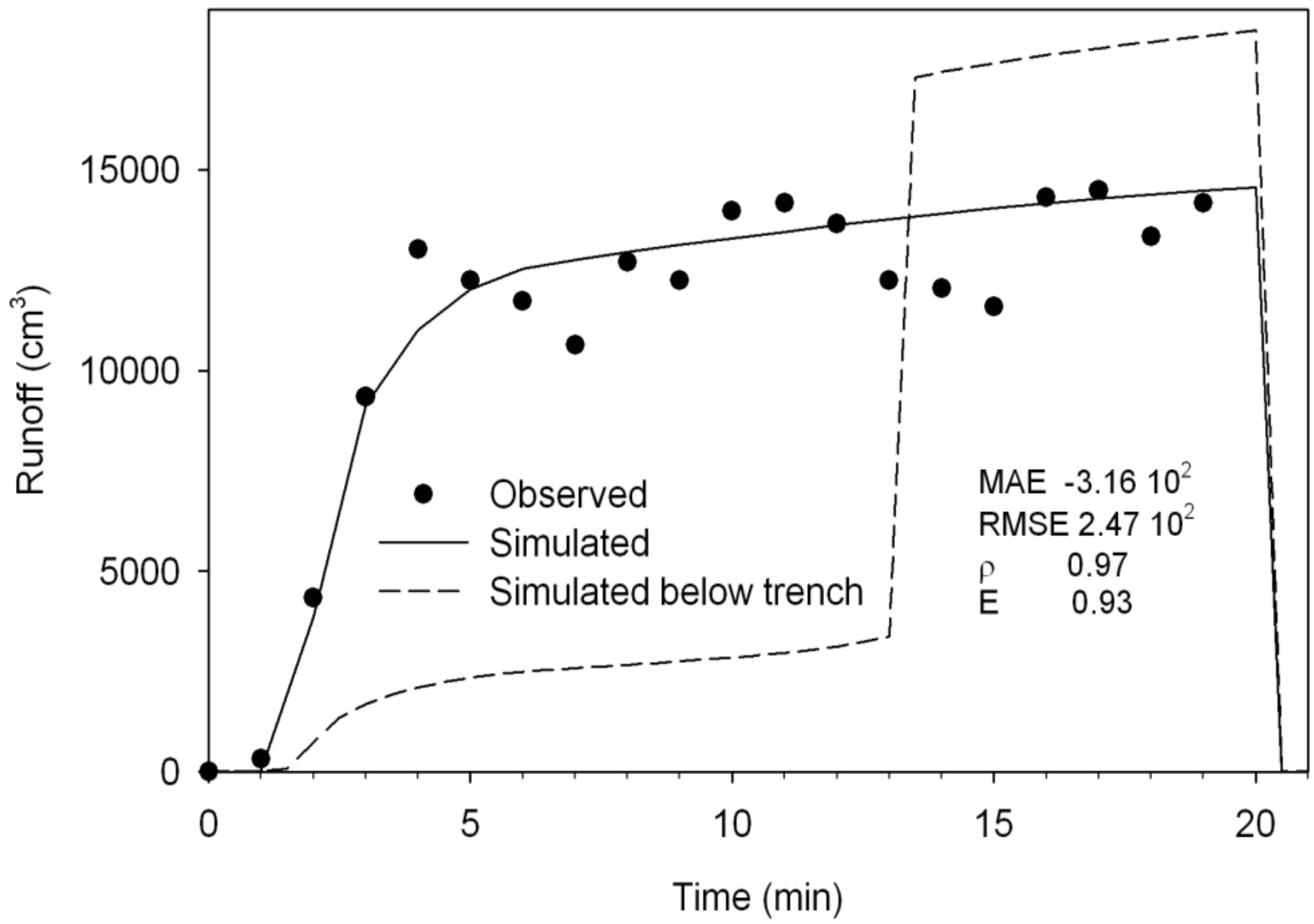


Verbist et al. (2012, VZJ)

→ well-posed model with unique inverse solution

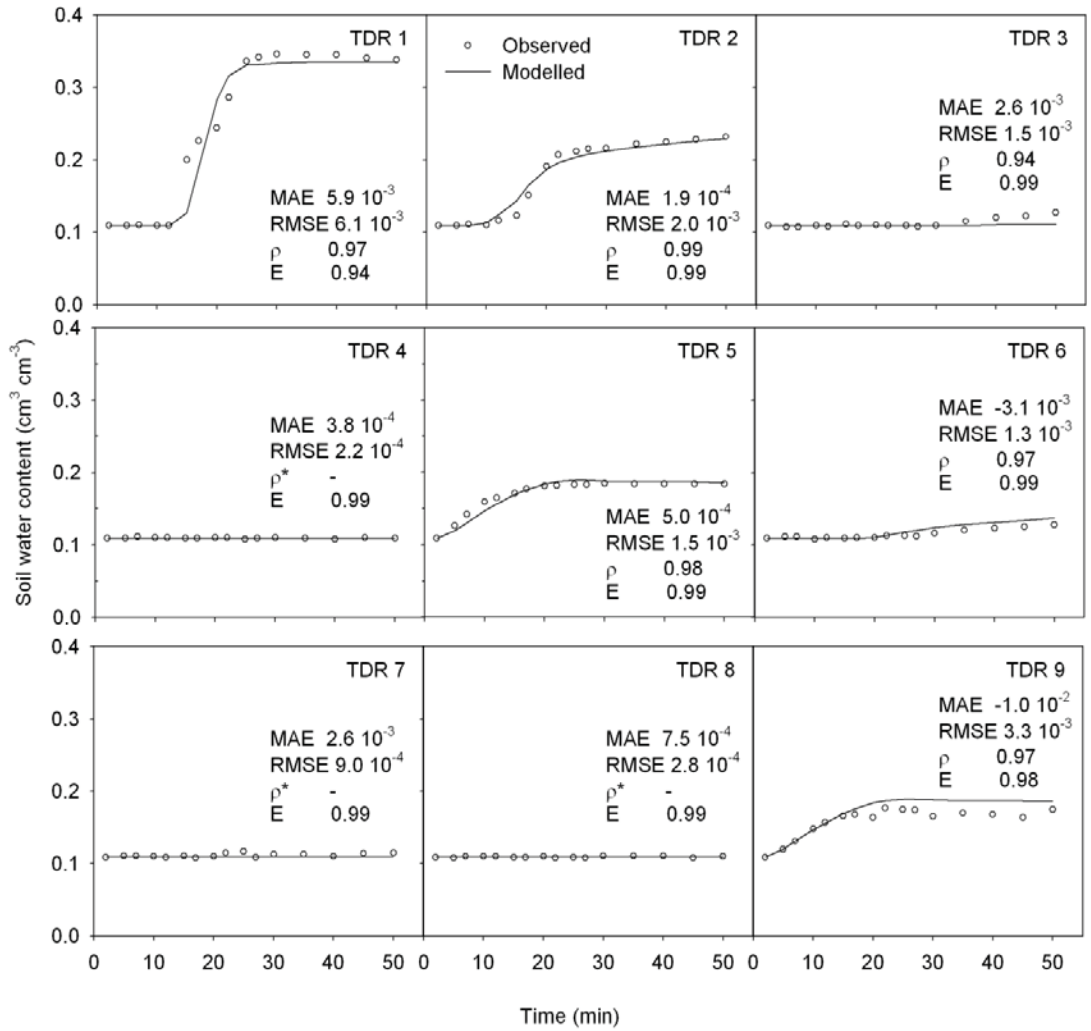


(3) model results: simulation of runoff

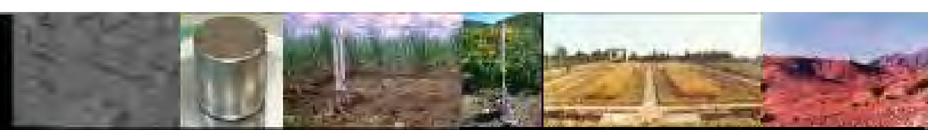


Verbist et al. (2012, VZJ)

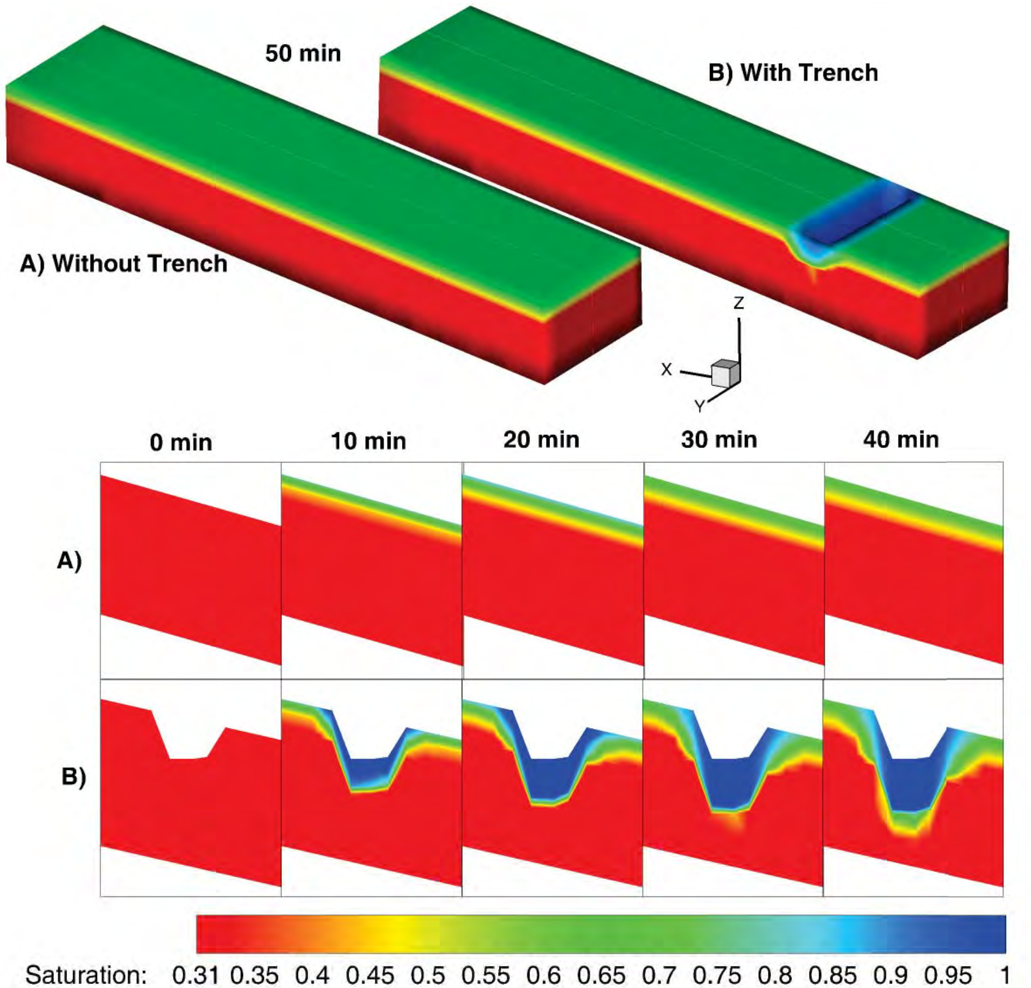
(3) model results (cont.): simulation of water content with time



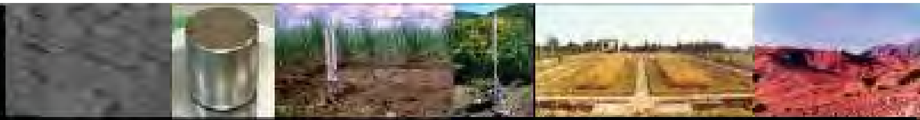
Verbist et al. (2012, VZJ)



(3) model results (cont.) : trench filling + redistribution

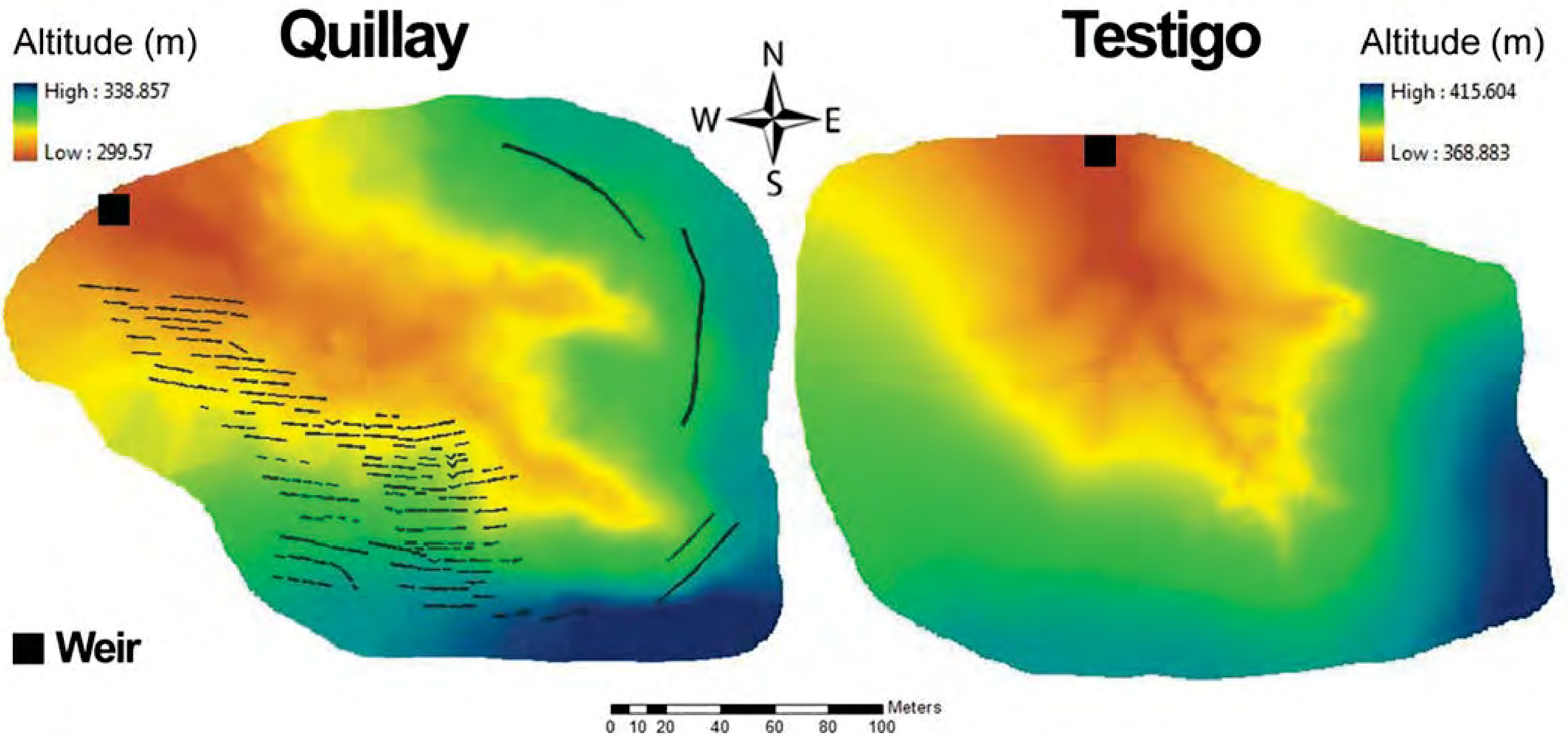


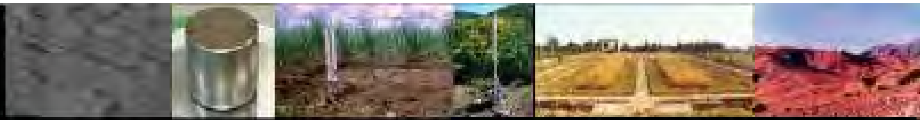
Verbist et al. (2012, VZJ)



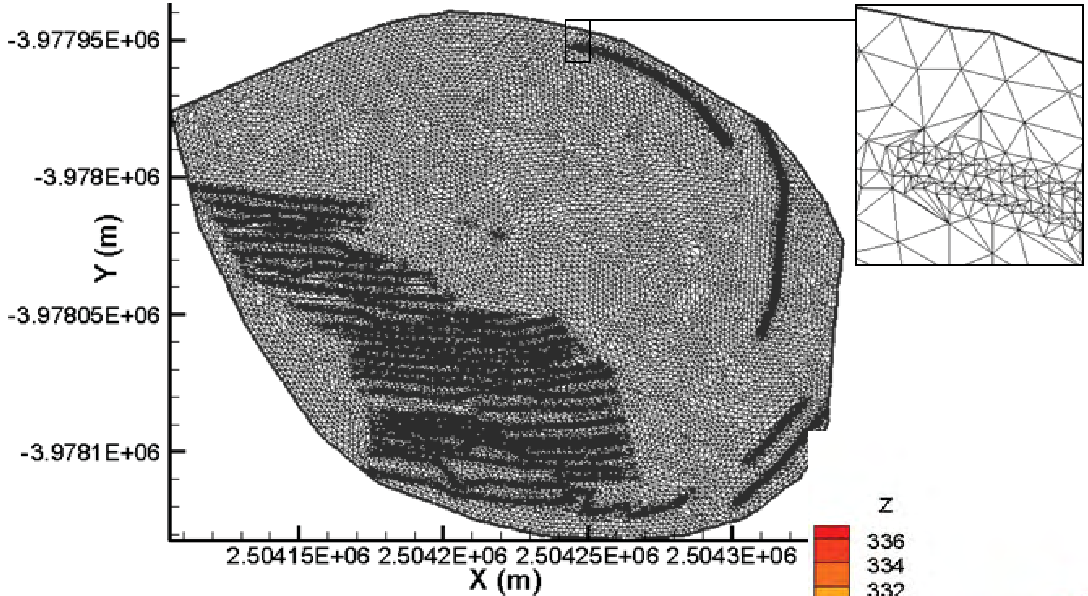
(1) flow domain + boundary conditions:

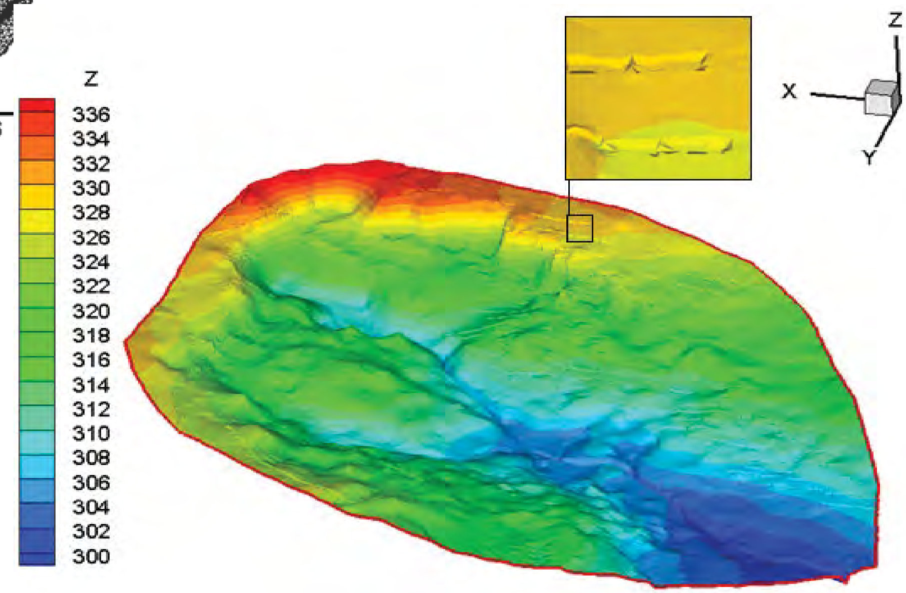
- ~3 ha
- loamy soils
- natural conditions





(1) flow domain + boundary conditions:



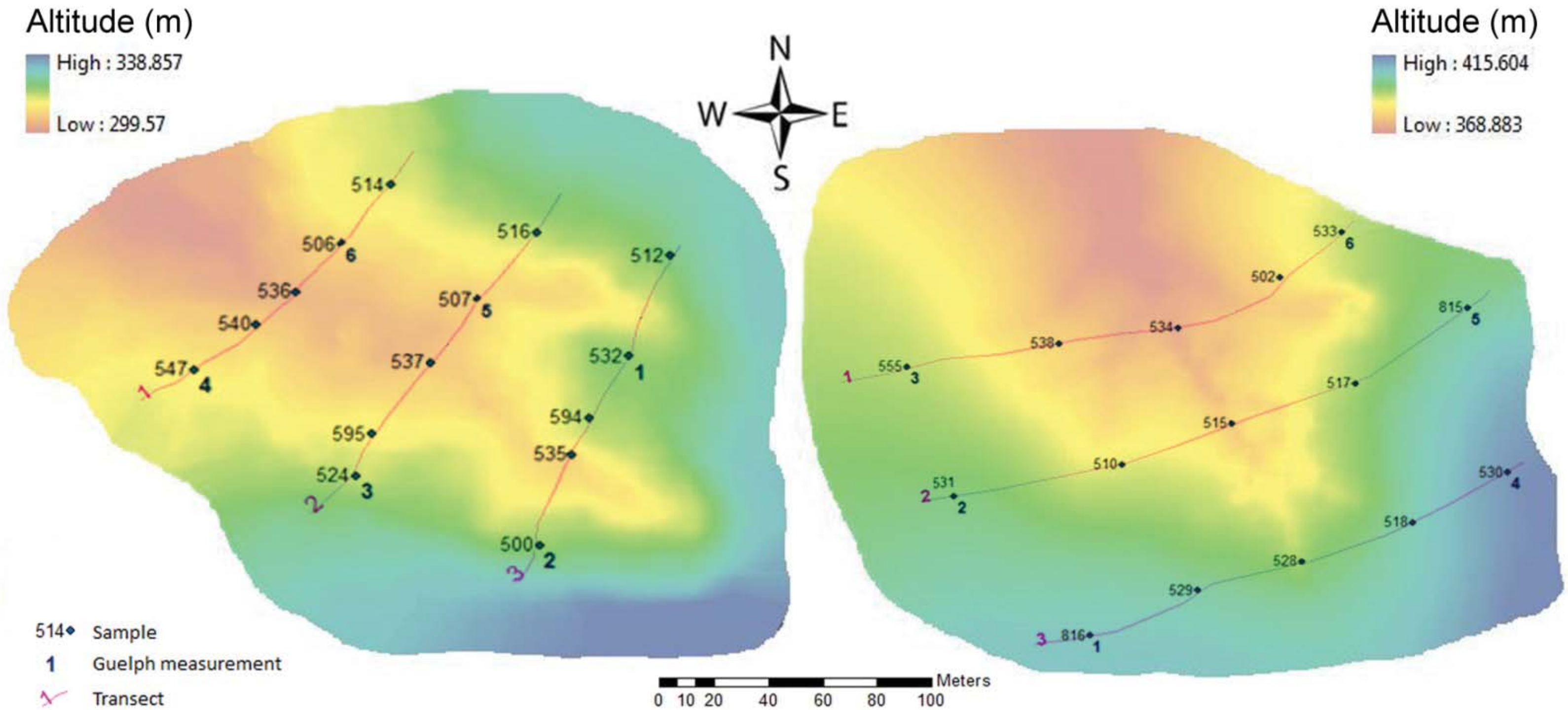


3b. Catchment study

(2) model parameterisation:
rainfall simulations 1x1 m plots (runoff + TDR water content)

(2) model parameterisation (cont.):

K_{fs} and WRC at 5 locations along 3 transects (9 reps per loc.)



(2) model parameterisation (cont.):
validation with runoff discharge data from outlet of watershed

(3) model results: simulation of pressure head at DOY1997

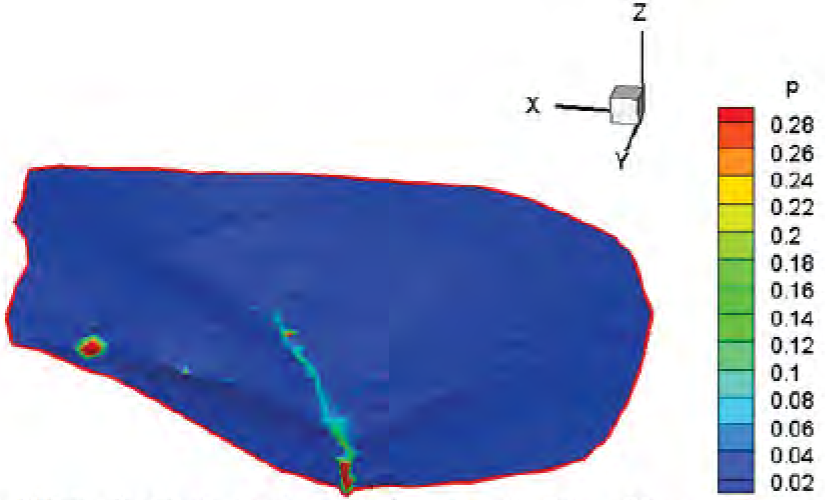


Figure 4.13: Tecplot 3D-visualization of Testigo with a simulation of the pressure head (meters)

without trenches

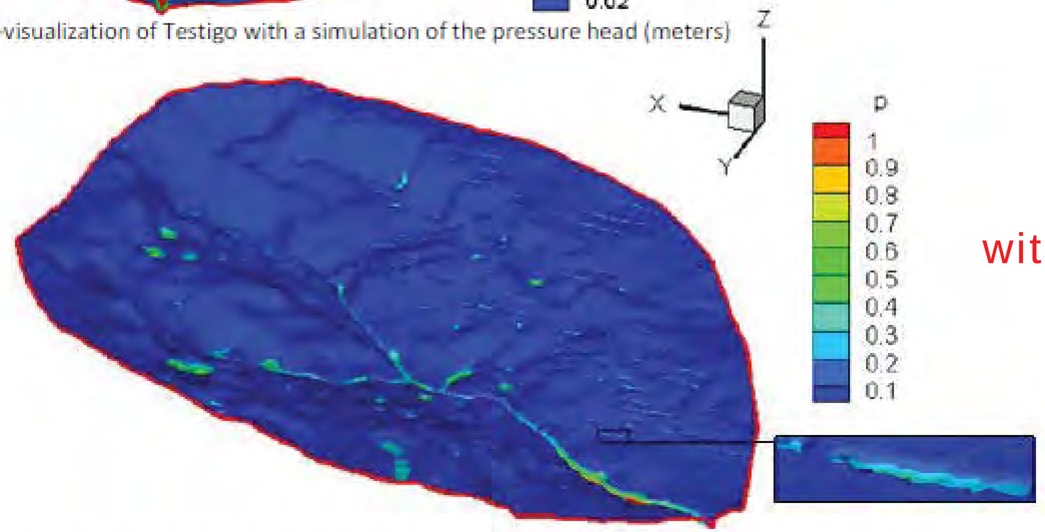
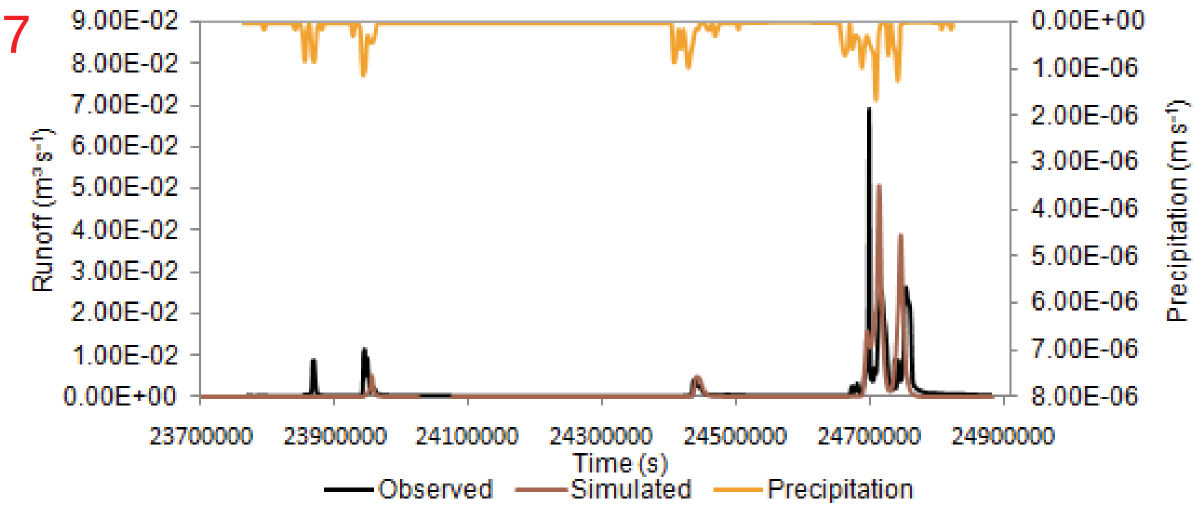


Figure 4.14: Tecplot 3D-visualization of Quillay with a simulation of the pressure head (meters)

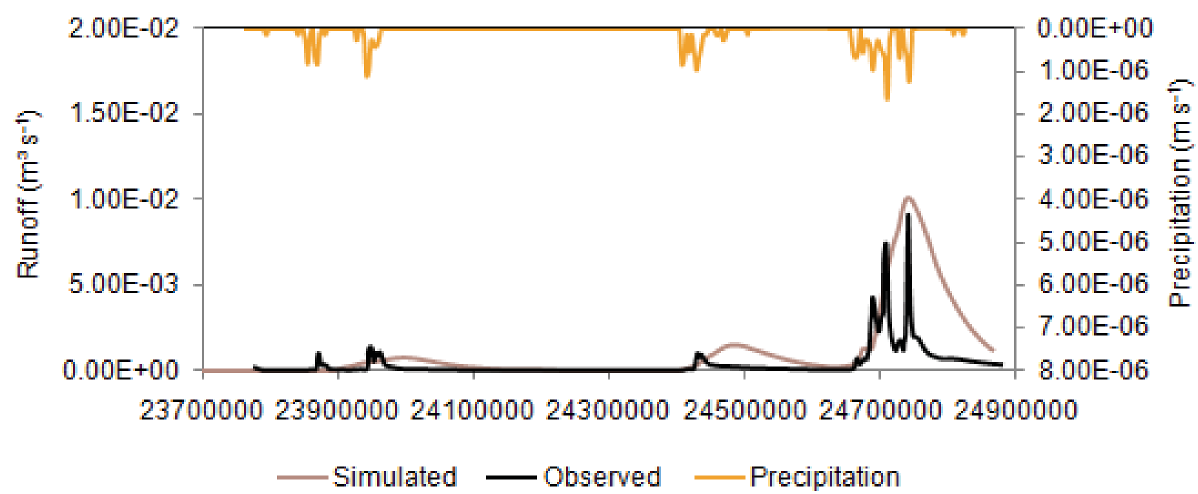
with trenches

(3) model results: simulation of runoff discharge

without WHT 1997



with WHT 1997



- model most sensitive to K_{fs}, van Genuchten parameters and coupling length
- enables to mimic runoff and changes in SWC in small hillslope plots and runoff discharge from watersheds → water balance
- versatile tool for improving design of WHT and evaluating their impact for current, past and future climates
- visualisation of water flow
- allows to evaluate upstream and downstream impact of WHT at watershed scale

- future work: testing for other techniques

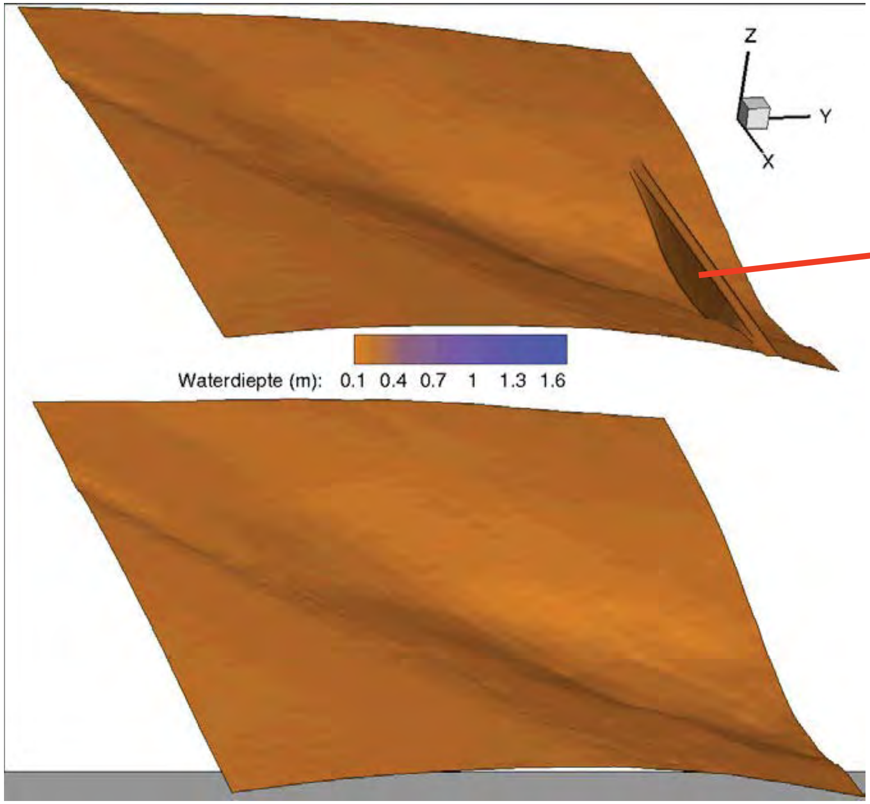

bed and furrows, Ethiopia


demi lunes, Niger


runoff strips , Ethiopia


zaï pits, Niger

- future work (cont.): sediment transport model




Thank you!