A Framework for Evaluating Water Harvesting Efficiency

Koen Verbist (1,3), Wim M. Cornelis (1), Rob G. McLaren (2), Guido Soto (3) and Donald Gabriels (1)

(1) Ghent University, Dept. Soil Management, UNESCO Chair on Eremology, Belgium
(2) Department of Earth Sciences, University of Waterloo, Canada
(3) Centro del Agua para Zonas Aridas y Semi-aridas de America Latina y el Caribe (CAZALAC), La Serena, Chile
Content

- Context and Objectives
- 3-D coupled overland-subsurface flow model
- Flow domain and boundary conditions
- Parameter estimation strategies
- Model calibration strategies
- Model results: effect of WHT
- Conclusions
Why do we need Water Harvesting?

Water needed to produce future food = HUGE

Green Revolution

2002

2030

2050

Increase to reach the Hunger Goal 2015

2002 base line
A conceptual change in the hydrological cycle

[Diagram showing water cycle with green and blue water resources and ET flows]
Need for an increase in water availability

- Irrigation cannot contribute much
- Efficient use of Green Water / soil water must be increased

Water harvesting will form an essential part of such effort!
Overall objective:

- Increase water availability through rainwater harvesting
  - infiltration trenches (zanjas)
Research questions:

- Can we model the infiltration-runoff pattern in this Water Harvesting Technique (WHT)?
- Which parameter estimation strategy is most appropriate for the selected model?
- What is the water retention efficiency of the WHT?
- What should be the optimal design of the WHT under different soil physical and climatic conditions?
500 km N of Santiago, near La Serena
Community Quebrada De Talca

- $P = 113$ mm
- $ET = 125$ mm
- $12 \, ^\circ C \, (Jul) < T < 19 \, ^\circ C \, (Jan)$

Arid (UNEP)
Objectives and context

- **soil:**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Clay (g kg⁻¹)</th>
<th>Silt (g kg⁻¹)</th>
<th>Sand (g kg⁻¹)</th>
<th>BD (Mg m⁻³)</th>
<th>OM (g kg⁻¹)</th>
<th>CaCO₃ (g kg⁻¹)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>146</td>
<td>226</td>
<td>628</td>
<td>1.63</td>
<td>3.8</td>
<td>2.2</td>
<td>SL</td>
</tr>
<tr>
<td>12.5</td>
<td>168</td>
<td>228</td>
<td>604</td>
<td>1.62</td>
<td>2.4</td>
<td>3.1</td>
<td>SL</td>
</tr>
<tr>
<td>32.5</td>
<td>134</td>
<td>160</td>
<td>706</td>
<td>1.60</td>
<td>1.7</td>
<td>2.6</td>
<td>SL</td>
</tr>
<tr>
<td>42.5</td>
<td>96</td>
<td>134</td>
<td>770</td>
<td>1.60</td>
<td>2.0</td>
<td>2.6</td>
<td>SL</td>
</tr>
</tbody>
</table>

- **slope:** 23%
Objectives and context

3-D coupled overland-subsurface flow model

Flow domain and boundary conditions

Parameter estimation strategies

Model calibration strategies

Model results: effect of WHT

Conclusions
governing equations:

- **porous medium**: 3D variably-saturated flow

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

**Richards' equation**:

\[q = -K \cdot k_r \nabla (\psi + z)\]

**Darcy equation**:

\[S_w \quad k_r\]

Mualem-van Genuchten formulation

- \(w_m\) = porous medium vol. fraction
- \(q\) = fluid flux
- \(\Gamma_{ex}\) = exchange flux
- \(Q\) = source/sink
- \(\theta_s\) = sat. vol. water content
- \(S_w\) = degree of saturation
- \(K\) = saturated hydraulic conductivity
- \(k_r\) = relative hydraulic conductivity
- \(\psi\) = pressure head
- \(z\) = elevation
governing equations:

- overland/stream: 2D surface flow

\[- \nabla \cdot (d \cdot q_o) - d \cdot \Gamma_o = Q_o = \frac{\partial \phi_o h_o}{\partial t}\]

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

flux equation:

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

- \(d_o\) = water depth
- \(q_o\) = fluid flux
- \(\Gamma_o\) = exchange flux
- \(Q_o\) = source/sink
- \(\phi_o\) = surface flow porosity
- \(h_o\) = water surface elevation
- \(K_o\) = surface conductance
- \(k_{ro}\) = relative hydraulic cond.
- \(z_o\) = land surface elevation
- \(n_x\) = Manning roughness coeff.
- \(S\) = max. slope
Model

- governing equations:

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

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

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

\[k_r = \text{relative hydraulic conductivity of exchange flux}\]

\[K_{zz} = \text{sat. hydr. conduct. in vertical dir.}\]

\[l_{exch} = \text{coupling length}\]
Objectives and context

3-D coupled overland-subsurface flow model

Flow domain and boundary conditions

Parameter estimation strategies

Model calibration strategies

Model results: effect of WHT

Conclusions
Flow domain and boundary conditions

Detailed study

- a field plot of 6 x 2 m
- one trench + catchment area
- runoff and moisture content measurements
- 3D mesh
Simulated rainfall:

- 20 min
- 120 mm h⁻¹
- 7 nozzles
Objectives and context

3-D coupled overland-subsurface flow model

Flow domain and boundary conditions

Parameter estimation strategies

Model calibration strategies

Model results: effect of WHT

Conclusions
Parameter estimation

7 model parameters need to be estimated

- **K**: saturated hydraulic conductivity
- $r$, $s$, $\theta_r$, $\theta_s$: van Genuchten-Mualem WRC parameters
- **n**: Manning coefficient
- **lexch**: coupling length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trench</th>
<th>Impluvium</th>
<th>Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kfs</td>
<td>0.51</td>
<td>0.36</td>
<td>0.12</td>
</tr>
<tr>
<td>lexch</td>
<td>0.44</td>
<td>0.25</td>
<td>0.08</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>0.31</td>
<td>0.76</td>
<td>0.11</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.15</td>
<td>0.23</td>
<td>0.08</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>0.35</td>
<td>0.60</td>
<td>0.07</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>0.03</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td>n</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Parameter estimation

Measurements of Kfs in 10 reps

IA: inverse augerhole
TI: tension infiltrometer
RFS: rainfall simulation

CH: constant well infiltrometer
SR: single ring infiltrometer
DR: double ring infiltrometer

Verbist et al., SSSAJ, 2009
Baetens et al., WRR, 2009
Verbist et al., 2010, VZJ.
Parameter estimation

Measurements of Kfs in 10 reps

![Box plot showing Kfs measurements for different methods (SR, DR, CH, IA, TI, RFS). The plot displays the distribution of Kfs values at different levels (1e-6, 1e-5, 1e-4) across the methods.](image)
Measurements of SWRC in 10 reps

- undisturbed soil cores (Kopecky – 100 cm³)
- tension table (Eijkelkamp Agr. Eq.) 0-10 kPa
- pressure chambers (Soilmoisture Eq.) 20-1500 kPa
Measurements of SWRC in 10 reps

Parameter estimation
## Initial parameter estimates for model calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated hydraulic conductivity</td>
<td>Kfs</td>
<td>2.2</td>
<td>2.0</td>
<td>10^{-5} m s^{-1}</td>
<td>measured</td>
</tr>
<tr>
<td>Saturated water content</td>
<td>s</td>
<td>0.35</td>
<td>0.02</td>
<td>m 3 m^{-3}</td>
<td>measured</td>
</tr>
<tr>
<td>Residual water content</td>
<td>r</td>
<td>0.11</td>
<td>0.01</td>
<td>m 3 m^{-3}</td>
<td>measured</td>
</tr>
<tr>
<td>Sorptivity</td>
<td>α</td>
<td>0.09</td>
<td>0.02</td>
<td>cm^{-1}</td>
<td>measured</td>
</tr>
<tr>
<td>Scaling parameter</td>
<td>n</td>
<td>1.61</td>
<td>0.10</td>
<td>-</td>
<td>measured</td>
</tr>
<tr>
<td>Pore-connectivity factor</td>
<td>lp</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>Mualem (1976)</td>
</tr>
<tr>
<td>Specific storage</td>
<td></td>
<td>0</td>
<td>-</td>
<td>cm^{-1}</td>
<td>observed</td>
</tr>
<tr>
<td>x- and y- friction factor</td>
<td>n</td>
<td>1.22</td>
<td>10^{-4}</td>
<td>-</td>
<td>Initial estimate</td>
</tr>
<tr>
<td>Rill storage height</td>
<td>hds</td>
<td>0</td>
<td>-</td>
<td>cm</td>
<td>observed</td>
</tr>
<tr>
<td>Coupling length</td>
<td>lexch</td>
<td>10</td>
<td>-</td>
<td>cm</td>
<td>Initial estimate</td>
</tr>
</tbody>
</table>
Objectives and context

3-D coupled overland-subsurface flow model

Flow domain and boundary conditions

Parameter estimation strategies

Model calibration strategies

Model results: effect of WHT

Conclusions
Calibration: optimizing the runoff hydrograph (from 10 independent rainfall simulations)
Model Calibration Strategies

Calibration: optimizing water content time series

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

- The capacity of the model to mimic the hydraulic behaviour of the soil:
  - Identifiability of soil hydraulic properties
  - Uniqueness of the inverse solution
  - Stability of the inverse solution

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

Coupling HGS with Parameter Estimation Software (PEST)

\[
\phi(\beta) = \sum_{j=1}^{M} \left\{ v_j \sum_{i=1}^{N_j} w_i \left[ q_j^*(t_i) - q_j(t_i, \beta) \right]^2 \right\}
\]
Model Calibration Strategies

What **data types** need to be considered for a well-posed model?

Construction of **response surfaces** for parameter couples: e.g Ks-β

Moisture Content $\theta(t)$    Runoff Data $RO(t)$    Both

$$\phi(\beta) = \sum_{i=1}^{n_1} \sum_{j=1}^{T_i} \left[ \theta^*_j(t_i) - \theta_j(t_i, \beta) \right]^2 + \sum_{j=1}^{n_2} \left[ RO^*(t_i) - RO(t_i, \beta) \right]^2$$
Model Calibration

- Model based on calibration of runoff AND moisture content
  - Good agreement between measured and simulated runoff
  - Correct representation of infiltration trench overfilling
Model based on calibration of runoff AND moisture content
• Objectives and context
• 3-D coupled overland-subsurface flow model
• Flow domain and boundary conditions
• Parameter estimation strategies
• Model calibration strategies
• Model results: effect of WHT
• Conclusions
Model results – surface runoff & accumulation

→ Runoff accumulation in the trench during rainfall
→ Drainage after rainfall has stopped
Model results - subsurface moisture redistribution
Model results - subsurface moisture redistribution
\[ P + R_{IN} = R_{OUT} + \left( E_{SW} + E_{OW} + E_{INT} \right) + T_{ACT} + \Delta W + D \]
Case study: 2008 rainfall events

- duration: 11 days
- maximum intensity: 6.6 mm hr\(^{-1}\)
- total rainfall: 49.8 mm

<table>
<thead>
<tr>
<th></th>
<th>With Trench</th>
<th>Without Trench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Infiltration</td>
<td>35</td>
<td>19</td>
</tr>
<tr>
<td>Runoff</td>
<td>15</td>
<td>31</td>
</tr>
</tbody>
</table>
Objectives and context

3-D coupled overland-subsurface flow model

Flow domain

Parameter estimation strategies

Model results: effect of WHT

Conclusions
Research questions:

- Can we model the 3D infiltration-runoff pattern in these WHT?
  
  Good agreement between measured and simulated runoff, and between measured and simulated moisture content

- Which parameter estimation strategy is most appropriate for the selected model?
  
  A combination of runoff and soil moisture data sets is
Research questions:

• **What is the water retention efficiency of the WHT?**
  A significant increase in infiltration and a reduction of excess runoff was observed for the 2008 wet season.

• **What should be the optimal design of the WHT under different soil physical and climatic conditions?**
  Work in progress using the water balance approach:
  -minimizing the losses (Evaporation, Runoff, Drainage)
  -maximizing the gains (Transpiration, Infiltration)
Gracias!