Testing the distributed hydrological wflow_sbm concept across different geographical domains

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Hills Rwanda, Photo Mark de Bel
Introduction

- Wflow_sbm, a distributed hydrologic model, fits well between low-resolution, low-complexity and high-resolution, high-complexity hydrologic models:
  - gravity-based infiltration and vertical flow through the soil column as well as capillary rise represents a simplified version of the Richards’ equation. A1-D kinematic wave approach for channel, overland and lateral subsurface flows similar to TOPKAPI (Todini and Ciaparica, 2002), G2G (Bell et al., 2007), 1K-DHM (Tanaka and Tachikawa, 2015) and Topog_SBM (Vertessy and Elsaesser, 1999) is used as an approximation for dynamic waves and variably saturated subsurface flow (Richards’ equation).
  - The advantage of this approach is that most wflow_sbm parameters have a clear physical meaning and at the same time wflow_sbm has a run time performance well suited for large scale modelling.
- This allows us to automatically setup a high resolution (~1km²) wflow_sbm model for any basin in the world:
  - We apply available point-scale (pedo)transfer functions (PTFs) with upscaling rules (see Imhoff et al., 2020) to global datasets to ensure flux matching across scales (Samaniego et al., 2010, 2017)
  - A new method (“Connecting Outlets Method” (COM)) to automatically upscale flow direction data to model resolution shows promising results (Eilander et al., in prep, “Global multi-resolution hydrography data”)
- As a final result we have a **calibration-less** wflow_sbm model:
  - depending on the geographical area of interest two model parameters, besides anthropogenic interference like reservoir and lake management, show most sensitivity: rooting depth and horizontal saturated hydraulic conductivity.
- Here we test the wflow_sbm concept across different geographical domains (USA, Europe, Africa, New Zealand and more testing and applications are underway)
Wflow_sbm (simple bucket model)

Part of wflow, the Deltares’ OpenStreams project, an open source modelling framework for distributed hydrologic modelling

Loosely based on Topog_SBM (Vertessy and Elsenbeer, 1999), main differences:

- Addition of evapotranspiration and interception losses.
- Addition of a root water uptake reduction function (Feddes et al., 1978).
- Addition of capillary rise.
- Addition of glacier and snow build-up and melting processes (where relevant).
- Routes water over an eight direction (D8) network.
- Multiple soil layers optional.

See also:
Wflow_sbm processes and modules

- Interception module (Gash or Modified Rutter)
- Soil module (based on Topog_SBM model) including optional multiple soil layers
- Lateral subsurface flow (kinematic wave)
- Snow and glacier module
- Kinematic wave routing module (river, overland)
- (Simple) reservoir and lake module
- Irrigation (based on PET and AET)

Schematisation of the soil and the connection to the river within the wflow_sbm model
Estimation of wflow_sbm parameters

- Based on earlier work by Imhoff et al (2020) that focused on the entire Rhine basin.
- Using available point-scale (pedo)transfer functions (PTFs) with upscaling rules to ensure flux matching across scales (Samaniego et al., 2010, 2017, Imhoff et al., 2020)
- Data sets (global) used to setup a wflow_sbm model for any basin in the world (Python scripts):
  - **Soil:**
    - SoilGrids (Hengl et al. (2017)) at ~250 m resolution
    - Depth to impermeable layers for Europe (ESDAC, 2004)
  - **Land cover:**
    - GlobCover-2009 (Arino et al., 2010) at ~300 m resolution
  - **Hydrography (flow direction, upstream area, stream order, river slope \( \beta_{river} \), river length \( L_{river} \), river width \( W_{river} \))**
    - MERIT Hydro (Yamazaki et al., 2019) at ~90 m resolution
    - Discharge data from Global Runoff Data Center (GRDC)
    - CHELSEA dataset at ~1 km resolution (Karger et al., 2017)
    - Köppen–Geiger climate zone map (Kottek et al., 2006)
  - **Lake and reservoir model parameters:**
    - HydroLAKES Version 1.0 (Messager et al., 2016)
    - GRanD v1.01 (Lehner et al., 2011)
    - GWSO (Pekel et al., 2016) extracted with https://github.com/openearth/hydro-engine

Deltares
Wflow_sbm parameter estimation (global)

Spatial data map(s)

Model parameter map

Pedotransferfunction

\[ K_{sat, sand} = \frac{10}{24} \times \exp[9.5 - 4.171 \times BD^2 - 0.688 \times OC + 0.0369 \times OC^2 - 0.332 \times \ln(Cl + Si)] \]
## PTFs and upscaling operators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PTF by</th>
<th>Upscaling operator</th>
<th>Additional notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>Rawls and Brakensieck (1989)</td>
<td>$\log A$</td>
<td>$\lambda$ upscaled with $\log A$, $c$ determined from $\lambda$ at model resolution</td>
</tr>
<tr>
<td>$k$</td>
<td>Van Dijk and Bruijnzeel (2001)</td>
<td>$A$</td>
<td>Look-up table from land cover</td>
</tr>
<tr>
<td>$kv$</td>
<td>Brakensieck et al. (1984)</td>
<td>$\log A$</td>
<td>For the soil depths $z$: 0, 5, 15, 30, 60, 100 and 200 cm</td>
</tr>
<tr>
<td>$LAI$</td>
<td>Myneni et al. (2015)</td>
<td>$A$</td>
<td></td>
</tr>
<tr>
<td>$M$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{\text{land}}$</td>
<td>Engman (1986); Kilgore (1997)</td>
<td>$A$</td>
<td>Lookup table land cover</td>
</tr>
<tr>
<td>$N_{\text{river}}$</td>
<td>Liu et al. (2005)</td>
<td>$A$</td>
<td>Lookup table land cover</td>
</tr>
<tr>
<td>$RTD$</td>
<td>Schenk and Jackson (2002); Fan et al. (2016)</td>
<td>$A$</td>
<td>$d_{75}$ rooting depth, look-up table land cover</td>
</tr>
<tr>
<td>$S_l$, $S_{\text{wood}}$</td>
<td>Pitman (1989); Liu (1998)</td>
<td>$A$</td>
<td>Lookup table land cover</td>
</tr>
<tr>
<td>$\beta_{\text{river}}$, $L_{\text{river}}$</td>
<td></td>
<td></td>
<td>Based on MERIT Hydro</td>
</tr>
<tr>
<td>$W_{\text{river}}$</td>
<td></td>
<td></td>
<td>Based on MERIT Hydro, GRDC, CHELSEA, Köppen–Geiger climate zones</td>
</tr>
<tr>
<td>$\beta_{\text{land}}$</td>
<td>Horn (1981)</td>
<td>$A$</td>
<td>Based on MERIT Hydro</td>
</tr>
<tr>
<td>$\text{Soilthickness}$</td>
<td>Hengl et al. (2017); ESDAC (2004)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_s$, $\theta_r$</td>
<td>Tóth et al. (2015)</td>
<td>$A$</td>
<td></td>
</tr>
</tbody>
</table>

$A = \text{arithmetic mean}$

$\lambda = \text{pore size distribution index (Brooks Corey, 1964)}$
wflow_sbm parameter upscaling

Rhine  see Imhoff et al. 2020 WRR

NSE & KGE as function of year

1733-HARRSELE KRV_NSE=0.23_KGE=0.37 (0.67,0.66,1.41)

436-SOLBERG_NSE=0.6_KGE=0.61 (0.83,1.05,1.35)

1630-GAUTRÄSK_NSE=0.68_KGE=0.62 (0.84,0.84,1.31)
White Nile (upstream of Juba)

- Use of CHIRPS for rainfall, downscaled ERA5 for estimating PET (de Bruin et al., 2016)
- $K_{sathorfrac}=100$ (lateral conductivity)
White Nile (upstream of Juba)

Lake Victora

NSE & KGE as function of year

R. Anyau at Arua - Moyo Road NSE=0.41 KGE=0.5 (0.64, 0.66, 1.02)

R. Sironko at Mbale - Moroto Road NSE=-0.04 KGE=0.44 (0.73, 1.45, 1.21)

In collab with Nynke Hofstra
Orange river at Oranjedraai (CHIRPS rainfall and ERA5 Temperature and PET de Bruin et al 2016)
Save river (CHIRPS rainfall and ERA5 Temperature and PET de Bruin et al 2016)
Acknowledgement NIWA for sharing their high res forcing data set
Androscoggin river example (ERA5 rainfall, temperature and PET de Bruin et al, 2016)

USGS 01053500 Androscoggin River at Errol, NH

NSE & KGE as function of year

NSE KGE

Androscoggin River near Wentworth Location, NH

Deltres
Conclusions

wflow_sbm derived with the Deltares wflow_sbm global setup seem to give reasonable results for many places

However (and not surprising) sensitive to
- rainfall forcing (CHIRPS in Africa, ERA5 in Scandinavia, EOBS/ERA5, NIWA dataset New Zealand )
- rooting depth (especially Africa \(\Rightarrow\) often needs adjustments seem to agree with Yang et al 2016 WRR)
- lateral hydraulic conductivity (ksathorfrac often in order 1-100)
- human activity (hydropower)
- underlying global datasets (for instance landuse as used for effective rooting depth)

wflow_sbm & wflow_sbm global setup improvements:
- a priori reservoir parameters seem to give reasonable estimates (Errol, Lake Victoria, Harrsele KRV)
- wetlands, lakes (not well modelled yet)
- rooting depth approach (fractions)
- better routing for flat rivers
- update global datasets

Avoiding calibration makes forcing datasets more comparable, however further sensitivity analysis needed especially for ksathorfrac (no PTF) and effective rooting depth.