Large-scale modelling of groundwater resources: insight from the comparison of models and in-situ observations

The Chronicles Consortium*

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The Chronicles Consortium

Multi-Decadal Groundwater Levels in Africa

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A pan-African inter-comparison of groundwater recharge from in-situ observations and large-scale models

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Groundwater Futures in Sub-Saharan Africa

Developing the scientific basis and participatory management processes by which groundwater resources can be used sustainably for poverty alleviation.
Dependence on groundwater is growing globally to sustain and amplify the production of food through irrigation and the provision of safe drinking water.

Why Africa? – home to the world’s most variable freshwater resources, the highest rates of population growth, lowest rates of per capita food production, and lowest proportions of national populations with access to safe water
groundwater is a fundamental component of the global hydrological system but inadequately represented in large-scale models despite recognition by GCOS & GEWEX of the influence of groundwater on the global climate system through surface moisture and energy budgets.
large-scale models (LSMs, GHMs) are, with a few exceptions (e.g. WaterGAP), uncalibrated.

lack of *in situ* hydrological observations beyond river discharge leads to ‘equifinality’ (non-uniqueness) in the development of large-scale models.

**evolution of large-scale models toward ‘hyperresolutions’** requires revision of model structures to explicitly represent *subgrid* hydrological processes – the understanding of which is informed by *in situ* observations.
large-scale models and hydrological process

- large-scale models mostly* disregard focused recharge - leakage from surface waters such as ephemeral streams - yet this is the dominant pathway of groundwater replenishment occurs in dryland regions

*except WaterGAP

ephemeral stream flow in central Tanzania during 2015-16 El Niño
Collation of observational data addresses the key challenge of groundwater data scarcity raised by GCOS and GEWEX and has the potential:

1. to evaluate the performance of large-scale models to simulate terrestrial water balances – addressing the problem of equifinality - and to estimate groundwater recharge; and

2. to inform the development of more robust large-scale models that simulate critical groundwater processes (e.g. focused recharge)
Collation of multi-decadal, *in situ* (piezometric) records of groundwater levels across Africa under *The Chronicles Consortium*.

<table>
<thead>
<tr>
<th>Location</th>
<th>No.</th>
<th>Geology</th>
<th>Climate</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benin</td>
<td>8</td>
<td>Quaternary sands Continentale Terminale</td>
<td>humid</td>
<td>1991-present</td>
</tr>
<tr>
<td>Burkina Faso</td>
<td>2</td>
<td>weathered crystalline rock Continentale Terminale</td>
<td>semi-arid</td>
<td>1978-present</td>
</tr>
<tr>
<td>Chad</td>
<td>15</td>
<td>Quaternary sediments</td>
<td>arid</td>
<td>1968-1989</td>
</tr>
<tr>
<td>Ghana</td>
<td>1</td>
<td>Quaternary sediments</td>
<td>humid</td>
<td>1976-present</td>
</tr>
<tr>
<td>Morocco</td>
<td>25</td>
<td>Plio-Quaternary sediments</td>
<td>arid</td>
<td>1970-present</td>
</tr>
<tr>
<td>Niger</td>
<td>50</td>
<td>Quaternary sediments</td>
<td>semi-arid</td>
<td>1987-present</td>
</tr>
<tr>
<td>South Africa</td>
<td>21</td>
<td>weathered crystalline rock limestone</td>
<td>semi-arid</td>
<td>1970-present</td>
</tr>
<tr>
<td>Tanzania</td>
<td>1</td>
<td>weathered crystalline rock</td>
<td>semi-arid</td>
<td>1954-present</td>
</tr>
<tr>
<td>Tunisia</td>
<td>70</td>
<td>Quaternary sediments</td>
<td>semi-arid</td>
<td>1969-present</td>
</tr>
<tr>
<td>Uganda</td>
<td>5</td>
<td>weathered crystalline rock</td>
<td>humid</td>
<td>1998-present</td>
</tr>
</tbody>
</table>
observations of stable-isotope tracers

“amount effect” enables the use of rainfall-groundwater stable-isotope (\(^{18}\text{O}:^{16}\text{O}\)) “pairings” to trace the intensity of rainfall to groundwater recharge
<table>
<thead>
<tr>
<th>Location</th>
<th>P samples</th>
<th>P period</th>
<th>Mean annual P</th>
<th>GW samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addis Ababa</td>
<td>299 (296)</td>
<td>1961-2009</td>
<td>1100</td>
<td>13</td>
</tr>
<tr>
<td>Bamako</td>
<td>147 (140)</td>
<td>1962-1998</td>
<td>920</td>
<td>10</td>
</tr>
<tr>
<td>Dar es Salaam</td>
<td>125 (117)</td>
<td>1960-1973</td>
<td>1140</td>
<td>9</td>
</tr>
<tr>
<td>Entebbe</td>
<td>197 (192)</td>
<td>1960-2006</td>
<td>1570</td>
<td>56 (IAEA TWIN)</td>
</tr>
<tr>
<td>Harare</td>
<td>257 (192)</td>
<td>1960-2003</td>
<td>890</td>
<td>none within 100 km</td>
</tr>
<tr>
<td>Kinshasa</td>
<td>60 (59)</td>
<td>1961-1968</td>
<td>1380</td>
<td>none within 100 km</td>
</tr>
<tr>
<td>Malange</td>
<td>330 (204)</td>
<td>1961-2009</td>
<td>1140</td>
<td>none within 100 km</td>
</tr>
<tr>
<td>Ndola</td>
<td>143 (133)</td>
<td>1968-2009</td>
<td>1210</td>
<td>none within 100 km</td>
</tr>
<tr>
<td>N’Djamena</td>
<td>86 (75)</td>
<td>1963-1995</td>
<td>550</td>
<td>320 (IAEA TWIN)</td>
</tr>
<tr>
<td>Pretoria</td>
<td>245 (168)</td>
<td>1958-2001</td>
<td>680</td>
<td>none within 100 km</td>
</tr>
<tr>
<td>Windhoek</td>
<td>141 (97)</td>
<td>1961-2001</td>
<td>360</td>
<td>1 (IAEA TWIN)</td>
</tr>
</tbody>
</table>
groundwater recharge (subsurface runoff) estimates from 7 global-scale models: 2 GHMs (WaterGAP, PCR-GLOBWB) and 5 LSMs (CESM-CLM4.5 & NASA’s GLDAS LSMs: CLM, NOAH, VIC, MOSAIC)

<table>
<thead>
<tr>
<th>Model</th>
<th>Grid</th>
<th>Precipitation</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLM2.0</td>
<td>1°</td>
<td>CMAP</td>
<td>SSR</td>
</tr>
<tr>
<td>NOAH</td>
<td>1°</td>
<td>CMAP</td>
<td>SSR</td>
</tr>
<tr>
<td>VIC</td>
<td>1°</td>
<td>CMAP</td>
<td>SSR</td>
</tr>
<tr>
<td>MOSAIC</td>
<td>1°</td>
<td>CMAP</td>
<td>SSR</td>
</tr>
<tr>
<td>CLM4.5</td>
<td>0.5°</td>
<td>CRU-NCEP (v.5)</td>
<td>GWR (diffuse only)</td>
</tr>
<tr>
<td>PCR-GLOBWB</td>
<td>0.5°</td>
<td>WFDEI</td>
<td>GWR (diffuse only)</td>
</tr>
<tr>
<td>WaterGAP</td>
<td>0.5°</td>
<td>CRU TS 3.23</td>
<td>GWR (diffuse only)</td>
</tr>
<tr>
<td>WaterGAP</td>
<td>0.5°</td>
<td>CRU TS 3.23</td>
<td>GWR (diffuse-focused)</td>
</tr>
</tbody>
</table>
substantial variations in the magnitude and distribution of mean annual SSR & groundwater recharge (GWR)

spatial extent & magnitude of recharge in semi-arid regions increase from WaterGAP (diffuse only) to WaterGAP (diffuse-focused)
simulated SSR & GWR grouped by climate

- simulated recharge in semi-arid regions increases with the inclusion of focused recharge in WaterGAP.

CGIAR Aridity Index
correlation of simulated GWR/SSR and precip

- precipitation and simulated GWR / SSR are strongly correlated in GLDAS-CLM and WaterGAP
- weaker correlations in GLDAS VIC and MOSAIC explained by very low, estimated SSR
semi-arid: Bamako (isotope pairing)
semi-arid: Makutapora (piezometry)

Makutapora (Tanzania)

Taylor et al. (2013)
Addis Ababa (Ethiopia)

Addis Ababa (isotope pairing)

- Addis GLDAS-CLM: $Y_{\text{incept}} = -0.31$, $R^2 = 0.66$
- Addis GLDAS-NOAH: $Y_{\text{incept}} = -5.83$, $R^2 = 0.32$
- Addis GLDAS-VIC: $Y_{\text{incept}} = 5.16$, $R^2 = 0.06$
- Addis GLDAS-MOSAIC: $Y_{\text{incept}} = -1.6$, $R^2 = 0.07$
- Addis CESM-CLM v.4.5: $Y_{\text{incept}} = -11.17$, $R^2 = 0.62$
- Addis PCR-GLOBWB: $Y_{\text{incept}} = -5.98$, $R^2 = 0.71$
- Addis WaterGAP: diffuse GWR: $Y_{\text{incept}} = -2.74$, $R^2 = 0.82$
- Addis WaterGAP: combined GWR: $Y_{\text{incept}} = -2.75$, $R^2 = 0.82$
Dar e Salaam (Tanzania)

- **Dar: GLDAS-CLM**
  \[ Y_{incept} = -6.65, R^2 = 0.56 \]
  \[ R^2 = 0.65 \]

- **Dar: GLDAS-NOAH**
  \[ Y_{incept} = -1.92, R^2 = 0.14 \]
  \[ R^2 = 0.12 \]

- **Dar: GLDAS-VIC**
  \[ Y_{incept} = 0.48, R^2 = 0.05 \]
  \[ R^2 = 0.05 \]

- **Dar: GLDAS-MOSAIC**
  \[ Y_{incept} = 0.02, R^2 = 0 \]
  \[ R^2 = 0 \]

- **Dar: CESM-CLM v.4.5**
  \[ Y_{incept} = 0.35, R^2 = 0.01 \]
  \[ R^2 = 0.02 \]

- **Dar: PCR-GLOBWB**
  \[ Y_{incept} = -2.94, R^2 = 0.41 \]
  \[ R^2 = 0.37 \]

- **Dar: WaterGAP: diffuse GWR**
  \[ Y_{incept} = -6.02, R^2 = 0.79 \]
  \[ R^2 = 0.79 \]

- **Dar: WaterGAP: combined GWR**
  \[ Y_{incept} = -6.06, R^2 = 0.79 \]
  \[ R^2 = 0.79 \]
• spatial extent and magnitude of simulated GWR & SSR vary substantially among large-scale models; in semi-arid regions, simulated estimates of GWR & SSR are substantially less in large-scale models disregarding focused recharge

• non-linearity, evident in the relationship between simulated GWR & SSR and precipitation (GLDAS-CLM, WaterGAP), is consistent with piezometric & isotopic observations

• simulated GWR & SSR and precipitation correlate well for some models (GLDAS-CLM, WaterGAP) but are very weakly correlated in others (GLDAS-VIC, MOSAIC)
addendum: inter-comparison from India

- database of ~5500 seasonal (quarterly) groundwater-level records across India from 2007 to 2011

- estimated recharge from water-level fluctuations compared to mean of 3 GLDAS LSMs (CLM, VIC, NOAH) and PCR-GLOBWB (with & without water management)
hydrogeological context in India

- distribution of aquifer types and human use of groundwater
human influences on terrestrial hydrology in India have a very long history...
recharge inter-comparison in India

- very substantial differences among “observed” recharge from piezometry (a), PCR-GLOBWB – natural (b), 3 GLDAS LSMs (c), and PCR-GLOBWB – water management (d)
recharge inter-comparison in India

- inclusion of human withdrawals for irrigation and return flows in PCR-GLOBWB amplifies simulated recharge in the Indo-Gangetic Basin but do not address substantial discrepancy with “observed recharge”

PCR-GLOBWB (water management) - PCR-GLOBWB (natural)