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

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Why conduct an inter-comparison of groundwater recharge simulated by GHMs with *in situ* observations in Africa?

[1] Groundwater is a vital resource upon which dependence is growing globally to sustain and amplify the production of food through irrigation and the provision of safe drinking water. These ambitions, enshrined in UN Sustainable Development Goals 6.1 & 6.4[1], are of vital importance in Africa, which is home to the world's most variable freshwater resources, the highest rates of population growth, the lowest rates of per capita food production, and lowest proportions of national populations with access to safe water.

[2] Current assessments of the sustainability of groundwater withdrawals and the impacts of climate and land-use change on freshwater resources commonly rely on Global Hydrological Models (GHMs) and Land-Surface Models (LSMs) either exclusively or in combination with remote-sensing products (*e.g.* GRACE). Dependence on these global-scale models is expected to intensify as model grid resolutions increase to *hyperresolutions*[2,3,4] (*e.g.* 0.5° to 0.1-1.0 km).

[3] Groundwater is a fundamental component of the global hydrological system yet is inadequately represented or ignored entirely in LSMs despite recognition by both GCOS (Global Climate Observing System) and GEWEX (Global Energy and Water Cycle Exchanges Project)[5,6] of the influence of groundwater on the global climate system through surface moisture and energy budgets[4,7]. As LSMs and GHMs are with few exceptions(e.g. 8) uncalibrated, the reliability of terrestrial water balances simulated by these models remains questionable not only for local water management - a long-term ambition - but also for understanding hydrological responses to global change – a contemporary aim. Global-scale models that explicitly estimate groundwater recharge (*e.g.* WaterGAP, PCR-GLOBWB, CESM-CLM4.5) are similarly untested due to an absence of available observational records.

[4] The limited availability of *in situ* hydrological observations beyond river discharge creates a fundamental problem of equifinality (non-uniqueness) in the development of global-scale models[9] as more than one model parameterisation or structure can be fitted to observations of river discharge alone. This problem of equifinality is particularly acute when a criterion as coarse as mean annual river discharge[10,11] is applied. As uncertainty among global-scale models in the representation of river discharge globally has been

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[1] https://sustainabledevelopment.un.org/

[2] Bierkens, M., et al., 2015. *Hydrol. Proc.* 29, 310-320.

[3] Bierkens, M., 2015. *Water Resour. Res*. 51, 4923-4947.

[4] Döll, P. et al., 2016. *Surv. Geophys.* 37, 195-221.

[5] Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report (2008), GCOS-117, WCRP-127, IGBP Report No. 58, (WMO/TD No. 1418)

[6] Trenberth, K. and Asrar, G.R., 2014. *Surv. Geophys*. 35, 515–532.

[7] Taylor, R.G. et al., 2013a. *Natur. Clim. Change* 3, 322-329.

[8] Döll, P. et al., 2003. *J. Hydrol.* 270, 105-134.

[9] Beven, K. and Freer, J., 2003. *J. Hydrol.* 249, 11-29.

[10] Milly, P.C.D. et al., 2005. *Nature* 438, 347-350.

[11] Müller Schmeid, H. et al., 2014. *Hydrol Earth Syst. Sci.* 18, 3511-3538.

found to exceed that of GCMs[12], there is a need to move toward multi-criteria model validation as recognised by Döll *et al.*[4]. GRACE satellite measurements of changes in total water storage (ΔTWS) provide a potential, additional global model validation criterion[13] but are currently constrained by their large spatial scale (*e.g.* 200 km) and the substantial variability that persists in the amplitude of ΔTWS among current gridded GRACE products (*e.g., GRCTellus*, MASCONS, GRGS)[14].

[5] The evolution of global-scale models toward hyperresolution is non-linear, requiring a revision of model structures to explicitly represent hydrological processes that are currently considered as subgrid concepts[2,3]. Such revisions to model structures, however 'computationally frugal', require a conceptual understanding of process that is derived empirically from local-scale, *in situ* observations. For example, preferential pathways of groundwater recharge that bypass soil matrices in karst environments, have been developed from observational records and incorporated in a large-scale, parsimonious model for Europe[15].

[6] Required improvements in model structure are not confined to sub-grid concepts. Indeed, indicative of the partiality in the representation of hydrological processes in current global-scale models is the fact that focused recharge, which derives from leakage from surface waters such as ephemeral streams, is disregarded by LSMs and GHMs (with one notable exception[13]) and even though it is the dominant pathway by which groundwater replenishment occurs in semi-arid and arid regions[16]. Consequently, current GHMs and LSMs systematically underestimate renewable groundwater resources in dryland environments globally. The sustainability of vital, groundwater-fed adaptations to ephemeral or perennial water scarcity in drylands may be substantially underestimated.

[7] The collation of multi-decadal, *in situ* (piezometric) records of groundwater levels, together with stable-isotope measurements, across Africa under *The Chronicles Consortium*[17] addresses the fundamental challenge of groundwater data scarcity raised by GCOS, GEWEX and recent reviews[3-5,7]. Such observational records have the potential: (i) to evaluate the performance of current GHMs and LSMs to simulate terrestrial water balances – addressing the problem of equifinality - and to estimate groundwater recharge; and (ii) to inform the development of more robust GHMs and LSMs that simulate critical groundwater processes (*e.g.* focused recharge) and dynamics (*e.g.* preferential flow).

[8] Improved global-scale models, informed by an understanding of groundwater processes and dynamics derived from *in situ* observations, will enable more robust analyses of the responses of groundwater systems to human withdrawals as well as climate and land-use change. Such model improvements will enable answers to key

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[12] Schewe, J. et al., 2014. *Proc. Nat. Acad. Sci*. 111, 3245-3250.

[13] Döll, P. et al., 2014. *Water Resour. Res.* 50, 5698-5720.

[14] Shamsudduha, M. et al. (in preparation)

[15] Hartmann, A. et al., 2015. *Geosci. Model Dev*. 8, 1729-1746.

[16] Scanlon, B. et al., 2006. *Hydrol. Proc.* 20, 3335-3370.

[17] https://www.un-igrac.org/special-project/chronicles-consortium

societal questions such as the sustainability of groundwater-fed irrigation to improve food security, and key science questions such as the conditions under which the intensification of precipitation in a warming world enhances or restricts groundwater recharge.

How to conduct an inter-comparison of simulated and observed groundwater recharge in Africa?

[1] We currently consider explicit estimates of groundwater recharge (or their proxy) from 7 global-scale models including 2 GHMs (*i.e.* WaterGAP, PCR-GLOBWB) and 5 LSMs comprising CESM-CLM4.5 and those compiled under the Global Land Data Assimilation System or GLDAS[18] (*i.e.* MOSAIC, NOAH, CLM, VIC). The 4 GLDAS LSMs do not specifically estimate groundwater recharge but possess a term, sub-surface runoff (SSR) representing drainage from soil profiles independent of geology. A key, unresolved question is whether appropriate selection of output from specific soil layers in LSMs can reasonably be equated to soil-water drainage committed to groundwater (*i.e.* equivalent to groundwater recharge). Here, we provisionally and simply equate recharge to SSR.

[2] Comparisons of *in situ* (piezometric) observations of groundwater recharge derived from groundwater-level hydrographs with recharge or SSR simulated by global-scale models face the problem of the exceptionality of point observations, which may not necessarily reflect grid-scale averaging (*i.e.* point-vs-grid)[19]. In many environments across Africa, we recognise that the number of *in situ* point observations of recharge is insufficient to develop a semi-variogram to evaluate spatial dependence.

[3] One approach is to abandon direct comparisons of simulated and *in-situ* measured recharge fluxes and to assess how groundwater recharge varies in response to changes in a primary driver of recharge, precipitation. Here, we provide preliminary scatter plots of monthly recharge (or SSR) versus precipitation from 1980 to 2014 at 6 provisional sites (Figures 3 & 5) where time series records of groundwater levels (Apac, Makutapora, Pallisa) and stable-isotope measurements (Addis Ababa, Bamako, Dar es Salaam) have been collate and analysed[20,21,22]. Indeed, an advantage of this approach is that linearity (or non-linearity) in relationships between precipitation and groundwater recharge can be evaluated using both piezometric and stable-isotope data[21]. The inclusion of evapotranspiration (ET) in this analysis may further inform the evaluation of potential precipitation thresholds for recharge in different climate zones.

[4] Another provisional advantage of assessing the relationship between recharge and precipitation is that each of global-scale models do not employ the same forcing precipitation data (Table 1). Previous analyses[4] have highlighted the dominant influence of precipitation on model outcomes. Ideally, all global-scale models would employ

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[18] Rodell, M. et al., 2004. *Bull. Am. Meteorol. Soc.* 85, 381-394.

[19] Mileham et al., 2008. *J. Hydrol*. 359, 46-58.

[20] Owor, M. et al., 2009, *Environ. Res. Lett.* 4, 035009.

[21] Jasechko, S. and Taylor, R.G., 2015. *Environ. Res. Lett.* 10, 124015.

[22] Taylor, R.G. et al., 2013b. *Natur. Clim. Change* 3, 374-378..

consistent forcing data to enable direct, quantitative model comparisons. At present, only WaterGAP considers a range of forcing precipitation data to drive their models[23].

Table 1. Global-scale model products employed in the current inter-comparison across Africa using monthly data from 1980 to 2014.

Model	Grid	Precipitation	Output	Contact
CLM	1°	CMAP	SSR	Matt Rodell
NOAH	1°	CMAP	SSR	Matt Rodell
VIC	1°	CMAP	SSR	Matt Rodell
MOSAIC	1°	CMAP	SSR	Matt Rodell
CLM4.5	0.5°	CRU-NCEP (v.5)	GWR (diffuse)	Min-Hui Lo
PCR-GLOBWB	0.5°	WFDEI	GWR (diffuse)	Yoshi Wada
WaterGAP	0.5°	CRU TS 3.23	GWR (diffuse)	Döll/Müller-Schmied
WaterGAP	0.5°	CRU TS 3.23	GWR (combined)	Döll/Müller-Schmied

[5] Other approaches to evaluate the performance of global-scale models that address scale differences include: (1) the selective replacement of forcing precipitation with observational (station) records at grid points where *in situ* observations of recharge exist; and (2) evaluating modelled recharge using catchment-level assessments of baseflow (*i.e.* groundwater discharge) derived from river discharge records. The former does not address the problem of grid-scale smoothing affecting other components of the terrestrial water balance (*e.g.* ET) as recognised by Mileham *et al.*[19] whereas the latter assumes stationarity, which is improbable[24], and is unable to account for transmission losses to atmosphere and subsurface that can substantially influence river discharge records in the tropics.

[6] The derivation of recharge time series from *in situ* (piezometric) observations of requires a consistent methodological approach for robust, comparative analyses. At present, a range of methods[20,22,25,26] has been applied across the compiled "chronicles" across Africa (Table 2). Each analysis also needs to identify and consider carefully the influences of local-scale controls on piezometric responses that include groundwater abstraction and geological heterogeneity.

[7] Potential pairings of stable-isotope ratios in precipitation and groundwater to test model representations of the relationship precipitation and recharge at IAEA stations across Africa have been compiled (Table 3). Evidence from 3 stations has been analysed[21] but there are opportunities to increase the size of this observational database if requisite numbers of stable-isotope ratios in groundwater can be collated from 6 locations (*i.e.* Harare, Kinshasa, Malange, Ndola, Pretoria, Windhoek).

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[23] Müller-Schmied, H. et al. 2016. *Hydrol. Earth Syst. Sci.* 20, 2877-2898.

[24] Milly, P. et al., 2008. Science 319, 573-574.

[25] Favreau, G. et al., 2009. Water Resour. Res. 45, W00A16.

[26] Cuthbert, M. and Tindimugaya, C., 2011. J. Wat. Clim. Change 1, 234-245.

Table 2. Identified multi-decadal groundwater-level time series records (chronicles) from 10 countries across Africa.

Location	No.	Geology	Climate	Duration	Contact
Benin	8	unconsolidated sediments sedimentary rocks	humid	1991-present	Moussa Boukari *Univ. d'Abomey Calavi*
Burkina Faso	2	basement complex sedimentary rocks	semi-arid	1978-present	Youssouf Kousssoubé *Univ. Ouagadougou*
Chad	15?	unconsolidated sediments	arid	1968-1989	B. Ngatcha / I. Goni *Ngaoundéré / Maiduguri*
Ghana	1?	unconsolidated sediments	humid	1976-present?	William Agyekem *WRI Accra*
Morocco	25	unconsolidated sediments	arid	1970-present	Lhoussaine Bouchaou *Université Ibn Zohr*
Niger	50	unconsolidated sediments	semi-arid	1987-present	Yahaya Nazoumou *Univ. Abdou Moumouni*
South Africa	21	basement complex sedimentary rocks	semi-arid	1970-present	T. Abiye / K. Villholth *Witwatersand / IWMI*
Tanzania	1	basement complex	semi-arid	1954-present	Japhet Kashaigili *Sokoine University*
Tunisia	70?	unconsolidated sediments	semi-arid	1969-present	Safouan Ben Ammar *ISTEUB Tunisia*
Uganda	5	basement complex	humid	1998-present	Michael Owor *Makerere University*

Table 3. Stable isotope rainfall-groundwater pairings where proximate (<100 km) groundwater isotope data exist; observations of stable isotope ratios of O and H in groundwater carefully screened to prevent the possibility that data derive from historical climates (*i.e.* palaeogroundwaters) or remote climates; parantheses in column 2 represent samples for ^{2}H:^{1}H versus ^{18}O:^{16}O.

Location	P samples	P period	Climate (mean annual P in mm)	GW samples
Addis Ababa	299 (296)	1961-2009	sub-humid (1100)	13
Bamako	147 (140)	1962-1998	sub-humid (920)	10
Dar es Salaam	125 (117)	1960-1973	humid (1140)	9
Entebbe	197 (192)	1960-2006	humid (1570)	56 (IAEA TWIN)
Harare	257 (192)	1960-2003	semi-arid (890)	none < 100 km
Kinshasa	60 (59)	1961-1968	humid (1380)	none < 100 km
Malange	330 (204)	1961-2009	sub-humid (1140)	none < 100 km
Ndola	143 (133)	1968-2009	humid (1210)	none < 100 km
N’Djamena	86 (75)	1963-1995	semi-arid (550)	320 (IAEA TWIN)
Pretoria	245 (168)	1958-2001	semi-arid (680)	none < 100 km
Windhoek	141 (97)	1961-2001	arid (360)	1 (IAEA TWIN)

What do preliminary scoping analyses reveal?

re: variations in forcing precipitation applied in LSMs and GHMs

- Current models runs employ a range of precipitation products: (1) GLDAS LSMs (CLM, NOAH, VIC, MOSAIC) apply NOAA CPC's Merged Analysis of Precipitation (CMAP) gridded data; (2) CLM 4.5 LSM applies CRU-NCEP (v.5); (3) PCR-GLOBWB employs WFDEI; and (4) WaterGAP runs here employ CRU TS 3.23; note that not all gridded products cover the Great Lakes Region of Africa.
- Spatial patterns represented by gridded precipitation products (1980-2014) are consistent with each other and highly comparable to long-term (1901–2014) CRU (TS 3.23) precipitation records.
- Variations in the magnitude of precipitation are more substantial than they appear as, for mapping purposes, a maximum cut-off value of 2000 mm was used so grids where mean annual precipitation exceeds 2000 mm are thus reported as 2000 mm yet considerable variations in maximum mean annual precipitation exist: 3000 mm CMAP), 2700 mm (CRU-NCEP v.5), 5100 mm (WFDEI), and 3000 mm (CRU TS 3.23).

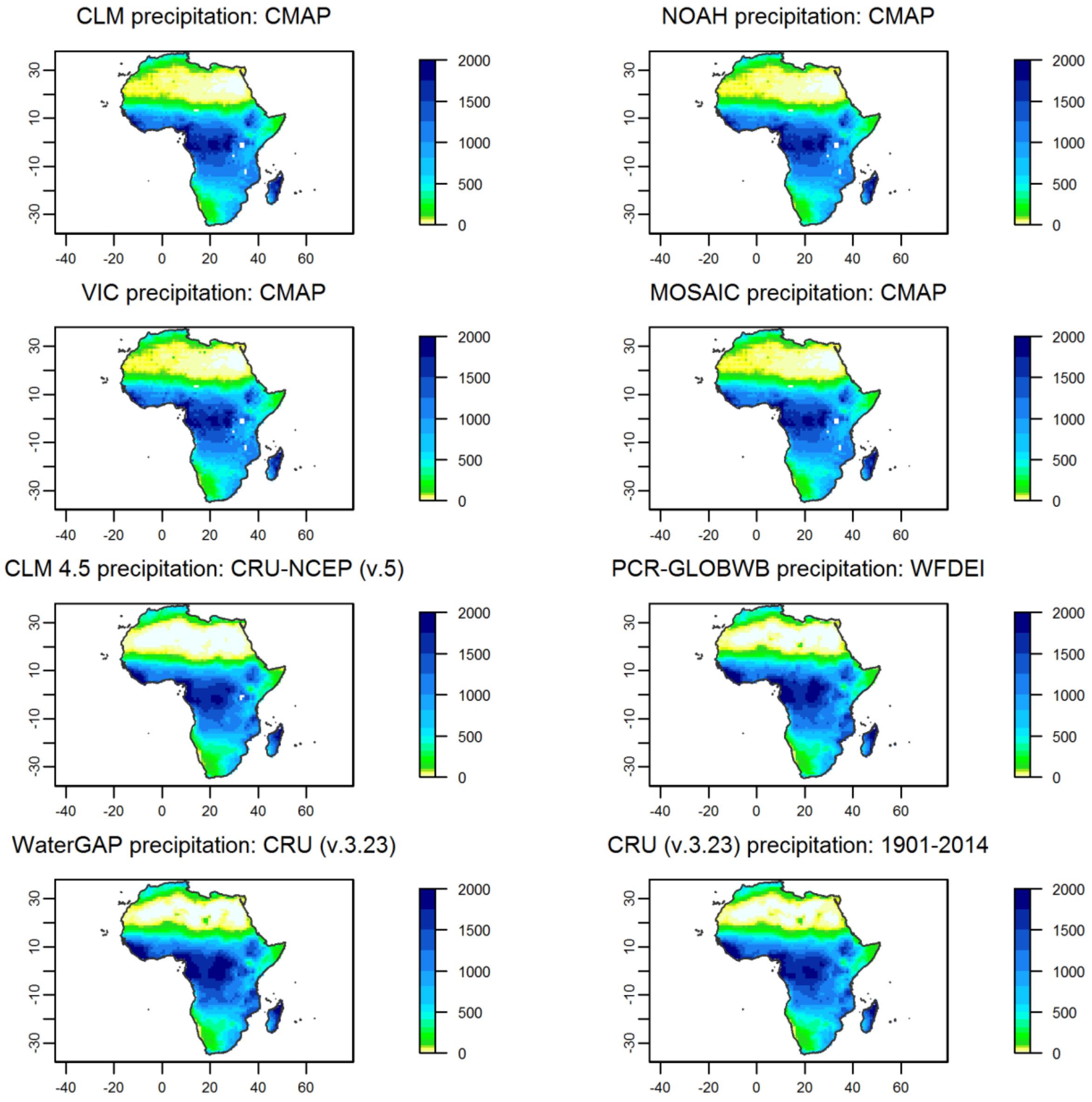


Figure 1: Mean annual precipitation (mm) used in GLDAS LSMs (CLM, NOAH, VIC, MOSAIC), CLM (4.5), PCR-GLOBWB, and WaterGAP for the period of 1980 to 2014; mean annual precipitation of CRU (3.23) data for the period of 1901 to 2014 (bottom right). Note: annual precipitation > 2000 mm is reported as 2000 mm.

re: variations in recharge and SSR simulated by large-scale models

- Very substantial variations in the magnitude and distribution of simulated mean annual SSR and groundwater recharge (GWR) are found among the 5 LSMs (CLM, NOAH, VIC, MOSAIC and CESM-CLM 4.5) and 3 GHMs (PCR-GLOBWB and both WaterGAP *diffuse only* and WaterGAP *diffuse plus focused models*);
- Maximum mean annual SSR and GWR values over grid points in Africa vary from as low as 140 mm in VIC to as high as ~3600 mm in PCR-GLOBWB; maximum mean annual values of SSR/GWR are ~1900 mm (NOAH), ~2400 mm (MOSAIC), ~960 mm (WaterGAP diffuse GWR) and ~2600 mm (WaterGAP combined GWR).
- We note further that the spatial extent and magnitude of recharge in semi-arid regions of Africa increases substantially between the two versions of WaterGAP (diffuse recharge only versus combined diffuse and focused recharge).

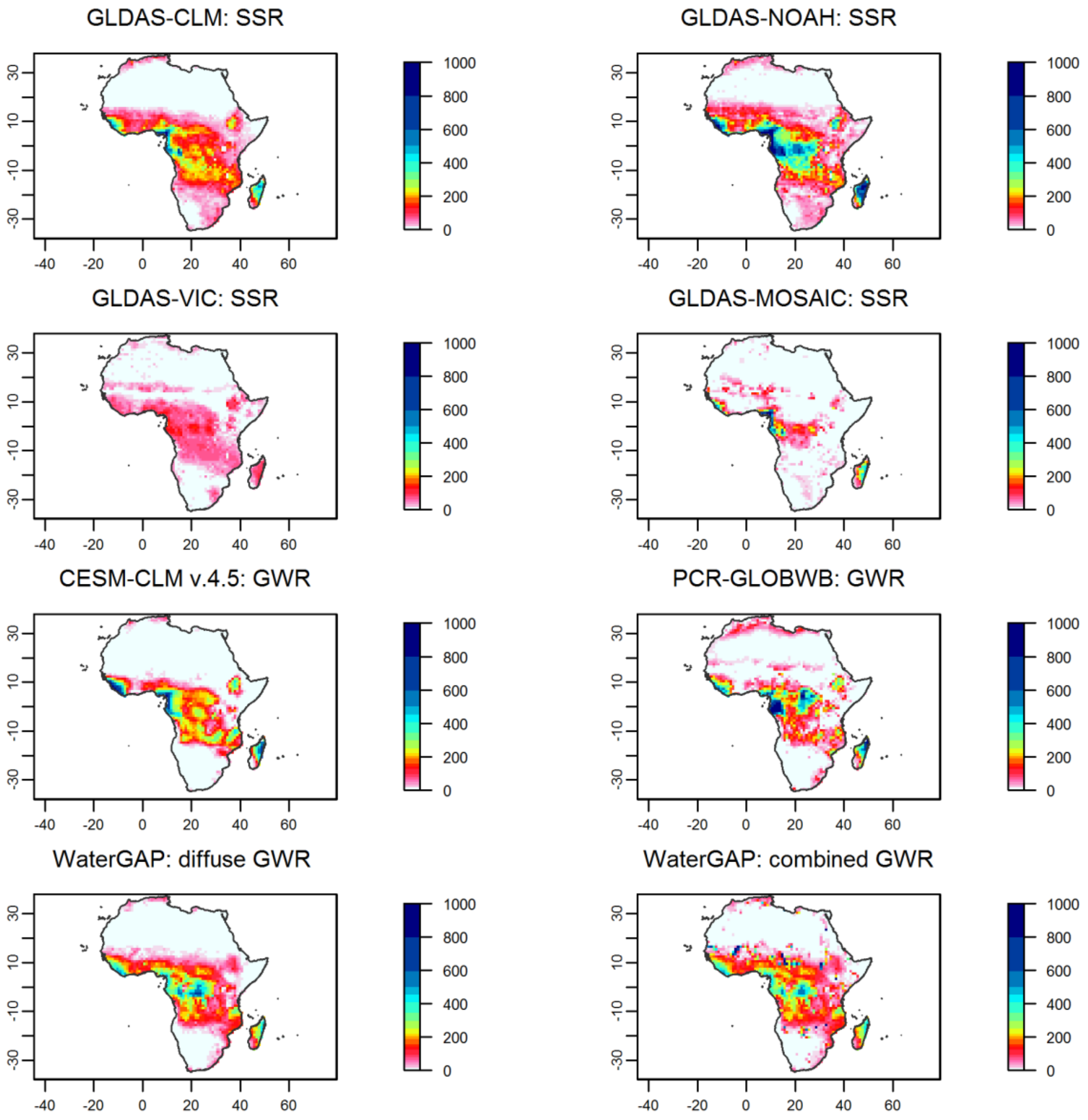


Figure 2: Mean annual (mm) subsurface runoff (SSR) simulated by GLDAS LSMs (CLM, NOAH, VIC, MOSAIC), and groundwater recharge (GWR) by CLM (4.5), PCR-GLOBWB, and WaterGAP (*diffuse* and *combined diffuse and focused recharge*) for the period of 1980 to 2014. Note: annual values of SSR and GWR > 1000 mm are reported as 1000 mm.

re: variations in simulated recharge and SSR by climate zones (defined in Figure 3)

- All 5 LSMs and 3 GHMs show a generalised increase in simulated SSR and GWR as aridity decreases from hyper-arid, arid to more humid zones but very substantial variations in the magnitude of SSR/GWR recharge as depicted by the box & whisker plots grouped by climate zones in Africa (Figure 4);
- Among the 4 GLDAS LSMs the magnitudes of aggregated SSR data within various climate zones are much smaller in VIC compared to NOAH;
- Among the 3 GHMs and CLM 4.5 the magnitudes of modelled recharge within each climate zone are comparable but both PCR-GLOBWB and CLM 4.5 produce lower estimates of GWR in semi-arid and sub-humid zones compared to the WaterGAP models; PCR-GLOBWB shows greater variability in humid and arid zones compared to WaterGAP and CLM 4.5 models; the combined (diffuse-focused) WaterGAP run simulates greater recharge in semi-arid and arid zones relative to the diffuse-only WaterGAP run.

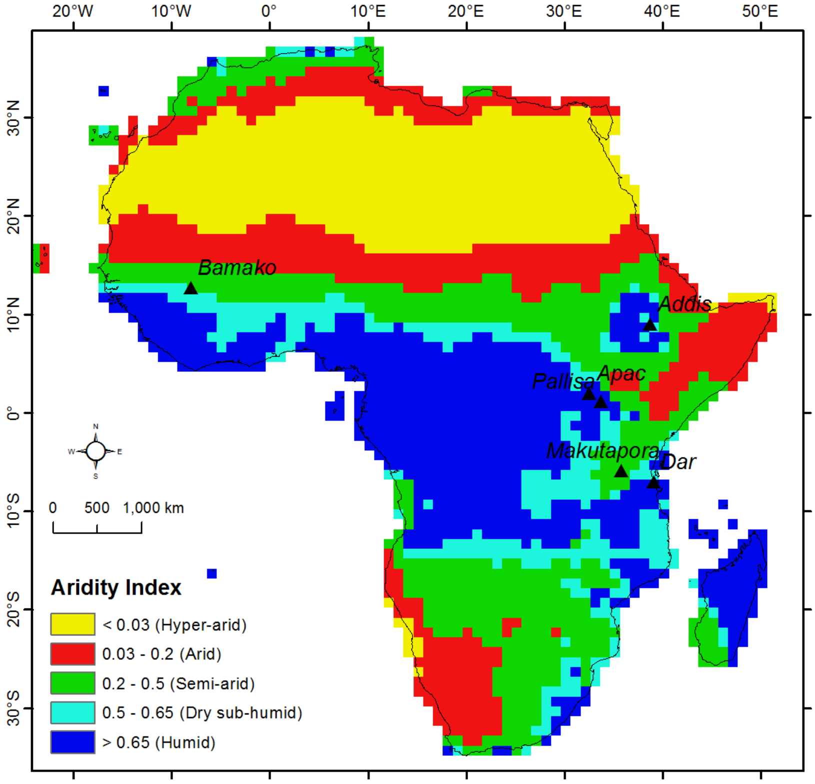


Figure 3: Climate zones in Africa defined by the CGIAR aridity index.

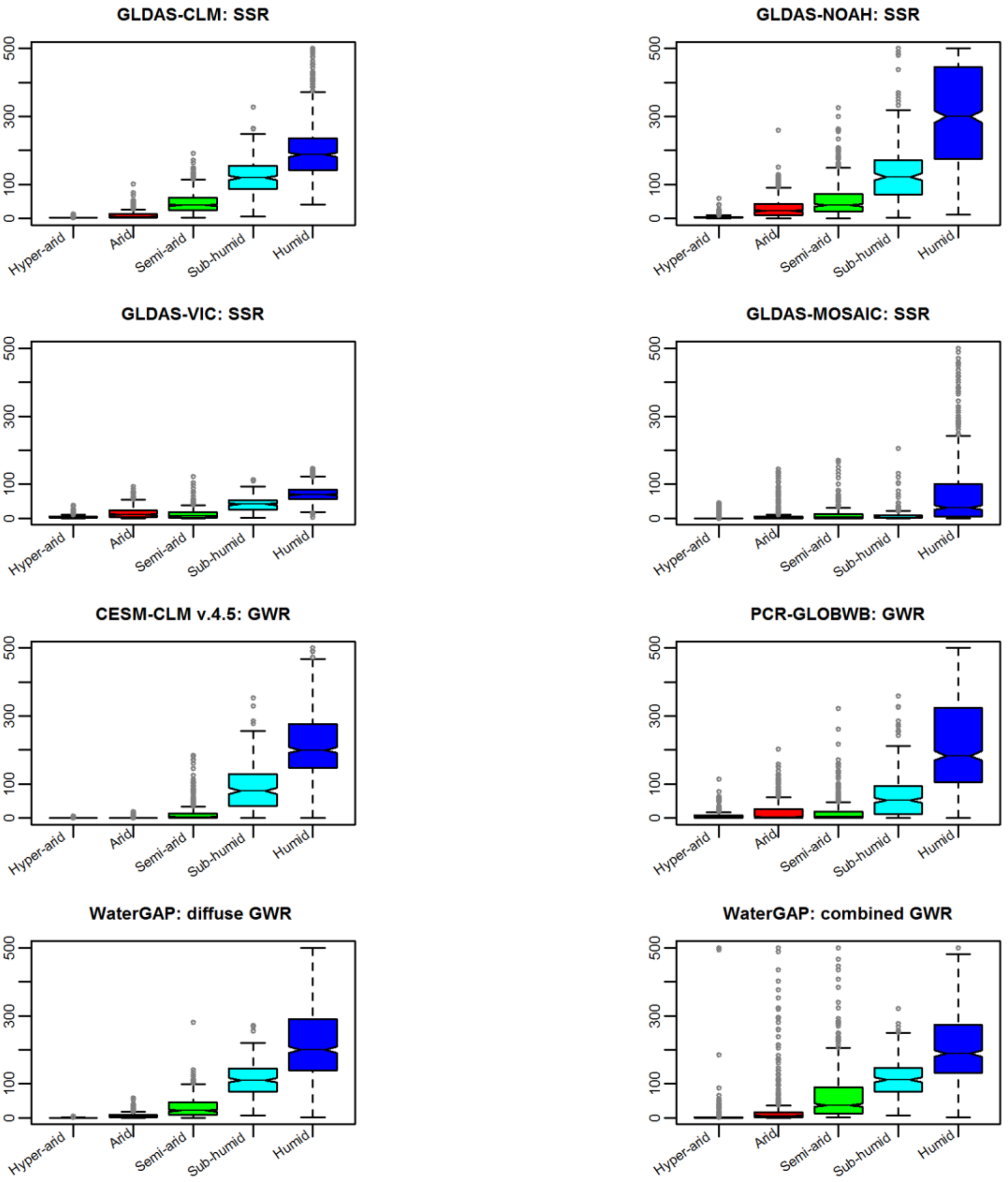


Figure 4: Simulated annual subsurface runoff (SSR) and groundwater recharge (GWR) aggregated within 5 aridity zones in Africa (CGIAR) 1980-2014.

re: variations in simulated recharge and SSR by geology (defined in Figure 5)

- All 5 LSMs and 3 GHMs show a greater median and inter-quartile (25th to 75th percentile) values of simulated SSR and GWR in the "basement complex" (predominantly metamorphic rocks in GLiM) relative to other lithologies including unconsolidated sediments; this observation is considered largely to result from greater precipitation over this geological unit that underlies much of humid tropical Africa;
- Similar to the results grouped by climate zone, the combined (diffuse-focused) WaterGAP run simulates greater recharge in unconsolidated sediments which are located predominantly in semi-arid zones relative to the diffuse-only WaterGAP run.

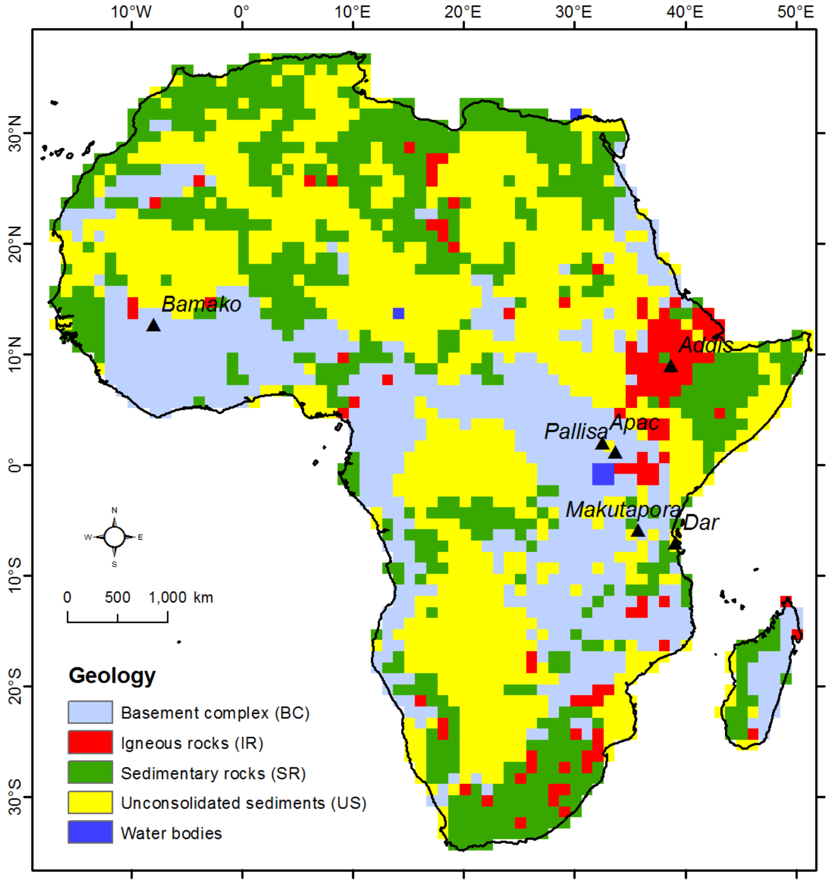


Figure 5: Geological zones in Africa based on GLiM (Global lithological map).

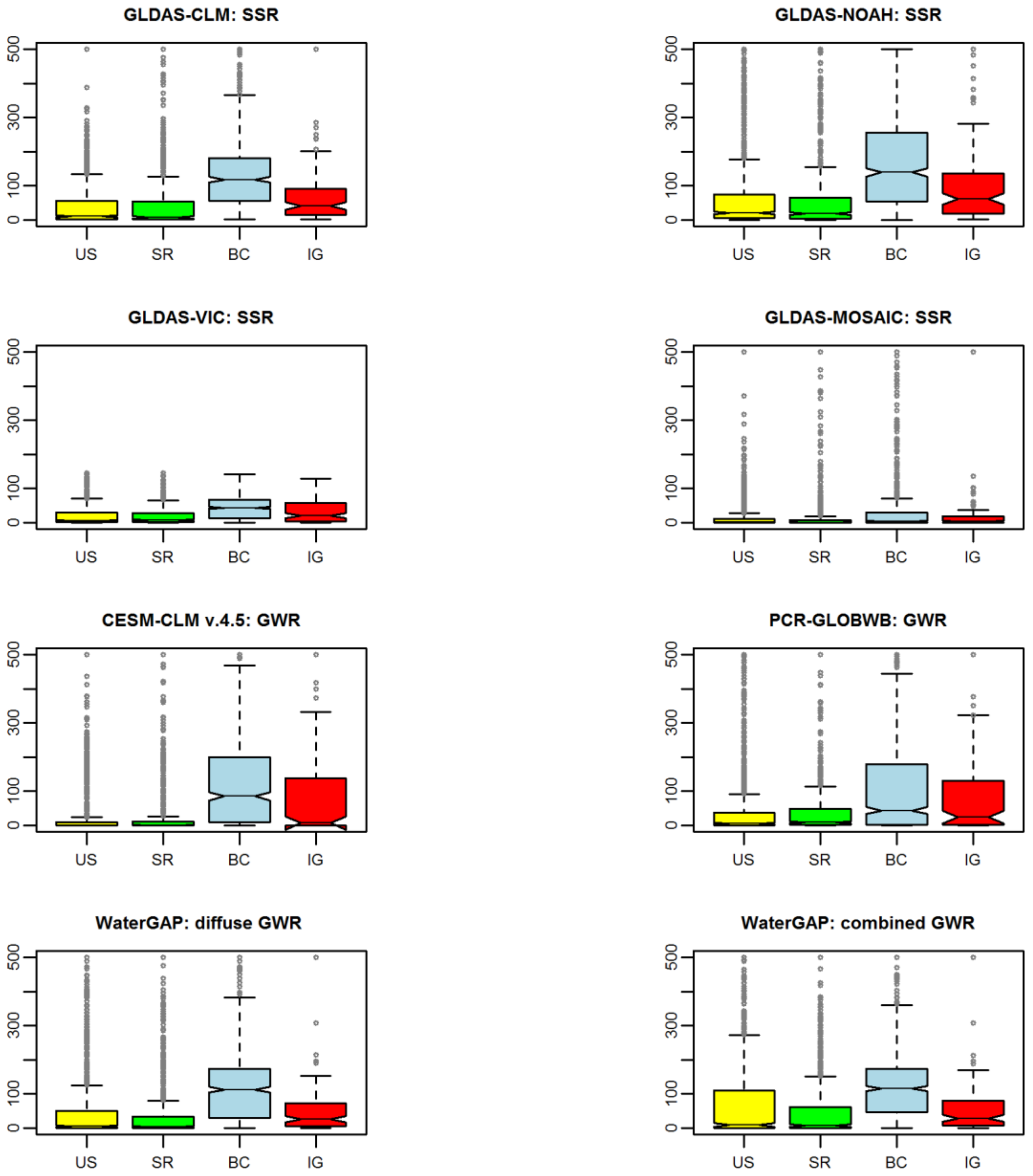


Figure 6: Simulated subsurface runoff (SSR) and groundwater recharge (GWR) aggregated within 4 geologicla classifications defined by GLiM.

re: correlations between precipitation and simulated recharge / SSR

- Strong correlations between precipitation and simulated recharge / SSR are observed in the humid and sub-humid climate zones, particularly for GLDAS-CLM and WaterGAP; lower correlations in GLDAS VIC and MOSAIC are thought to be a result of the low SSR values estimated by these LSMs.

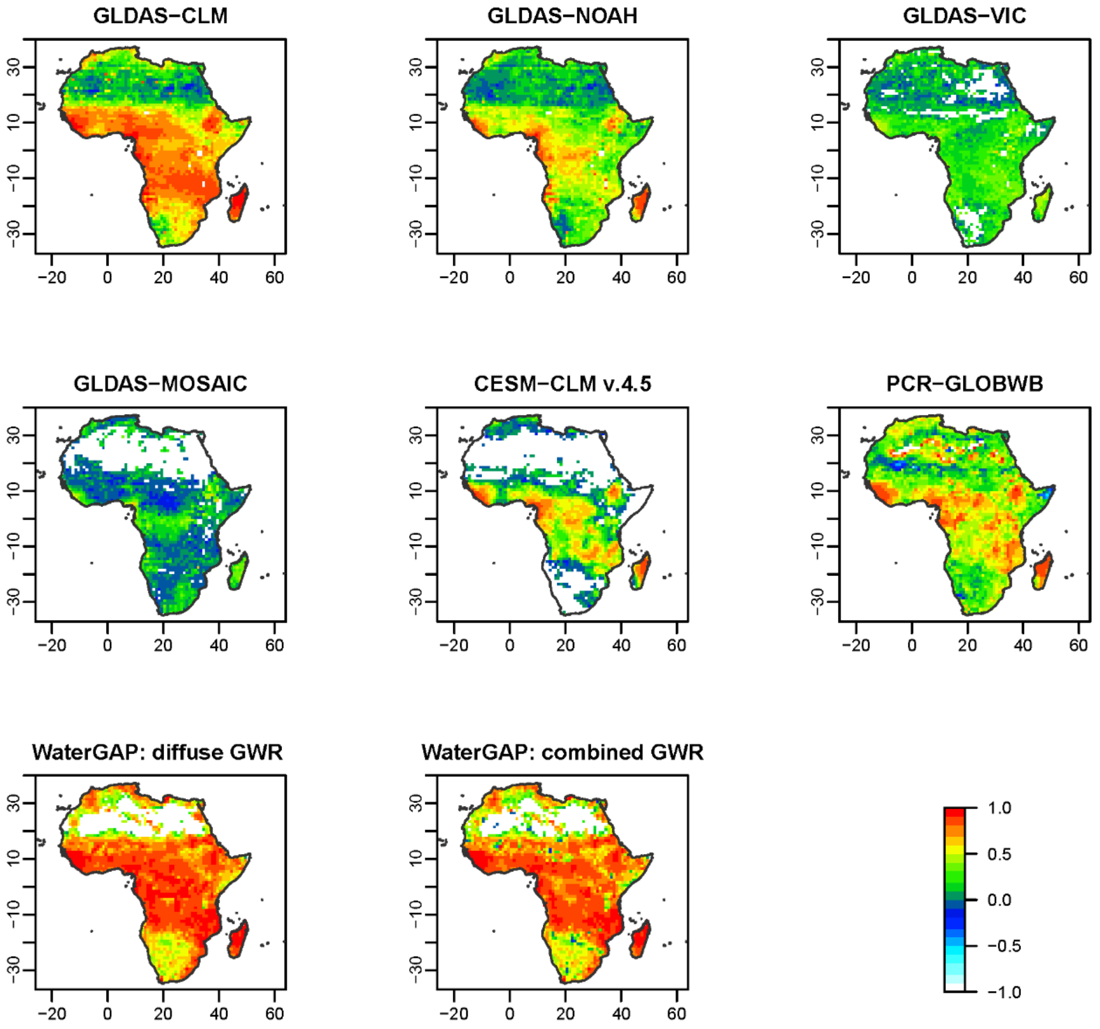
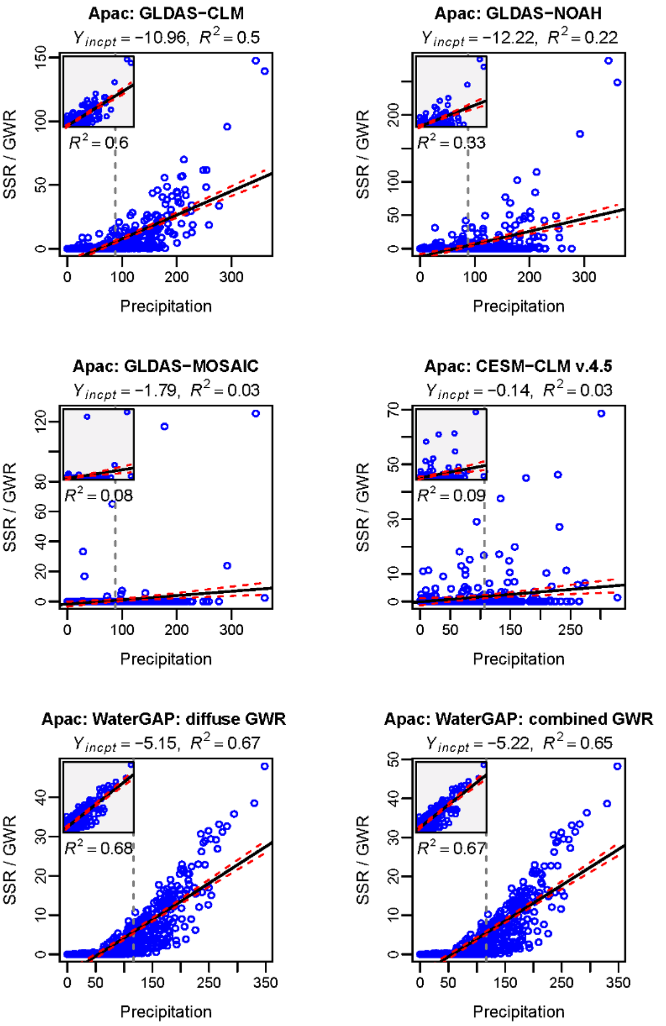


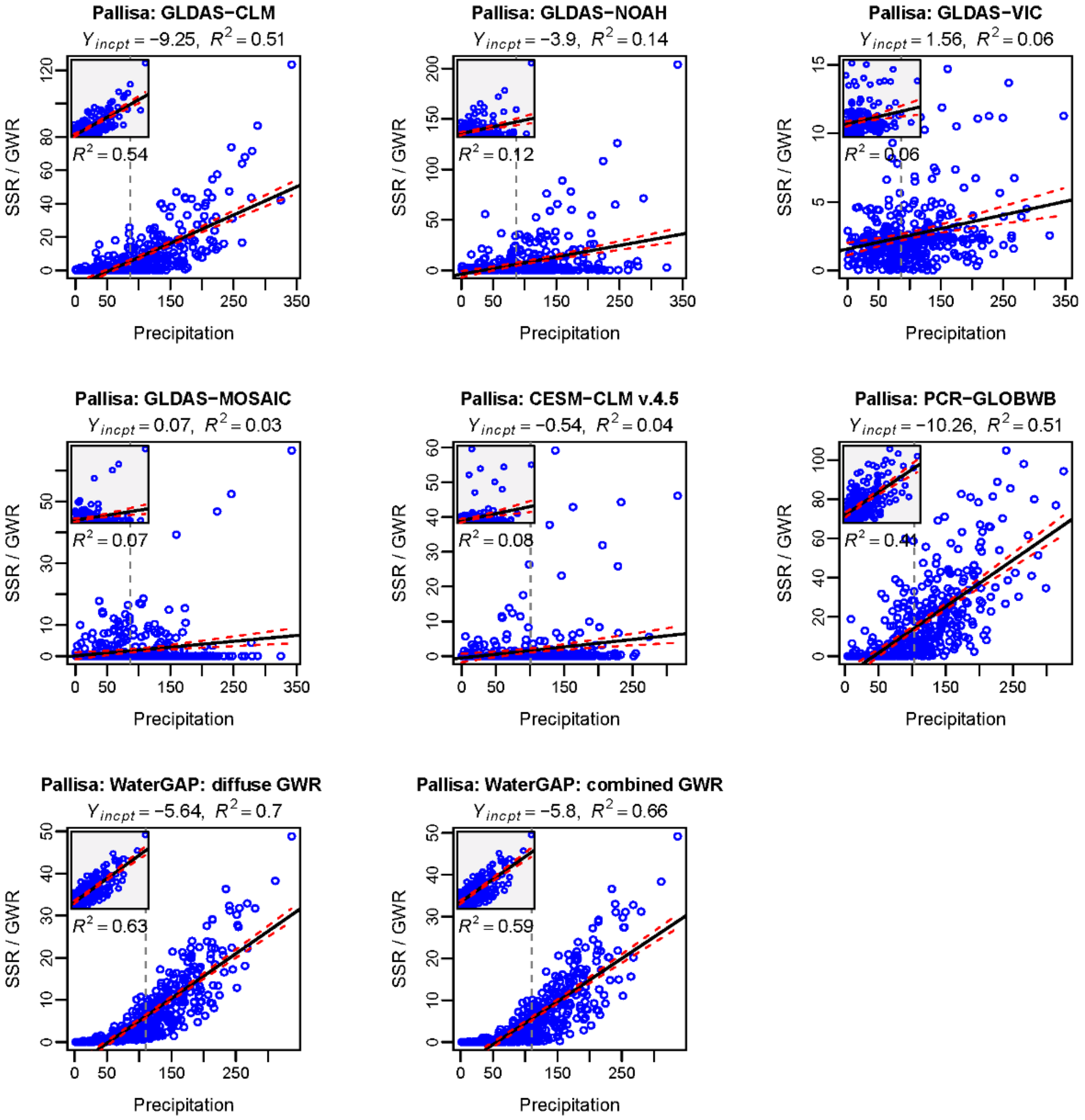
Figure 7: Pearson correlation co-efficients between simulated subsurface runoff (SSR) / groundwater recharge (GWR) and precipitation for various global-scale models in Africa from 1980 to 2014.

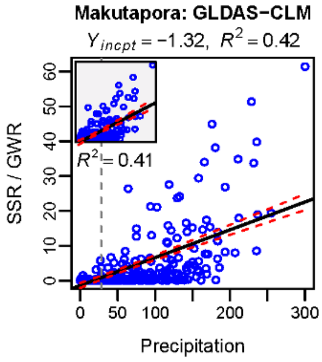
re: bivariate relationships between precipitation and simulated recharge / SSR at 6 locations

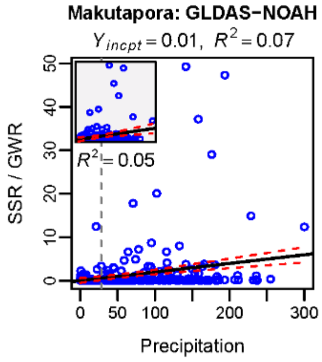
- Non-linearity is evident in the relationship between monthly simulated recharge and SSR and precipitation for both WaterGAP models and GLDAS CLM (*e.g.* Apac, Pallisa, Addis Ababa, Bamako), consistent with the analysis of observations[20,21], which is effectively linear when months of monthly rainfall less than then median (50th percentile) are excluded (inset plots);
- SSR and recharge simulated by the CESM-CLM4.5 LSM and 3 of the GLDAS LSMs (NOAH, VIC, MOSAIC) vary substantially in their estimated quantities and in their relationship to precipitation;
- Greater recharge is consistently estimated by PCR-GLOBWB than both WaterGAP GHMs and the CESM-CLM4.5 LSM with the possible exception of the semi-arid location in Tanzania (Makutapora); relationships between simulated recharge and precipitation for PCR-GLOBWB also much more variable than both WaterGAP models and GLDAS CLM – note that values of negative recharge computed by PCR-GLOBWB as soil-capillary flows, have been set to 0 for mapping purposes.

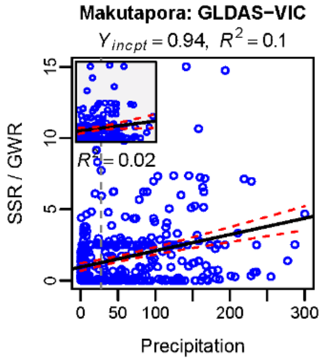
Figure 8: Scatter plots of monthly simulated subsurface runoff (SSR) / groundwater recharge (GWR) versus forcing precipitation (P) for the period of January 1980 to December 2014 for (a) Apac (Uganda), (b) Pallisa (Uganda), (c) Makutapora (Tanzania), (d) Addis Ababa (Ethiopia), (e) Dar es Salaam (Tanzania), and (f) Bamako (Mali); black solid line shows the fitted linear trend with 95% confidence levels as dashed red lines whereas the inset figure shows the scatter plot for a subset of time-series records of simulated SSR/GWR that occurs in P greater than 50th percentiles (median) as shown as a vertical dashed black line on the main scatter plot.

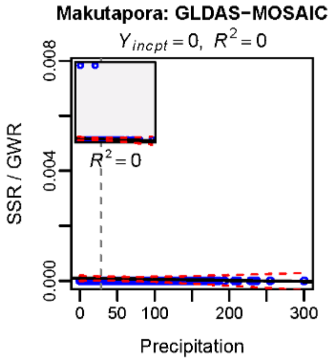


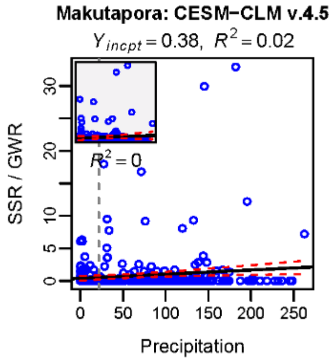

Pallisa: GLDAS−CLM
$Y_{incpt} = -9.25$, $R^2 = 0.51$
$R^2 = 0.54$
Pallisa: GLDAS−NOAH
$Y_{incpt} = -3.9$, $R^2 = 0.14$
$R^2 = 0.12$
Pallisa: GLDAS−VIC
$Y_{incpt} = 1.56$, $R^2 = 0.06$
$R^2 = 0.06$
Pallisa: GLDAS−MOSAIC
$Y_{incpt} = 0.07$, $R^2 = 0.03$
$R^2 = 0.07$
Pallisa: CESM−CLM v.4.5
$Y_{incpt} = -0.54$, $R^2 = 0.04$
$R^2 = 0.08$
Pallisa: PCR−GLOBWB
$Y_{incpt} = -10.26$, $R^2 = 0.51$
$R^2 = 0.44$
Pallisa: WaterGAP: diffuse GWR
$Y_{incpt} = -5.64$, $R^2 = 0.7$
$R^2 = 0.63$
Pallisa: WaterGAP: combined GWR
$Y_{incpt} = -5.8$, $R^2 = 0.66$
$R^2 = 0.59$
SSR / GWR
Precipitation
0
50
150
250
350

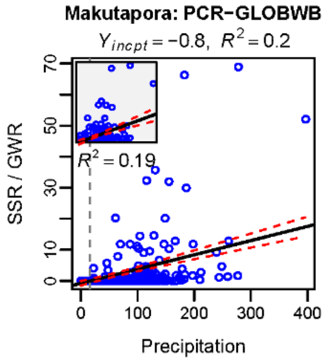

Makutapora: GLDAS−CLM
$Y_{incpt} = -1.32,\ R^2 = 0.42$
$R^2 = 0.41$
SSR / GWR
0
10
20
30
40
50
60
0
50
100
200
300
Precipitation

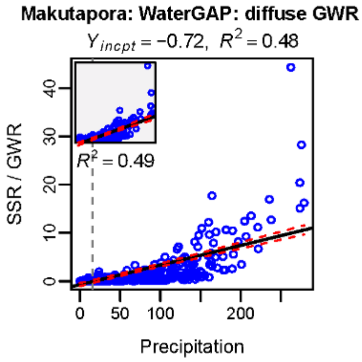

Makutapora: GLDAS−NOAH
$Y_{incpt} = 0.01,\ R^2 = 0.07$
$R^2 = 0.05$
SSR / GWR
0
10
20
30
40
50
0
50
100
200
300
Precipitation

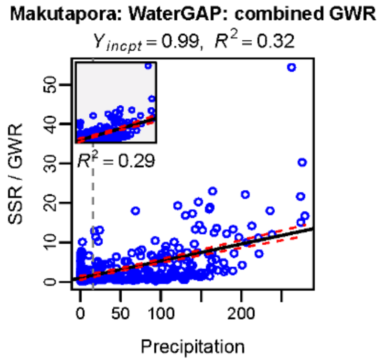

Makutapora: GLDAS−VIC
$Y_{incpt} = 0.94,\ R^2 = 0.1$
$R^2 = 0.02$
SSR / GWR
0
5
10
15
0
50
100
200
300
Precipitation

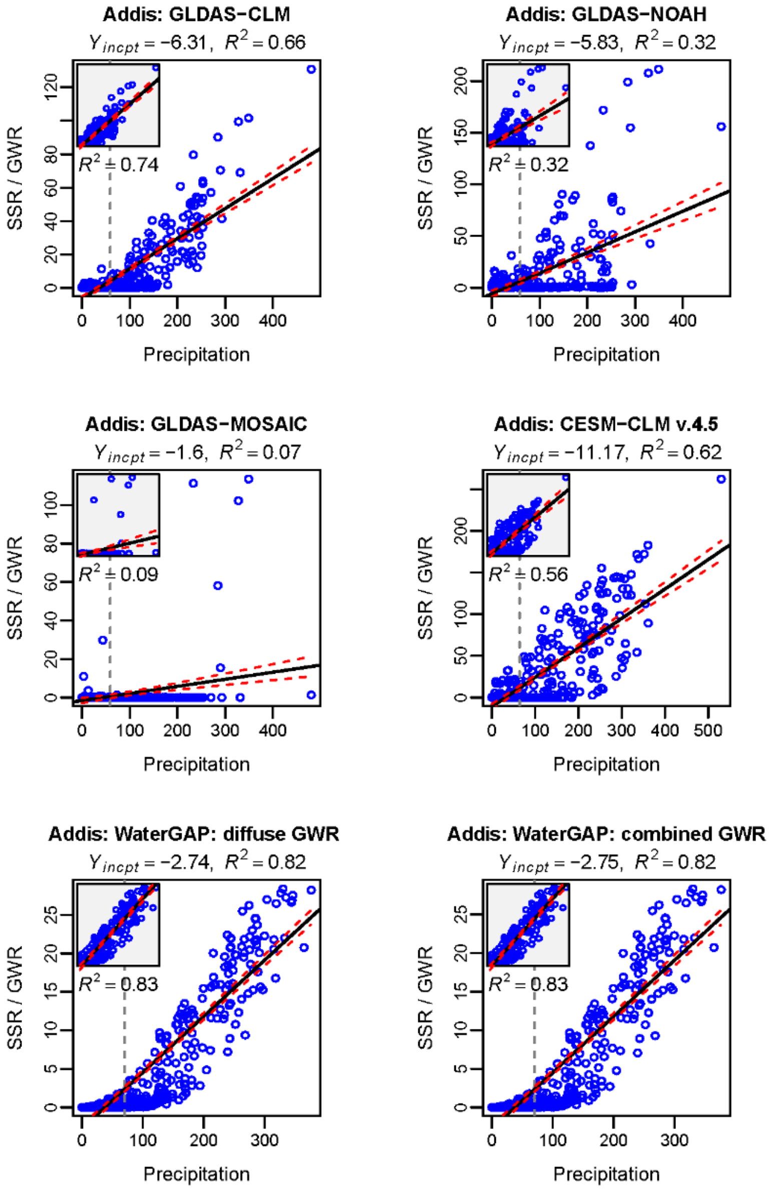

Makutapora: GLDAS−MOSAIC
$Y_{incpt} = 0,\ R^2 = 0$
$R^2 = 0$
SSR / GWR
0.000
0.004
0.008
0
50
100
200
300
Precipitation

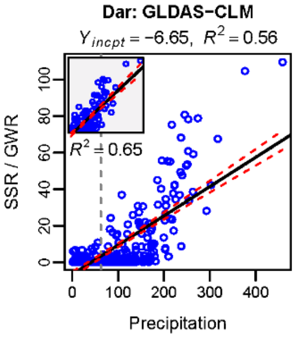

Makutapora: CESM−CLM v.4.5
$Y_{incpt} = 0.38,\ R^2 = 0.02$
$R^2 = 0$
SSR / GWR
0
5
10
20
30
0
50
100
150
200
250
Precipitation

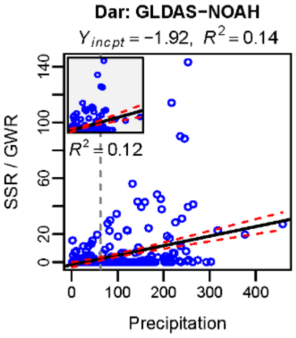

Makutapora: PCR−GLOBWB
$Y_{incpt} = -0.8,\ R^2 = 0.2$
$R^2 = 0.19$
SSR / GWR
0
10
30
50
70
0
100
200
300
400
Precipitation

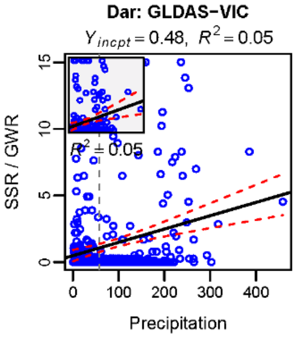

Makutapora: WaterGAP: diffuse GWR
$Y_{incpt} = -0.72,\ R^2 = 0.48$
$R^2 = 0.49$
SSR / GWR
0
10
20
30
40
0
50
100
200
Precipitation

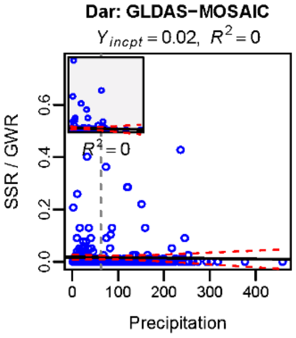

Makutapora: WaterGAP: combined GWR
$Y_{incpt} = 0.99,\ R^2 = 0.32$
$R^2 = 0.29$
SSR / GWR
0
10
20
30
40
50
0
50
100
200
Precipitation

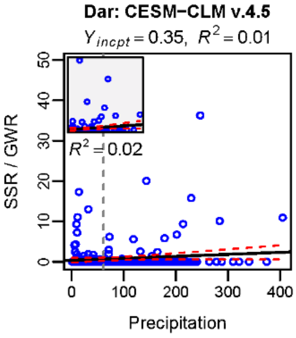

Addis: GLDAS−CLM
$Y_{incpt} = -6.31$, $R^2 = 0.66$
$R^2 = 0.74$
Addis: GLDAS−NOAH
$Y_{incpt} = -5.83$, $R^2 = 0.32$
$R^2 = 0.32$
Addis: GLDAS−VIC
$Y_{incpt} = 5.16$, $R^2 = 0.06$
$R^2 = 0.09$
Addis: GLDAS−MOSAIC
$Y_{incpt} = -1.6$, $R^2 = 0.07$
$R^2 = 0.09$
Addis: CESM−CLM v.4.5
$Y_{incpt} = -11.17$, $R^2 = 0.62$
$R^2 = 0.56$
Addis: PCR−GLOBWB
$Y_{incpt} = -5.98$, $R^2 = 0.71$
$R^2 = 0.54$
Addis: WaterGAP: diffuse GWR
$Y_{incpt} = -2.74$, $R^2 = 0.82$
$R^2 = 0.83$
Addis: WaterGAP: combined GWR
$Y_{incpt} = -2.75$, $R^2 = 0.82$
$R^2 = 0.83$
SSR / GWR
Precipitation

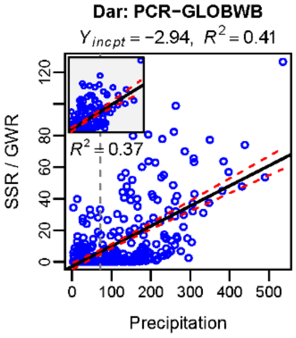

Dar: GLDAS−CLM
$Y_{incpt} = -6.65,\ R^2 = 0.56$
$R^2 = 0.65$
SSR / GWR
0
20
40
60
80
100
0
100
200
300
400
Precipitation

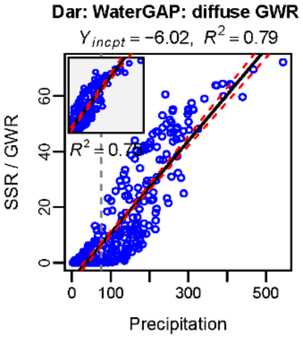

Dar: GLDAS−NOAH
$Y_{incpt} = -1.92,\ R^2 = 0.14$
$R^2 = 0.12$
SSR / GWR
0
20
60
100
140
0
100
200
300
400
Precipitation

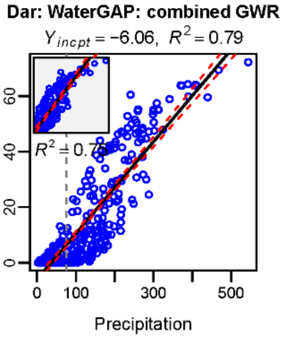

Dar: GLDAS−VIC
$Y_{incpt} = 0.48,\ R^2 = 0.05$
$R^2 = 0.05$
SSR / GWR
0
5
10
15
0
100
200
300
400
Precipitation

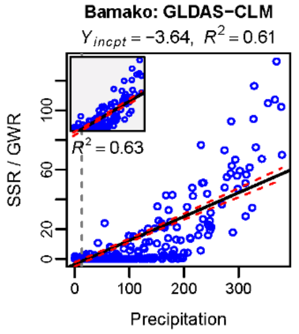

Dar: GLDAS−MOSAIC
$Y_{incpt} = 0.02,\ R^2 = 0$
$R^2 = 0$
SSR / GWR
0.0
0.2
0.4
0.6
0
100
200
300
400
Precipitation


Dar: CESM−CLM v.4.5
$Y_{incpt} = 0.35,\ R^2 = 0.01$
$R^2 = 0.02$
SSR / GWR
0
10
20
30
40
50
0
100
200
300
400
Precipitation


Dar: PCR−GLOBWB
$Y_{incpt} = -2.94,\ R^2 = 0.41$
$R^2 = 0.37$
SSR / GWR
0
20
40
60
80
120
0
100
200
300
400
500
Precipitation

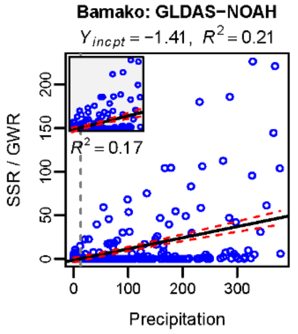

Dar: WaterGAP: diffuse GWR
$Y_{incpt} = -6.02,\ R^2 = 0.79$
$R^2 = 0.75$
SSR / GWR
0
20
40
60
0
100
300
500
Precipitation


Dar: WaterGAP: combined GWR
$Y_{incpt} = -6.06,\ R^2 = 0.79$
$R^2 = 0.75$
SSR / GWR
0
20
40
60
0
100
300
500
Precipitation



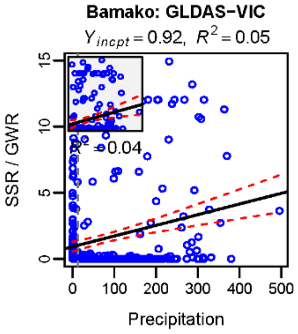
Bamako: GLDAS−CLM

$Y_{incpt} = -3.64, \; R^2 = 0.61$



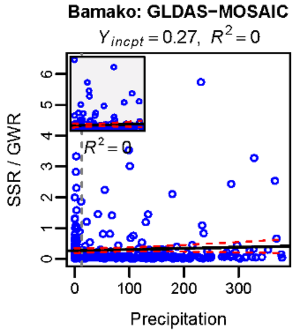
Bamako: GLDAS−NOAH

$Y_{incpt} = -1.41, \; R^2 = 0.21$



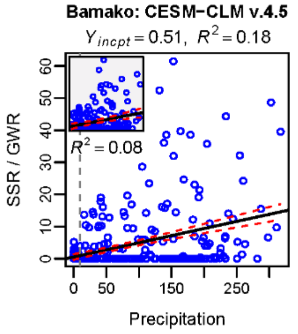
Bamako: GLDAS−VIC

$Y_{incpt} = 0.92, \; R^2 = 0.05$



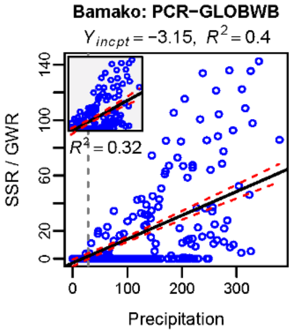
Bamako: GLDAS−MOSAIC

$Y_{incpt} = 0.27, \; R^2 = 0$



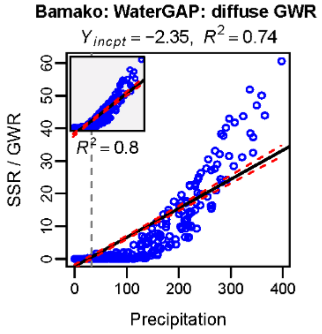
Bamako: CESM−CLM v.4.5

$Y_{incpt} = 0.51, \; R^2 = 0.18$



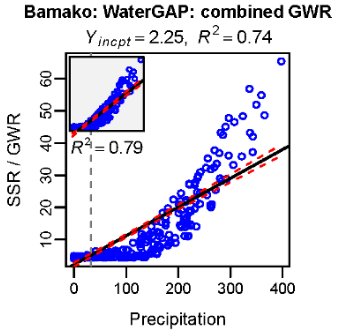
Bamako: PCR−GLOBWB

$Y_{incpt} = -3.15, \; R^2 = 0.4$



Bamako: WaterGAP: diffuse GWR

$Y_{incpt} = -2.35, \; R^2 = 0.74$



Bamako: WaterGAP: combined GWR

$Y_{incpt} = 2.25, \; R^2 = 0.74$

re: relationship between stable-isotope ratios (^{18}O:^{16}O) and the magnitude of monthly precipitation at available IAEA stations in Africa

- The "amount effect" in which heavier rainfalls become progressively depleted in their heavy (^{18}O) isotope content with rainfall amount, is observed consistently in long-term records across Africa and thereby enable the source of groundwater recharge to be related to rainfall intensity.

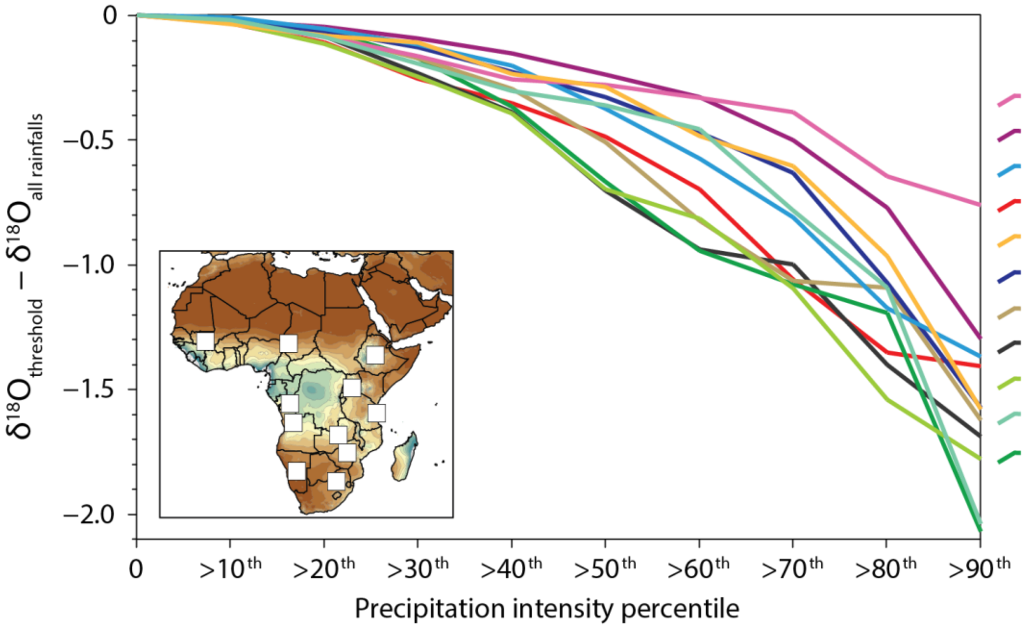


Figure 9: Scatter plot of stable-isotope (^{18}O:^{16}O) ratios, normalised with respect to the long-term, weighted mean ("all rainfalls") as a function of precipitation intensity percentile following method of Jasechko and Taylor[21]; inset map shows the locations of the 11 IAEA stations in Africa.