Climate-groundwater dynamics inferred from GRACE and the role of hydraulic memory

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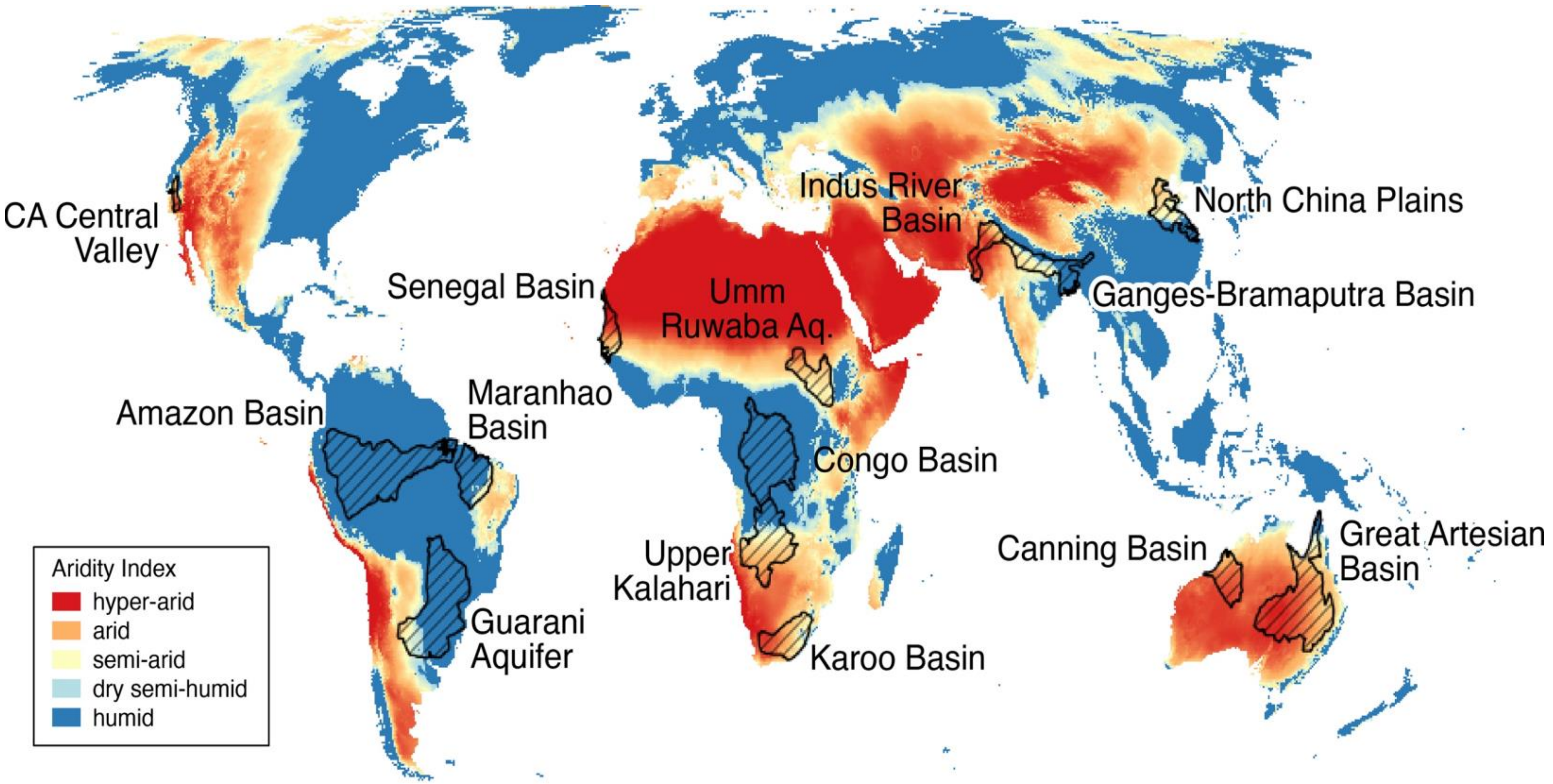
Using new compiled monthly GRACE satellite measurements (2002-2016) in the tropics and sub-tropics, we show that the imprint of precipitation history on groundwater storage - ***hydraulic memory*** - is longer in drylands than humid environments.



14 of the World's Large-scale Aquifers (WHYMAP) overlaid on CGIAR-CSI Global-Aridity dataset *(Trabucco & Zomer, 2019).*

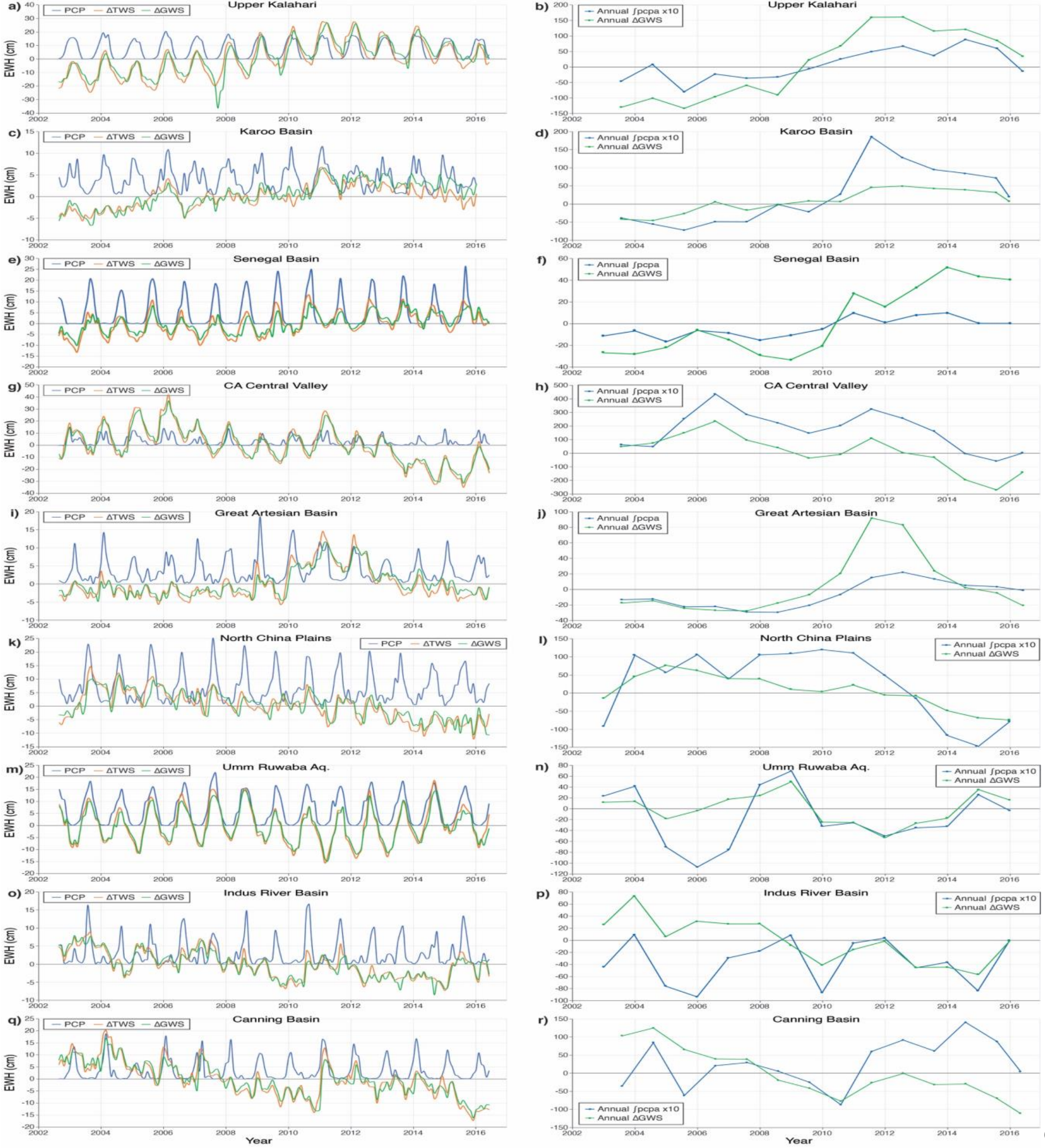
GRACE-derived changes in groundwater storage are resolved using GRACE JPL Mascons and the CLM Land Surface Model.

These GWS changes are related to precipitation time series.

Aquifer System	Monthly PCP vs ΔTWS	Monthly PCP vs ΔGWS	Monthly PCPA vs ΔGWS	Annual PCPA vs ΔGWS	Monthly ∫PCPA vs ΔGWS	Annual ∫PCPA vs ΔGWS	Aridity Class	Aridity Index	GWS Net Change over SRP
Upper Kalahari	0.64 (2)	0.47 (2)	0.13 (2)	0.22 (2)	0.67 (2)	0.88 (2)	Semi-Arid	0.42	Increasing
Karoo	0.15 (7)	0.25 (7)	0.07 (7)	0.21 (7)	0.71 (7)	0.88 (7)	Semi-Arid	0.28	Increasing
Senegal	0.67 (2)	0.55 (2)	0.15 (2)	0.14 (2)	0.61 (2)	0.87 (2)	Semi-Arid	0.20	Increasing
California Central Valley	0.53 (2)	0.46 (2)	0.26 (2)	0.56 (2)	0.60 (2)	0.84 (2)	Semi-Arid	0.22	Decreasing
Great Artesian	0.45 (2)	0.33 (2)	0.34 (2)	0.67 (2)	0.61 (2)	0.80 (2)	Arid	0.18	Stable
North China Plains	0.34 (2)	0.22 (2)	0.18 (2)	0.26 (2)	0.65 (2)	0.80 (2)	Dry Sub-Humid	0.57	Decreasing
Umm Ruwaba	0.87 (2)	0.83 (2)	0.12 (2)	0.55 (2)	0.20 (2)	0.64 (2)	Semi-Arid	0.33	Stable
Congo	0.67 (2)	0.67 (2)	0.11 (3)	0.43 (3)	0.27 (3)	0.62 (3)	Humid	1.22	Stable
Maranhao	0.82 (2)	0.75 (2)	0.30 (2)	0.74 (2)	0.11 (2)	0.40 (2)	Humid	0.91	Decreasing
Indus River	0.30 (1)	0.11 (1)	0.19 (3)	0.37 (3)	0.15 (3)	0.34 (3)	Arid	0.16	Decreasing
Amazon	0.88 (2)	0.82 (2)	0.08 (2)	-0.12 (2)	0.13 (2)	0.33 (2)	Humid	1.99	Stable
Guarani	0.50 (3)	0.48 (3)	0.42 (3)	0.78 (3)	0.01 (3)	0.26 (3)	Humid	0.90	Increasing
Ganges-Brahmaputra	0.75 (2)	0.69 (2)	0.06 (2)	0.03 (2)	0.03 (2)	0.01 (2)	Humid	0.86	Decreasing
Canning	0.35 (2)	0.19 (2)	0.15 (3)	0.26 (3)	-0.15 (3)	-0.01 (3)	Arid	0.13	Decreasing
Indus River post ‘08	0.42 (1)	0.15 (1)	0.21 (3)	0.73 (3)	0.34 (3)	0.89 (3)	Arid	0.16	Decreasing
Canning post ’06	0.41 (2)	0.24 (2)	0.22 (3)	0.61 (3)	-0.02 (3)	0.24 (3)	Arid	0.13	Decreasing

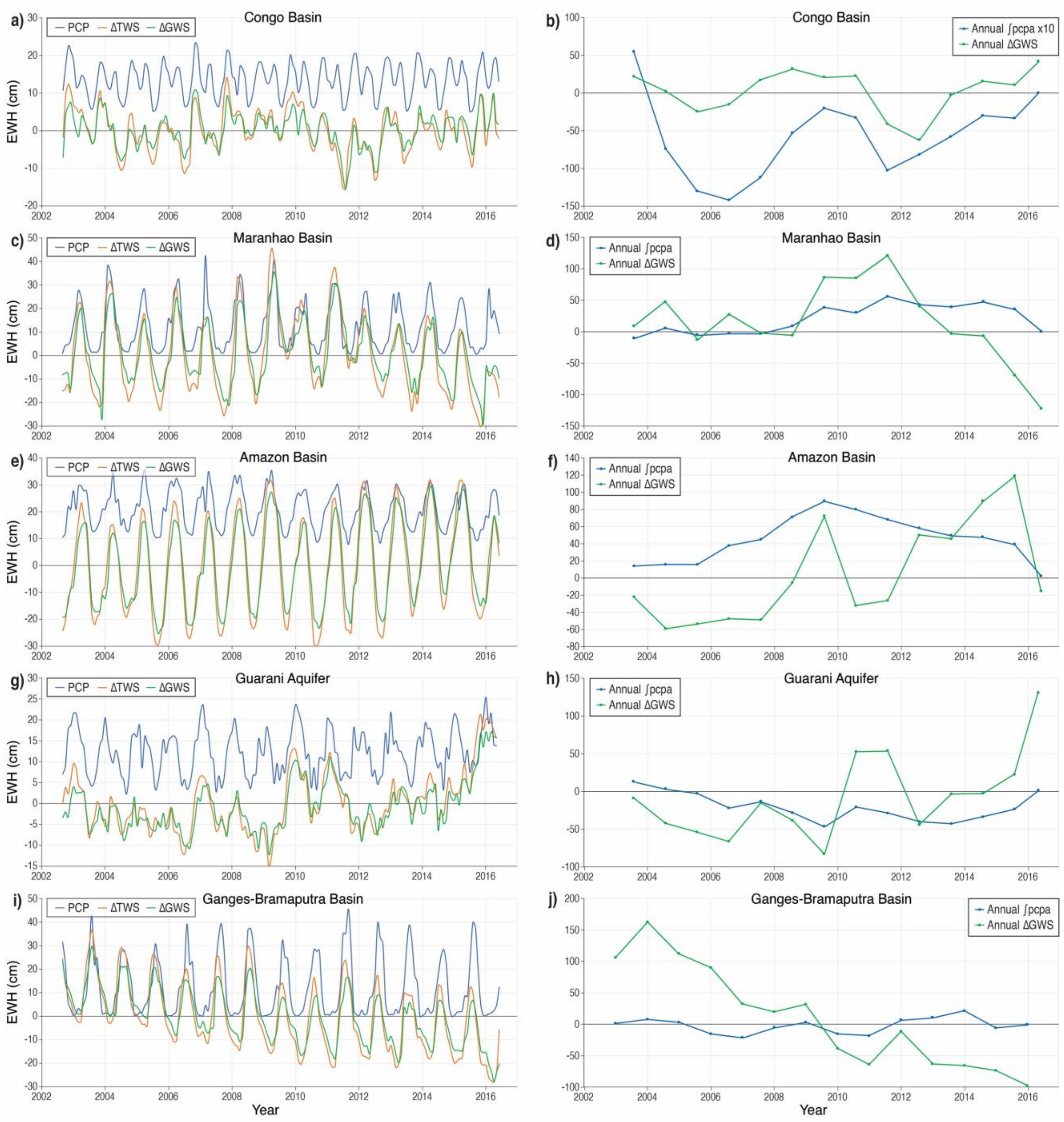
Summary Table of Results from Monthly & Annual Time Series & Aridity Datasets. Summary of all correlation results from time series datasets [Pearson Correlation Coefficient (PCC) & (lag in months)] and the aridity indices derived from the CGIAR-CSI Global-Aridity dataset (Trabucco and Zomer, 2019). ΔGWS trend over Study Reference Period (SRP) also shown. Aquifers are ranked in order of Pearson Correlation Coefficient for Annual ∫PCPA vs ΔGWS. Truncated time series results shown for 2 systems.

Aquifers in **dryland environments** exhibit *long-term hydraulic memory* through strong correlations between groundwater storage changes and **annual** precipitation **anomalies integrated over the time series**.



Monthly ΔTWS & ΔGWS vs PCP and Annual ΔGWS vs ∫PCPA Time Series. Systems are ordered by decreasing PCC for annual ΔGWS vs ∫PCPA. All time series are plotted to the aquifer system lag as set out in previous Table, where ΔTWS (ΔGWS) lags PCP (PCPA) by the specified number of months. Y-axis units are Equivalent Water Height (EWH) in cm. Note the variation in the y-axis scales. 7 of the annual ∫PCPA data series have been scaled x10 for clarity, where indicated.

Aquifers in **humid environments** show *short-term memory* through strong correlations between groundwater storage changes and **monthly** precipitation.



Monthly ΔTWS & ΔGWS vs PCP and Annual ΔGWS vs ∫PCPA Time Series. Systems are ordered by decreasing PCC for annual ΔGWS vs ∫PCPA. All time series are plotted to the aquifer system lag as set out in previous Table, where ΔTWS lags PCP by the specified number of months. Y-axis units are Equivalent Water Height (EWH) in cm. Note the variation in the y-axis scales. Congo Basin annual ∫PCPA data series has been scaled x10 for clarity.

The classification of ***hydraulic memory*** is consistent with estimates of **Groundwater Response Times** estimated from the hydrogeological properties of each aquifer system - **long (short) hydraulic memory associated with slow (rapid) response times**.

Aquifer System	Aridity Classification	Aridity Index	Annual ∫PCPA vs ΔGWS [PCC] (lag in months)	GRT: log (GRT) (GRT in yrs)
Indus River post '08	Arid	0.16	0.89 (3)	3.96
Upper Kalahari	Semi-Arid	0.42	0.88 (2)	2.95
Karoo	Semi-Arid	0.28	0.88 (7)	5.74
Senegal	Semi-Arid	0.20	0.87 (2)	5.70
California Central Valley	Semi-Arid	0.22	0.84 (2)	3.01
Great Artesian	Arid	0.18	0.80 (2)	6.33
North China Plains	Dry Sub-Humid	0.57	0.80 (2)	2.74
Umm Ruwaba	Semi-Arid	0.33	0.64 (2)	4.42
Congo	Humid	1.22	0.62 (3)	2.12
Maranhao	Humid	0.91	0.40 (2)	2.55
Indus River	Arid	0.16	0.34 (3)	3.96
Amazon	Humid	1.99	0.33 (2)	2.03
Guarani	Humid	0.90	0.26 (3)	2.20
Ganges-Brahmaputra	Humid	0.86	0.01 (2)	2.10
Canning	Arid	0.13	-0.01 (3)	6.46

Relationship between Aridity Index, Climate and Regional-Scale Hydrogeology: Data linking climate and regional-scale hydrogeology to GW dynamics. Original GRT dataset from: (Cuthbert et al., 2019) https://www.nature.com/articles/s41558-018-0386-4

Large-scale aquifers in **drylands** are shown to be **less sensitive to seasonal climate variability but vulnerable to long-term trends from which they will be slow to recover**.

Large-scale aquifers in **humid environments** exhibit **greater sensitivity to seasonal climate disturbances** such as ENSO-related drought **but are expected to be relatively quick to recover**.

Exceptions to this general pattern are traceable to human interventions through groundwater abstraction.

Read the manuscript at https://www.earth-syst-dynam-discuss.net/esd-2019-83/