Observed controls on resilience of groundwater to climate variability in Africa

Cuthbert, Mark O.* (Department of Geography, University College London, UK; School of Geography, Earth and Ocean Sciences, Cardiff University, UK; Water Research Institute, Cardiff University, UK; Connected Waters Initiative Research Centre, UNSW Australia)

Taylor, Richard (Department of Geography, University College London, UK)

Favreau, Guillaume (Institut Recherche pour le Développement (IRD), Niger)

Todd, Martin (Department of Geography, University of Sussex, UK)

Villholth, Karen (International Water Management Institute (IWMI), South Africa)

MacDonald, Alan (British Geological Survey, Lyell Centre, Edinburgh EH14 4AP, UK)

Shamsudduha, Mohammad (Department of Geography & IRDR, University College London, UK)

Scanlon, Bridget R. (Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, USA)

Kotchoni, D.O. Valerie (Université d'Abomey Calavi; INE ; ICMPA, Benin)

Vouillamoz, Jean-Michel (IRD, University Grenoble Alpes, CNRS, Grenoble INP, IGE, France)

Lawson, Fabrice M.A. (Université d'Abomey Calavi; INE; ICMPA, Benin)

Adjomayi, Philippe Armand (DG-Eau, Benin)

Kashaigili, Japhet (Sokoine University of Agriculture, Tanzania)

Seddon, David (Department of Geography, UCL, UK)

Sorensen, James (British Geological Survey, Maclean Building, Wallingford OX10 8BB, UK)

Ebrahim, Girma Yimer (International Water Management Institute (IWMI, South Africa)

Owor, Michael (Department of Geology and Petroleum Studies, Makerere University, Uganda)

Nyenje, Philip (Department of Civil and Environmental Engineering, Makerere University, Uganda)

Nazoumou, Yahaya (Université Abdou Moumouni, Niger)

Goni, Ibrahim (Department of Geology, University of Maiduguri, Nigeria)

Ousman, Boukari (Université Abdou Moumouni de Niamey, Niger)

Sibanda, Tenant (Cemex, West Midlands, UK)

Ascott, Matt (British Geological Survey, Maclean Building, Wallingford OX10 8BB, UK)

Macdonald, David (British Geological Survey, Maclean Building, Wallingford OX10 8BB, UK)

Agyekum, William (Water Research Institute, Ghana)

Koussoubé, Youssouf (Université Ouaga I, Ouagadougou, Burkina Faso)

Wanke, Heike (University of Namibia, Namibia; University of the West of England, UK)
Kim, Hyungjun (The University of Tokyo, Japan)
Wada, Yoshihide (International Institute for Applied Systems Analysis (IIASA), Austria)
Lo, Min-Hui (National Taiwan University, Taiwan)
Oki, Taikan (The University of Tokyo, Japan)
Kukuric, Neno (International Groundwater Resources Assessment Centre (IGRAC), The Netherlands)

*corresponding author: cuthbertm2@cardiff.ac.uk

Summary Paragraph

Groundwater in Africa supports livelihoods and poverty alleviation[1,2], maintains vital ecosystems, and strongly influences terrestrial water and energy budgets[3]. However, hydrologic processes governing groundwater recharge sustaining this resource, and their sensitivity to climatic variability, are poorly constrained[4,5]. Here we show, through analysis of multi-decadal groundwater hydrographs across sub-Saharan Africa, how aridity controls the predominant recharge processes whereas local hydrogeology influences the type and sensitivity of precipitation-recharge relationships. Some humid locations show approximately linear precipitation-recharge relationships with small rainfall intensity exceedance thresholds governing recharge; others show surprisingly small variation in recharge across a wide range of annual precipitation. As aridity increases, precipitation thresholds governing initiation of recharge increase, recharge becomes more episodic, and focussed recharge via losses from ephemeral overland flows becomes increasingly dominant. Extreme annual recharge is commonly associated with intense rainfall and flooding events, themselves often driven by large-scale climate controls. Intense precipitation, even during lower precipitation years, produces substantial recharge in some dry subtropical locations, challenging the 'high certainty' consensus that drying climatic trends will decrease water resources in such regions[4]. The likely resilience of groundwater in many areas revealed by improved understanding of precipitation-recharge

relationships is critical for informing reliable climate change impact projections and adaptation strategies.

Main Text (1983 plus 347 in figures)

Groundwater is a fundamental component of the global hydro-climatic system[3,5] and plays a central role in sustaining water supplies and livelihoods in sub-Saharan Africa due to its widespread availability[6], generally high quality, and intrinsic ability to buffer[7] the impacts of episodic drought and pronounced climate variability that characterizes this region[1]. Groundwater in sub-Saharan Africa is poised to enable increased freshwater withdrawals as demand rises[8] and climate change increases variability in surface water resources. It is therefore critical to understand the renewability of groundwater under current and future climate. Groundwater levels and fluxes are governed by a dynamic interplay between recharge (replenishment of groundwater) and discharge (loss of groundwater to streams, lakes, oceans or atmosphere) with a variety of controls and feedbacks from climate, soils, geology, landcover and human abstraction[9]. It is notoriously difficult[10] to determine variations in recharge magnitudes over time and space and their relationship to climate as direct, long-term observations of groundwater levels to inform such understanding in this region are sparse[11]. Regional water security assessments have therefore relied heavily on large-scale hydrological models to derive estimates of potential groundwater resources across the continent[8] but these remain unvalidated by groundwater observations[5,12]. A robust, data-driven, understanding of groundwater recharge, and critically its dependence on climate, is fundamentally required to inform water resource decision-making. Improved understanding of groundwater-climate sensitivity is also integral to understanding important hydro-climate-ecological-human interactions across the region, both in the present day[13] and the deeper past[14].

We address this challenge here by exploring precipitation-recharge (P-R) relationships across a diverse range of climatic and geological contexts in sub-Saharan Africa, using a unique archive of multi-decadal, groundwater level hydrographs (time series). By applying a consistent methodology across the archive we are able to characterize the climate-groundwater relations observed into indicative types which each lead to implications for understanding climate change impacts on groundwater systems and sustainable water management.

We contend that long term (i.e. decadal or longer) groundwater level hydrographs, with little or known interference from human activities, offer the most direct way of assessing variations in groundwater storage and, via inversion using a water table fluctuation (WTF) technique (see Methods), assessing temporal sensitivity of groundwater recharge to climate variability. We have, therefore, collated new unpublished records and updated previously published records to evaluate recharge and relationships with climate using a WTF methodology. The 14 multi-decadal hydrographs and accompanying precipitation records collated from nine countries in Sub-Saharan Africa cover a wide range of climate zones from hyper-arid to humid, including both the unimodal precipitation regimes (local summer wet season) of the northern and southern hemisphere subtropics and bimodal Equatorial regime, as well as a diverse range of geological and landscape settings (Figure 1, Table S1).

Most groundwater hydrographs show seasonal groundwater-level rises of varying magnitude that indicate recharge in excess of net groundwater drainage at some point during most years on record. The exceptions are Tanzania, Namibia and South Africa (Modderfontein) where multi-year continuous groundwater-level declines are observed, punctuated by episodic recharge events (Figure 1). Long term rising trends observed in the Niger hydrographs reflect increases in recharge rates since clearance of native vegetation in the 1960s[15] which have not yet equilibrated with rates of net groundwater drainage due to long groundwater response times[9] in the area. The absence of long term trends in other areas indicates a relatively stable balance between long term (i.e. multi-decadal) rates of groundwater recharge and discharge.

Groundwater recharge is often described on a continuum between 'focussed' (or 'indirect') recharge taking place via leakage of ephemeral streams or ponds, to 'diffuse' (or 'direct') recharge occurring in a more evenly distributed manner via the direct infiltration of precipitation at the land surface[16,17]. The predominance of focussed recharge is thought to increase with aridity[18] although there is no established threshold for when this occurs and diffuse recharge can also be significant in some semi-arid areas[19]. As part of conceptual models derived for each site, we developed a process-based understanding of recharge, resolving specifically whether diffuse or focussed recharge is dominant. This was assessed for each location based on additional reports, data, local knowledge and analysis of the form of the groundwater hydrographs themselves (see Methods, Table S3). We found that the transition from focussed-dominated to diffuse-dominated recharge occurs around the boundary between semi-arid and sub-humid conditions (Aridity Index, $P/PEt \gtrsim 0.5$, Table S1).

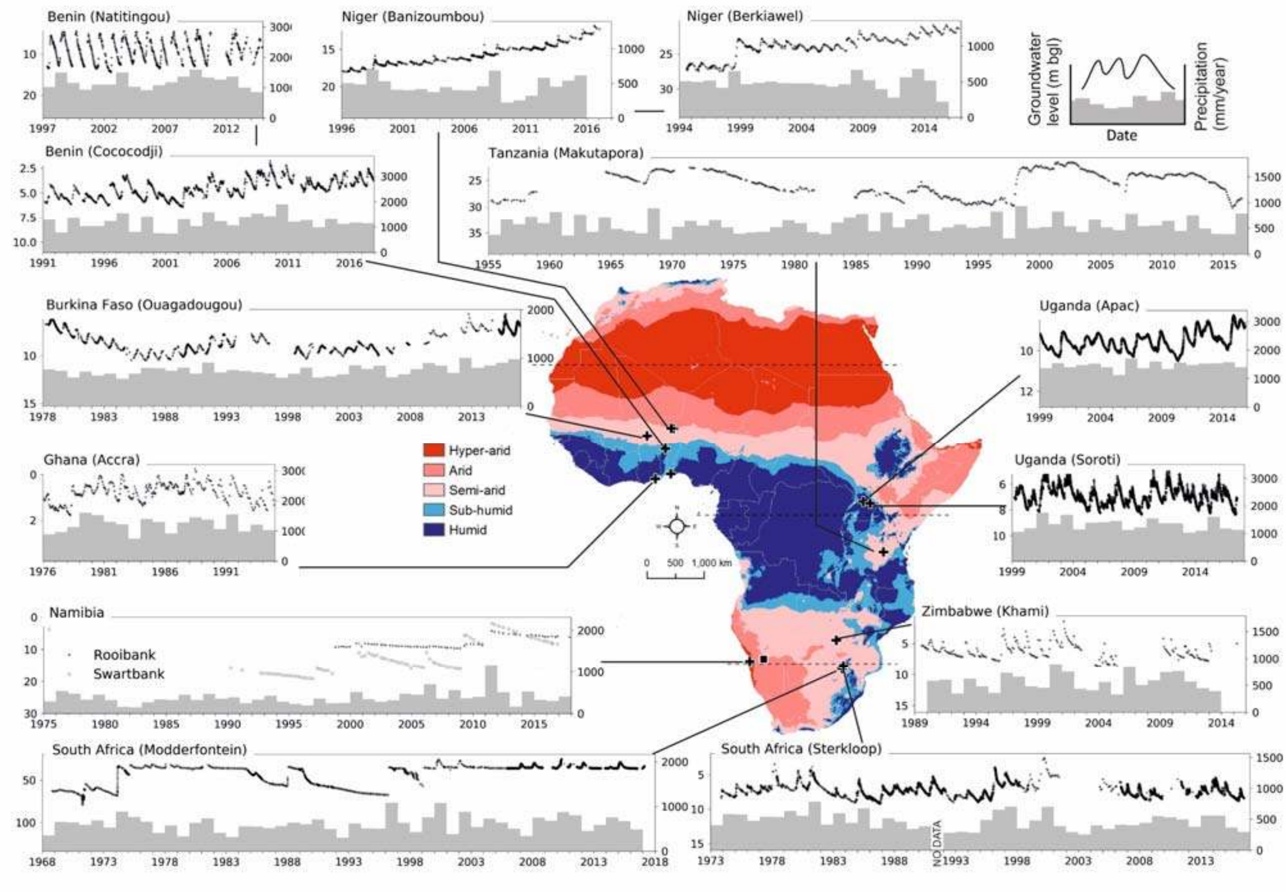

Figure 1. Collated multi-decadal groundwater-level and precipitation time series in sub-Saharan Africa. A wide range of hydrograph responses, e.g. relatively consistent (Natitingou, Benin) or highly variable (Cococodji, Benin) annual fluctuations, highly episodic variations (Namibia, Tanzania), inter-decadal oscillations (Ouagadougou) or long term

trends (Niger), reflect the complex interplay of climate, geology, soils and landcover represented across the monitoring locations. The analysed Namibian rain gauge is indicated by a filled black square. Aridity index classes are defined by the CGIAR-CSI Global-Aridity and Global-PET Database[20].

We have classified hydrographs according to their sensitivity of annual recharge to precipitation as reflected in the annual precipitation-recharge cross plots (herein ‘P-R plots’, Figure 2) and an analysis of how the proportion of recharge accumulates when years are ranked by annual precipitation (herein ‘rP-cR plots’, Figure 3, Figure S3). We then used a suite of idealised forward recharge modeling experiments to investigate how observed precipitation-recharge relationships relate to the magnitude of precipitation thresholds required to initiate recharge (see Methods and Figure S3). We observe three distinct types of precipitation-recharge sensitivity based on the empirical relationships derived from the data as follows (see Methods for site by site details):

(1) ***Consistent recharge rates from year to year across the range of annual precipitation*** (purple in Figures 2 to 4). This regime, exemplified by Natitingou (Benin) and Soroti (Uganda) shows little variation in annual recharge across a wide range of precipitation on P-R plots (Figure 2) and lies close to the 1:1 line in rP-cR plots (Figure 3). This type of precipitation–recharge response is found in sub-humid to humid locations and reflects the impact of local geology and soils in governing diffuse recharge processes.

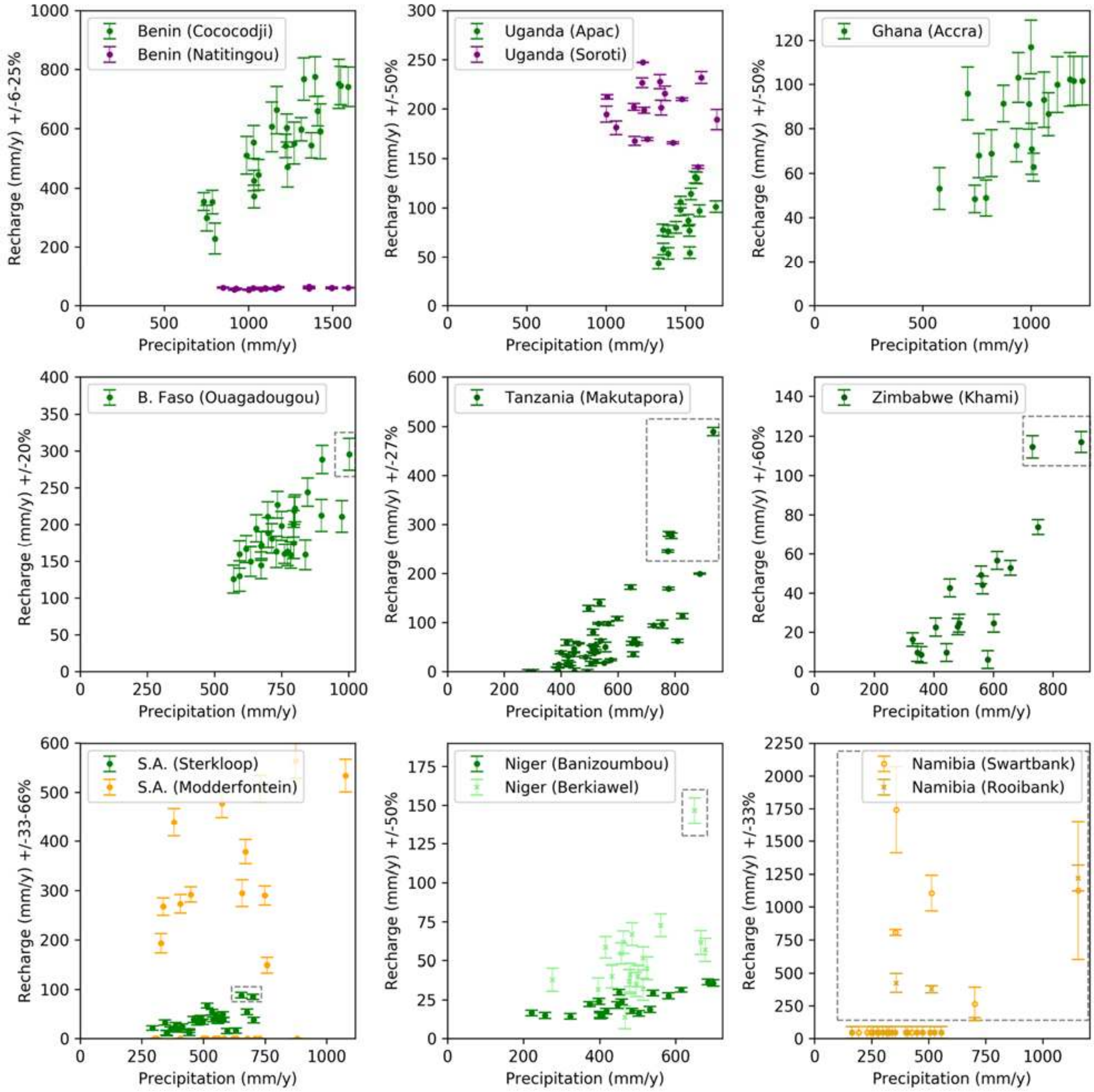

Figure 2. Observed relationships between precipitation and groundwater recharge on an annual (hydrological years) basis (P-R plots). Error bars are based solely on uncertainty in recession within the WTF method. A best estimate of specific yield was used to estimate groundwater recharge values. Percentage errors in recharge due to uncertainty in specific yield as stated on the y-axis will result in a linear rescaling of values along that axis, but not alter the form of the relationships. Dashed boxes outline Tukey outlier values of extreme recharge. Note variable axis ranges. Sites are colour coded to represent the precipitation-recharge relationship types defined in Figure 3 and also used in Figure 4.

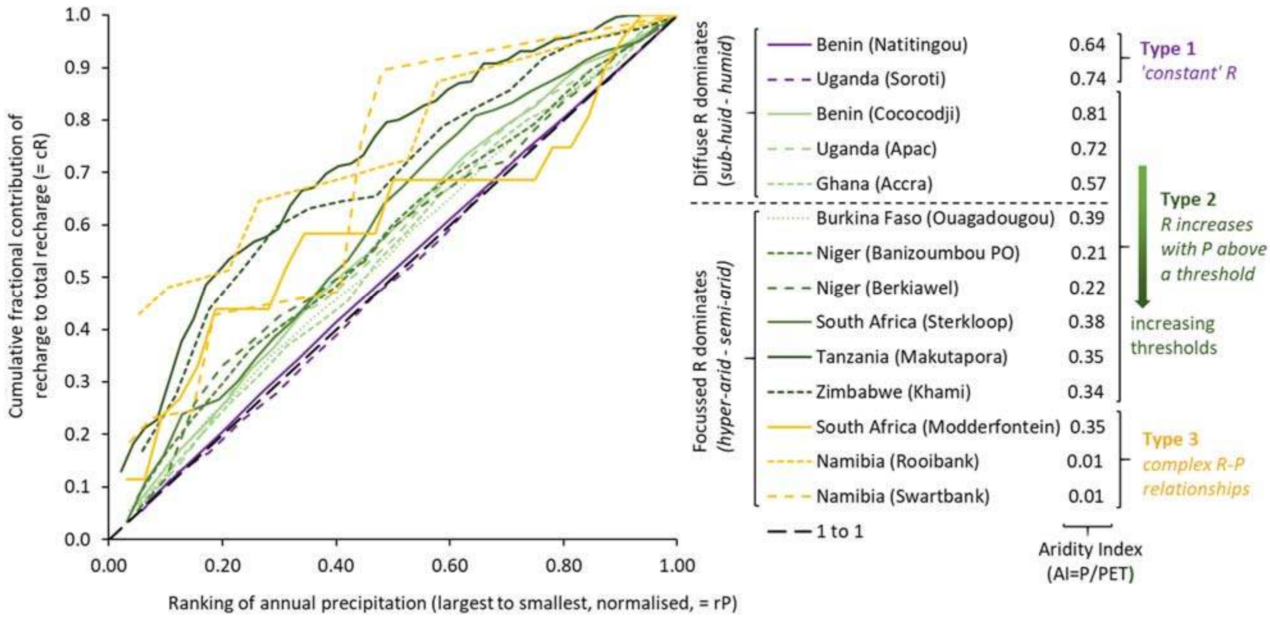

Figure 3. Cumulative contribution of annual recharge (by hydrological year) to total recharge for ranked annual precipitation (largest to smallest) (rP-cR plots). Values on both axes have been normalized by the total number of years in the record to provide fractional contributions for comparative purposes. Categorisation as either predominantly diffuse or focussed recharge is made on the basis of derived site conceptual models described in Table S3. Site colour coding is consistent with Figures 2 & 4.

(2) ***Increasing annual recharge with annual precipitation above a threshold*** (green in Figures 2 to 4). This type of regime shows positive P-R correlations (Figure 2) and shifts in the rP-cR relationship increasingly deviating to the left of the 1:1 line (Figure 3). This type is found at a majority of sites (n=9), across a wide range of aridity from humid to semi-arid conditions, and in areas dominated by both diffuse or focussed recharge. Sites with the largest apparent precipitation thresholds for recharge are located in semi-arid regions (Tanzania, Zimbabwe and South Africa-Sterkloop).

(3) ***Complex relationships between annual precipitation and recharge amount*** (orange in Figures 2 to 4). This type shows greater scatter on the P-R plots (Figure 2) and large 'steps' in rP-cR plots (Figure 3) as shown by Swartbank and Rooibank (Namibia) and Modderfontein (South Africa). A key feature of the annual P-R relationship is that some of the largest recharge events can occur during relatively low total precipitation years. This type is found in semi-arid to hyper-arid locations dominated by focussed recharge.

Key insights regarding the relationships among aridity, recharge frequency, dominant recharge process and rP-cR relationships across the records are synthesized in Figure 4. This indicates the complex reality of controls on groundwater recharge and a lack of one to one correspondence with any individual factor. For example, while there is some relationship between the rP-cR relationships and degree of aridity (Figure 3 and Figure S2d,e), variation in local conditions (principally in soils/geology and precipitation intensity) results in distinctive characteristics in each location's recharge response to precipitation (see Methods). Hence, as aridity increases, while there is a transition from seasonal to episodic recharge frequency and from diffuse to focused recharge, there is also a significant spread of rP-cR types across different climates. Whilst not informed directly by our data, we also recognize that groundwater in some currently hyper-arid regions was recharged when a wetter climatic regime prevailed in the past (referred to as having 'Paleo' recharge frequency in Fig 4).

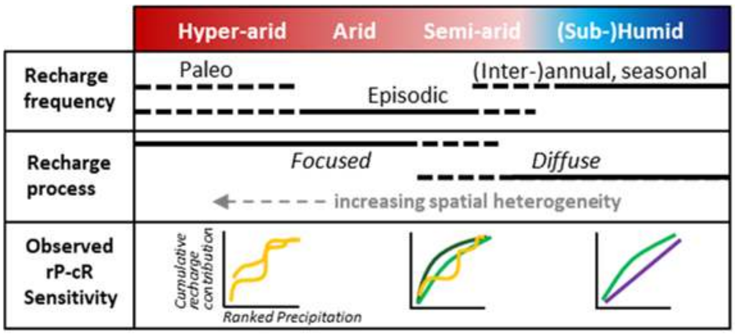

Figure 4. Idealised schematic of controls on recharge variations and processes in time and space in sub-Saharan Africa. As aridity increases, groundwater recharge tends to become increasingly heterogeneous in both space and time. Where recharge occurs via focused pathways, recharge may become 'increasingly indirect' as aridity increases meaning that the distance between the location of rainfall and the location of recharge increases. Paleo-recharge refers to recharge that occurred in some currently hyper-arid regions when a wetter climatic regime prevailed.

Where larger P thresholds for R are inferred, a smaller proportion of precipitation years yields the majority of long term recharge, and a majority of the variance in this relationship can be explained by increased aridity or coefficients of precipitation variability (Figure S2d-g), where wetter years contribute disproportionally to recharge. Further, values of extreme annual recharge identified as Tukey outliers (see Methods) were only found in more arid locations (AI<0.4, Table S1). By considering the wider regional precipitation distribution and the associated climate drivers during those years, we find that most years of substantial recharge are associated with widespread regional and seasonal scale precipitation anomalies, themselves associated with major known modes of global and/or regional climate variability (Table S2, Figure S4). As such, substantial variability in local groundwater recharge in piezometric records reflects the local impact of large-scale climate processes.

The different precipitation-recharge sensitivities observed have clear implications for understanding potential changes to groundwater levels and fluxes under climate change and therefore for developing sustainable strategies for groundwater provision for water supply or improving food security in Sub-Saharan Africa. Type 1 relationships imply that climate change impacts on precipitation may have little impact on recharge (other factors being equal). However, decreased groundwater levels due to pumping in such environments could provide more ‘room’ for recharge to occur via capture[26] of evapotranspiration (ET) or runoff. Increasing the distribution of groundwater monitoring in sub-Saharan Africa would help to identify Type 1 locations where groundwater abstraction can induce additional recharge. In these cases, and also for Type 2 sites with small P thresholds, sensitivity of recharge to changes in potential ET (PET) may also be low, because recharge is either not sensitive to P (Type 1) or factors other than P (Type 2) such as soil-moisture status. For Type 2 locations where thresholds are more highly influenced by antecedent dryness, recharge may be more sensitive to climate change impacts on both precipitation and PET, and land use change could also be important if soil structure is altered and impacts runoff and infiltration processes[27].

The episodic nature of recharge in more arid locations and the preponderance of large groundwater response times[9] in such areas together indicate the importance of long timescale planning horizons. In this context, the observed dependence of recharge on large-scale patterns of climate variability within Types 2 and 3 suggests the potential for a degree of predictability with seasonal lead times. Further it suggests that future changes in variability are likely to be of greater importance than mean precipitation. There is therefore a need to understand potential changes to such climate processes in longer multi-decadal climate change projections, currently a major challenge for climate models[28].

In contrast to rather uncertain recharge projections, modelled projections of increased flood hazards are more consistent for tropical Africa[4] and focused recharge is likely to be widespread during such events. Hence, an important climate change adaptation strategy recommendation is for more widespread consideration of schemes to harness and enhance focused recharge during flood flow, storing water in the subsurface via managed aquifer recharge[29]. Thus the increased flood risk under climate change may have a silver lining in this respect, water quality issues notwithstanding, and schemes to more effectively store flood water also have the potential to mitigate flood risk downstream. For Type 3, a key insight provided by our results in dry subtropical areas is that precipitation intensification, on the particular temporal and spatial scale determined by local conditions, may actually increase recharge, and thus available renewable water resources, despite an overall drying trend in annual precipitation totals[30].

Our data-driven results imply greater resilience to climate change than previously supposed in many locations from a groundwater perspective and thus question, for example, the model-driven IPCC consensus that *"Climate change is projected to reduce renewable surface water and groundwater* *resources significantly in most dry subtropical regions (robust evidence, high agreement)"*[4]. More observation-driven research is needed to clarify this issue, and address the balance of change between groundwater and surface water resources. Our results also pose a challenge to the reliance on standard large scale model assessments for inferring climate-groundwater dependencies until climate models can simulate with greater credibility both the large scale and local scale drivers of precipitation variability in the region, and hydrological models include the necessary recharge processes and the influence of geological variability. The establishment of greatly increased spatial coverage of long-term groundwater monitoring is needed to address the challenge of model validation in this context.

Acknowledgements

- MOC acknowledges support for an Independent Research Fellowship from the UK Natural Environment Research Council (NE/P017819/1); RGT: acknowledges support from The Royal Society (UK) and Leverhulme Trust Senior Fellowship (Ref. LT170004); RGT, JK and MOC acknowledge support from EPSRC (UK) Global Challenges Research Fund administered by UCL (Ref. 172313)
- RGT, GF, MS, MT, JK, DS, JV, FMAL, DOVK, YN, MO, PN, AMM, JS, DJM, MA, acknowledge support from NERC-ESRC-DFID UPGro programme under *GroFutures* (NE/M008207/1 and NE/M008932/1), Hidden Crisis (NE/L001969/1), BRAVE (NE/M008827/1), and T-Group (NE/M008045/1) consortia.
- We acknowledge the pivotal contribution of government officers and academics who have created the long-term groundwater records through years of dedicated service that include in Uganda (Dr. Callist Tindimugaya, Leo Mwebembesi), Tanzania (Lister Kongola, Emmanuel Nahozya), Benin (Professor Moussa Boukari), and Zimbabwe (Samuel Sunguro).
- Data for this project were obtained from the Namibian Ministry of Agriculture, Water and Forestry, Division Geohydrology, GROWAS2 and Mr Freyer from Claratal; Ministry of Water and Environment, Uganda; Ministry of Water and Irrigation, Tanzania; Direction

Générale de l'Eau and Université Abomey Calavi, Benin; Water Research Institute, Ghana; Department of Water and Sanitation, South Africa; Zimbabwe National Water Authority; Ministère de l’Hydraulique et de l’Environnement, Niger; and Direction Générale des Ressources en Eau, Agence Nationale de la Météorologie and Université Ouaga I, Burkina Faso.

- AM, MA, DM, JS publish with the permission of the Executive Director of the British Geological Survey, NERC.
- We acknowledge the very constructive comments provided by Petra Döll and Hannes Müller-Schmied at Goethe-University Frankfurt (Germany) on early drafts of this manuscript.

Methods (>4000 words – ie. a lot over the "ideally of no more than 3000 words"!)

Groundwater hydrograph and precipitation data collation and processing

Multi-decadal time series of groundwater levels and precipitation were compiled by the authors from records of observation wells initiated and maintained by government departments and research institutions in nine countries in sub-Saharan Africa (Table S1, Figure 1). The pan-African collation of these hydrographs was initiated at the 41^{st} Congress of the International Association of Hydrogeologists (IAH) in Marrakech (Morocco) on 14^{th} September 2014. All records were subjected to a rigorous review by the authors during which the integrity, continuity, duration and interpretability of records were evaluated. This process included dedicated workshops in Benin, Tanzania, and Uganda, and records failing these tests were discarded from the analysis. Procedures included taking of the first time derivative to identify anomalous spikes in records commonly associated with errors of data-entry. Where multiple records in same geographic and climate zone were available (e.g. Benin, South Africa) we prioritized records remote from potential areas of intensive abstraction. Statistical clustering of records was also used in the Limpopo Basin of South Africa to identify the representativity of employed records at Modderfontein and Sterkloop. Hierarchical clustering was done on hydrographs converted into a Standard Groundwater Index[31] and identified three clusters through a *kmeans* approach, one of which was an intermediary type hydrograph between two end members represented by Modderfontein and Sterkloop.

Recognising that the substantial spatial variability of precipitation in sub-Saharan Africa may impact observed relationships between precipitation and recharge, we used precipitation records which are representative of the recharge generation process (i.e. diffuse or focussed). As a result, raingauges are either co-located (e.g. < 5 m away) with groundwater monitoring sites or we employed the most proximate rain gauge typically less than 10 km away (Table S1). In the case of the Namibian data, the relevant raingauge was based more than 200 km away from the groundwater monitoring locations to be representative of the runoff generation area in the Kuiseb river, which acts as the source for focussed recharge in these locations.

Each groundwater record thus has an accompanying daily (9 of the 14 records) or monthly (5 of the 14 records) precipitation record covering the same period. Infilling of occasional gaps of less than a week in daily groundwater-level records was achieved by linear interpolation. All locations show seasonal, mostly unimodal, precipitation (*P*) distributions with the exception of those in Uganda, southern Benin (Natitingou) and Ghana with a more complex bimodal pattern (Figures S1).

Relationships between average climatic variables, large scale climate processes and recharge

Coefficients of monthly (or annual) precipitation variability were calculated as the standard deviation of monthly (or annual) precipitation of the whole record divided by the mean precipitation of the whole record multiplied by 100%. For analysis of wider climatic anomalies during major recharge events we use gridded data of: Global Precipitation Climatology Centre (GPCC) monthly precipitation product v8 [32] at 1.0° resolution; Daily precipitation at 0.1° resolution from the Climate Hazards InfraRed Precipitation with Station Data[33]; The Extended Reconstructed Sea Surface Temperature (ERSST) version 4 data from the National Oceanographic and Atmospheric Administration (NOAA)[34] on a monthly 2° grid.

Linear regression analysis indicates a strong correlation (R^2=0.90) between *P* and aridity index (*P*/*PEt*) (Figure S2a) since rates of potential evapotranspiration (*PE*t) have a relatively small range across these tropical latitudes in comparison to annual average rainfall. *PEt* neither correlates with *P* (R^2=0.00) or *P*/*PEt* (R^2=0.00). Aridity index is strongly correlated to the coefficient of monthly *P* variability (R^2=0.82), but less so with the coefficient of annual *P* variability (R^2=0.36) (Figure S2b,c) together indicating that aridity is a strong control on the degree of rainfall seasonality.

Long-term average recharge rates correlate poorly with rainfall or aridity (Figure S2h). In humid regions this is expected due to geological variations causing large differences in absolute recharge rates; in Benin for example, Cococodji recharge is nearly an order of magnitude greater than that in Natitingou despite similar rainfall and aridity (Figure 2). In more arid regions, increasing spatial heterogeneity in recharge rates is expected due to the increasingly predominance in focused recharge (Figure 4). Thus, the Namibian records, for example, show high rates of recharge reflective of the 'footprint' of the observation well located near an ephemeral stream; such values which are often higher than the local precipitation, would nevertheless be expected to be larger than average recharge rates for the wider hyper-arid region. Thus, the direct comparison of recharge rates between sites could be misleading without considering these potentially confounding factors.

We show that most of the extreme recharge events, which are identified as recharge outliers (Figure 2), are associated with relatively widespread regional and seasonal scale precipitation anomalies (see exemplar in Figure S3). These precipitation anomalies themselves can be associated with large-scale structures of climate variability known to impact the various regions of Africa (Table S2). Whilst recognising that observed precipitation variability typically results from a complex set of drivers occurring simultaneously over various spatial and temporal scales, we note the following association of large-scale precipitation anomalies during the outlier extreme local recharge years and climate drivers.

Across our sites south of the equator we note that the major recharge years are associated with: El Niño events concurrent with the positive phase of the Indian Ocean Zonal Mode (IOZM[35]) in the East Africa (Tanzania) site, and La Niña events in Southern Africa (South Africa and Zimbabwe, see Figure S3 as an example). This is consistent with the well-established north-south dipole precipitation response to El Niño-Southern Oscillation (ENSO) events which typically, but neither exclusively nor consistently, bring wet (dry) rainfall anomalies across East (Southern) Africa during El Niño events and the reverse during La Niña[36,37].

Further west in the hyper-arid Namibia sites the drivers of the outlier recharge events are more complex, as expected given the complex 'Type 3' relationship of precipitation to the highly episodic recharge (Figure 2), dependent on triggering of ephemeral surface river flow. Of the five outlier recharge events, two can be linked to regional/seasonal scale rainfall anomalies associated with an anomalous warming of the cold Benguela current off the west coast of Africa. Such 'Benguela Niño' events[38] are known to trigger convection and rainfall across much of Northern Namibia and Southern Angola[39,40]. The remaining three events appear linked to spatially extensive but shorter duration heavy rainfall anomalies from sub-seasonal variability. This includes the notable, anomalous westward propagation of tropical cyclone Eline in February 2000 from the Indian Ocean basin to Namibia, which also caused widespread precipitation extremes across much of South-eastern Africa compounding existing La Niña related rainfall, as well as synoptic scale tropical low pressure systems in 2009.

The West African sites show a smaller number of outlier recharge events. The 2012 event at Burkina Faso appears part of wider, regional and seasonal scale precipitation anomalies, in which the Sahel region as a whole experienced the strongest monsoon season since 1953, likely resulting from the combination of seasonal tropical Atlantic temperature anomalies[41] and sub-seasonal variability from active phases of the Madden Julian Oscillation[42]. The 1998 recharge event in Niger coincided with far less spatially coherent seasonal anomalies and likely resulted from intensive sub-seasonal precipitation events.

Site conceptual models

For each hydrograph location, a conceptual hydrogeological model was formulated based on available data, literature, and site visits by the authors, as necessary (Table S3). These included an assessment of the main hydrogeological boundaries such as groundwater divides and perennial or ephemeral drainage features; the local context for factors which may influence recharge such as geology, soils, climate variables, groundwater abstraction and the thickness of the unsaturated zone; and estimations of aquifer storage and transmissivity. A particular focus was to develop an appreciation, based on the local context, of how 'diffuse' the recharge is likely to be spatially, or whether 'focussed' recharge is likely to be more significant in causing local variations in the magnitude of water table fluctuations. Of most importance for determining the predominance of diffuse versus focussed recharge is: the presence or absence or perennial versus ephemeral streams; co-incident timing of ephemeral or seasonal stream flows with water table responses; and the form of groundwater hydrographs with respect to the presence or absence of groundwater mounding as indicative of focussed recharge (see further details is the Section 'Groundwater recessions' below). The conceptual hydrogeological model development also enabled us to ensure that observed groundwater level changes are likely to be representative of water table fluctuations in an unconfined aquifer (i.e. vertical flow in the aquifer is insignificant and that poro-elastic or other 'confined' responses are negligible).

Recharge estimation using water table fluctuation (WTF) method

Approach and equations: inverse WTF models were used to infer the recharge timing and magnitude at the location of each hydrograph. The WTF technique is the most direct method of transient groundwater recharge estimation available and has very few embodied assumptions in comparison to other methods such as geochemical tracers or modelling approaches[16,43]. In a recent review of recharge estimation methods it was strongly recommended for application in humid and semi-arid African regions[10] and it is also applicable for both diffuse[44,45] and focussed[46] recharge situations.

We assume that groundwater level (or hydraulic head, h [L]) at an observation point is naturally controlled by the combined influence of the rate of net groundwater recharge (R [LT^{-1}]), balanced by the rate of 'net groundwater drainage' (D [LT^{-1}]) acting at that point in space and time. Further variations in WTF may be superimposed due to the rate of "net drawdown" (s [LT^{-1}]) caused by changes in groundwater abstraction occurring at some distance from the observation point.

The following water balance equation was used to approximate a time series (with time step Δt) of the ratio of recharge (R_t) to specific yield (S_y [-]):

$$\frac{R_t}{S_y} = \frac{\left(h_t - h_{(t-\Delta t)}\right)}{\Delta t} + GWL_r + s_t \qquad (1)$$

where GWL_r ($=\frac{D_t}{S_y}$) is the rate of groundwater level recession[47] [LT^{-1}]. Values for absolute value of recharge were then also calculated by multiplying by the applicable specific yield at the position of the water table.

To enable exact accounting periods for comparison with precipitation records, and between hydrographs, where observations were less frequent than daily, linear interpolation was used between groundwater level observations. Calculations were carried out on a daily time step and sums were calculated for hydrological years (in both R and P). If observations were missing across either end of the hydrological year in the first or last years of record, those years were removed from further analysis. Within the annual recharge time series generated "Tukey" outliers were identified as any years with values greater than 1.5 times the interquartile range above the third quartile.

Groundwater recessions: the GWL_r term was estimated based on the observed form and magnitude of the groundwater hydrograph during long dry periods by either setting a constant rate, or an exponential decay controlled by the following equation:

$$GWL_r = \frac{h_{(t-\Delta t)} - h_b}{C} \qquad (2)$$

Where h_b is the elevation of the assumed lateral groundwater drainage boundary [L] and C is a decay constant [T^{-1}].

Most of the hydrographs have very distinctive seasonal precipitation patterns with long dry seasons during which the true form of groundwater recession (i.e. a groundwater level decline in the absence of any recharge) can be directly observed, assuming no human interferences[47]. This enables the choice of recession model (constant rate or exponential) to be confidently made, and constant rates or decay constants to be easily determined. This is in comparison to more humid parts of the world with limited dry periods where the WTF is harder to apply robustly[44,45]. For hydrographs in Ghana, South Africa (Modderfontein) and Burkina Faso, an exponential recession model was used due to the presence of a shallow water table, inferred high permeability fracture flow, and close proximity of the groundwater drainage boundary, respectively (see Table S3 for more information). For Uganda (Soroti), the absence of long dry seasons, and the observed form of groundwater level declines did not make the choice between exponential and straight line recessions obvious, and so both were applied to represent the uncertainty. For all other locations, the observed variation of dry season groundwater-level recessions was used to define maximum and minimum constant rate end members to constrain the uncertainty in recharge estimates due to this parameter. This is consistent with theoretical expectations of linear recessions for these locations with drainage boundaries (where known) being sufficiently distant given the aquifer properties[47].

For the cases where focussed recharge is significant due to local infiltration from ephemeral streams and ponds, the expected theoretical form[46] is for groundwater hydrographs to show steep recessions following a rise in the water table, then trend to a relatively constant lower 'background' recession rate. This is observed for example in Zimbabwe, Tanzania, South Africa (Sterkloop), Niger and Namibia and is explained by localised groundwater 'mounding' near the location of focussed recharge dissipating on a much quicker timescale than the regional background recession, which operates on much longer spatial scales. In these cases, with the exception of Namibia, the local mounding dissipates before the end of the hydrological year enabling a seasonal WTF accounting period to be used following the method of ref[46]. In Namibia, the recession of the recharge mounds occurred over timescales greater than a single season, and therefore had to be extrapolated leading to much greater uncertainty in the output recharge values (as evidenced by larger error bars in Figure 2). The application of this method thus enables recharge rates to be derived which are representative of integrated processes across larger areas of the catchment or aquifer (whichever define the hydraulic boundaries), rather than simply reflecting the local conditions near the stream. However, the spatial representativity of recharge estimated at each location is variable and, as such, direct comparisons of absolute recharge rates from site to site should only be made where this can be accounted for.

Groundwater abstractions*:* once at steady state, groundwater abstractions should have no effect on water table fluctuations. However, transient abstractions cause time-varying drawdown at the groundwater monitoring location. If not accounted for, they will therefore cause recharge underestimations when drawdown is increasing, and overestimations when drawdowns are decreasing (e.g. if abstraction temporally reduces (increases) causing recovery (decline) in groundwater levels). In most cases, the observation wells are located far from the influence of major changes in groundwater abstraction as documented in the meta-data (Table S3) and s_t was assumed to be zero. In one location (Makutapora, Tanzania), the monitoring wells are located within a major well-field where abstraction rates have been highly variable during the monitoring period. Corrections were therefore made for this site using a 3D groundwater model to estimate a time series of net drawdown to account for the changes in recession due to variations in pumping rate. (i.e. accounting for drawdown due to increases in pumping, and recovery during decreases in pumping) (meta-data Table S3).

Specific yield: ranges of specific yield were estimated based on local information and literature for each groundwater level record as described in the meta-data (Table S3) and assumed to be constant in time, and across the range of water table fluctuations at a given location. The uncertainty in specific yield can be considerable and represents the main uncertainty in the derived absolute values of recharge. As well as being notoriously hard to estimate[48], it is also known that specific yield can vary in time due to vertical heterogeneity in lithology, due to shallow water tables or where swelling clays are present[44,49]. The variation in the value for specific yield has no impact on the form of the relationship that recharge has with precipitation or the ranking of recharge events used in Figure 2 and 3 (and Figure S3). However, we report the likely range of uncertainty in specific yield for each location as this does impact the absolute magnitude of the recharge estimates, and is one reason why inter-site comparisons of long term average recharge by this method can be problematic.

Model experiments and interpretation of observed precipitation-recharge (rP-cR) relationships

P-R cross plots (Figure 2) showing annual recharge against annual precipitation, allow an initial characterization of precipitation-recharge relationships to be developed. For comparative purposes across all records, we then normalized annual recharge by a cumulative sum as a fraction of the total recharge for all years in a given record, and plotted this against the fractional precipitation ranking for each record (rP-cR plots, Figure 3). To inform process-based inferences from these plots, we ran a suite of numerical recharge model experiments using models with different structures, for two chosen time series from contrasting climates in sub-Saharan Africa: Dodoma (semi-arid Tanzania) and Cococodji (humid Benin). The purpose was not to calibrate models for each of the locations across Africa but rather to understand the generic features of rP-cR plots for aiding interpretation of the relationships we observe in the data.

Three model structures of increasing complexity were explored: (a) Recharge was assumed to be constant for precipitation events above a daily or annual threshold. Note that, since the values were normalized against the total recharge in all years, the actual recharge value is irrelevant to the result. (b) The second model structure, in the manner of ref[21], assumes that a constant proportion of precipitation becomes recharge above a specified daily precipitation threshold. Thresholds were applied at a daily time step and then results aggregated for yearly comparisons. Since the values were normalized against the total recharge in all years, the chosen proportion of rainfall that becomes recharge is irrelevant to the result. (c) The third model was a dynamic single layer soil moisture balance model (SMBM), in the manner of refs[23,50], also run at a daily time step and then aggregated to annual values. It was assumed in all SMBM model runs that the readily available water (RAW) was 50% of the total available water (TAW), that the crop coefficient was equal to 1 (e.g. for grass land cover), that the ratio of actual to potential evapotranspiration rates (AET/PET, a proxy for plant stress) decreased linearly from 1 to 0 as soil moisture deficit values increased from RAW to TAW, and that runoff was zero.

For Dodoma, daily PET values were derived using the Hargreaves and Samani equation[51] from temperature data from the Dodoma Meteorological Station. In the case of missing data, the average value from the month is used or when, early in the record, entire months are without data the average temperature values for the corresponding month from the entire record was substituted. The calculated values were calibrated on pan evaporation data from the same location. For Cococodji, daily PET values derive from pan evaporation data collected from the meteorological station at the IITA (International Institute of Tropical Agriculture) office in Cotonou.

The generic style of each type of rP-cR plot (Figure 3) is well captured by the models, for either of the two contrasting precipitation time series (Figure S3); both show three distinct types of relationships and it is clear that different models (and thus processes) can lead to a similar sensitivity – i.e. a critical point is that each type of observed P-R sensitivity does not necessarily correspond to a particular recharge process. The first type (purple in Figure S3) plots close to the 1:1 line indicating very consistent R values each year despite wide variations in P. The second type (green in Figure S3) deviates from the 1:1 line increasingly as the size of the potential thresholds in the SMBM (governed by TAW) or the actual thresholds in the linear models increase. The third type (orange in Figure S3) shows pronounced steps in the curve generated by the largest thresholds in the linear model. Clearly, P-R responses in reality fall on a continuum, but we propose that classifying by three types highlights the end member responses. This classification can be further tested and refined as more data become available for sub-Saharan Africa (or other parts of the world).

More details of the observed P-R and rP-cR plots (Figures 2 and 3) summarized in the main text are as follows:

Type 1: Natitingou is characterised by low storage fractured bedrock (S_y = 0.4%)[21]; water-table variations are around 10 m annually and each year the subsurface fills to a shallow level. In combination with straight recessions, this hydrogeological context leads to temporally small variation of recharge each year despite large variations in annual precipitation (observed range is 850-1592 mm/y). At Soroti, the water table is always deeper than 5 m below ground level (bgl) within weathered basement rock but, despite this, exhibits rapid responses to precipitation events indicative of preferential flow processes[22]. The observed consistency in recharge from year to year may be controlled by a finite near surface water store to which the water table responds[23] although further site-investigations are needed to confirm precise controls.

Type 2: Where diffuse recharge is predominant, this type of sensitivity is expected if precipitation thresholds are governed by prevailing soil moisture deficits (or other near-surface storage/losses). We may expect increased deviation to the left of the 1:1 line on the rP-cR plots to increase with aridity and the build-up of larger soil moisture deficits. However, we may also expect exceptions to this to occur in cases where preferential flow processes[22] are prevalent and recharge can 'bypass' soil moisture deficits and thus precipitation thresholds may be lower than anticipated than under uniform flow assumptions. Where focussed recharge is predominant, thresholds for its occurrence are expected to be governed by hydrological processes which dominate in drylands, such as generation of infiltration-excess runoff producing ephemeral channel flow[24]. These processes can be locally variable and have complex dependencies on, for example, land cover, drainage network density, soil structure and antecedent moisture conditions. In the observed responses of this type in the humid to sub-humid environments (i.e. Benin (Cococodji), Uganda (Apac) and Ghana (Accra)), thresholds appear to be relatively small. This is consistent with detailed analysis available for Cococodji and Apac which suggest values of 5 mm/d and <10 mm/d respectively for these sites; there are no existing studies to corroborate this for Ghana. We observe that much larger precipitation thresholds may need to be overcome for recharge to occur for semi-arid sites in Tanzania and Zimbabwe; here, the forward models suggest precipitation thresholds greatly in excess of 100 mm/d (darker green in Figures 2 to 4). Again, this is consistent with detailed analysis carried out for Tanzania which indicates that recharge occurs only after persistent rainfall of over 90 mm over a 7 day period[52]. For the two Niger sites, despite also having greater aridity, thresholds are apparently much lower but this is explained by daily precipitation thresholds of 10-20 mm d^{-1} known to be required to generate stream flow[25], and thus focussed recharge, in this area. In Burkina Faso, focussed recharge from a nearby managed reservoir ("barrage") is thought to moderate the impact of inter-annual precipitation variability on recharge variability moving the rP-cR line closer to the 1:1 (Figure 3) than might be the case without a reservoir.

Type 3: The two Namibian sites are in a hyper-arid environment dependent on runoff generation from a large upstream catchment to supply focussed recharge during streamflow events. Conditions for runoff generation are governed by intense monthly precipitation occurring not necessarily within years of relatively high total precipitation. In contrast, at Modderfontein (South Africa), focussed recharge is much more local, but the limestone bedrock in this location is typified by highly non-linear hydrological processes which generate complex P-R relationships (see Table S3).

In summary, the controls on the observed P-R and rP-cR sensitivities are a complex interaction between the prevailing climate and local controls on recharge generation.

Data Availability Statement

Where permissions allow, digital datasets are freely available to download online from https://doi.org/10.6084/m9.figshare.5103796 including calculated annual recharge values. and time series of groundwater-level deviations from the mean and precipitation anomalies (also available at IGRAC 'link TBC' and NERC 'link TBC').

Author Contributions

The paper was conceived by RT, GF and MOC. The paper was written by MOC and RT with input from all authors. RT and GF led the collation of the data. MOC designed the applied WTF methodology. MT conducted climate data analyses. All authors carried out other data analysis or interpretation of results.

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