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Mapping groundwater recharge in Africa from ground observations and implications for water security

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Abstract

Groundwater forms the basis of water supplies across much of Africa and its development is rising as demand for secure water increases. Recharge rates are a key component for assessing groundwater development potential, but have not been mapped across Africa, other than from global models. Here we quantify long-term average (LTA) distributed groundwater recharge rates across Africa for the period 1970–2019 from 134 ground-based estimates and upscaled statistically. Natural diffuse and local focussed recharge, where this mechanism is widespread, are included but discrete leakage from large rivers, lakes or from irrigation are excluded. We find that measurable LTA recharge is found in most environments with average decadal recharge depths in arid and semi-arid areas of 60 mm (30–140 mm) and 200 mm (90–430 mm) respectively. A linear mixed model shows that at the scale of the African continent only LTA rainfall is related to LTA recharge—the inclusion of other climate and terrestrial factors do not improve the model. Kriging methods indicate spatial dependency to 900 km suggesting that factors other than LTA rainfall are important at local scales. We estimate that average decadal recharge in Africa is 15 000 km^3 (4900–45 000 km^3), approximately 2% of estimated groundwater storage across the continent, but is characterised by stark variability between high-storage/low-recharge sedimentary aquifers in North Africa, and low-storage/high-recharge weathered crystalline-rock aquifers across much of tropical Africa. African water security is greatly enhanced by this distribution, as many countries with low recharge possess substantial groundwater storage, whereas countries with low storage experience high, regular recharge. The dataset provides a first, ground-based approximation of the renewability of groundwater storage in Africa and can be used to refine and validate global and continental hydrological models while also providing a baseline against future change.

1. Introduction

Quantifying the rate of groundwater recharge is fundamental to assessing current water security and help forecast future changes (Taylor *et al* 2013a, Gleeson *et al* 2020). However, recharge is a hydrological parameter that is difficult to quantify accurately (Scanlon *et al* 2002, Healy 2010). In Africa, where considerable groundwater resources exist (MacDonald *et al* 2012), groundwater south of the Sahara has not yet been widely exploited other than for low-yielding drinking-water supplies (WHO and UNICEF 2015). Only 1% of the cultivated land of Africa is estimated to be irrigated by groundwater (Siebert *et al* 2010); 80% of this occurs in North Africa. Across the continent there is no recent evidence of significant widespread decline in groundwater storage in regional aquifers (Bonsor *et al* 2018) but localised depletion, particularly in urban areas, has been observed (Adelana *et al* 2008, Oiro *et al* 2020).

Rapid population growth and development in many African countries, together with the increasing availability of solar powered pumps (Wu *et al* 2017) have now focused attention on increased development of groundwater for irrigation and piped drinking-water supplies (Gaye and Tindimugaya 2019, Cobbing 2020). In many other parts of the world, rapid increases in groundwater abstraction have led to unsustainable conditions, characterised by falling water tables and problems with water quality (Scanlon *et al* 2012, MacDonald *et al* 2016, Rodell *et al* 2018). Consequently, reliance alone on maps of groundwater storage and aquifer permeability is insufficient to inform effective governance and investment decisions (Edmunds 2012). Quantifying the scale of groundwater recharge is required to characterise the resilience of groundwater supplies to both increased abstraction and climate change.

Estimating groundwater recharge is challenging with no widely applicable method available that can directly and accurately quantify the volume of rainwater that reaches the water table (Scanlon *et al* 2002, Healy 2010). Instead, several different methods are relied upon to estimate recharge. The most common are: chloride mass balance (CMB); soil physics methods; environmental and isotopic tracers; groundwater-level fluctuation methods; water balance (WB) methods (including groundwater models (GMs)); and the estimation of baseflow (BF) to rivers. Regional, continental and global estimates of recharge commonly derive from global hydrological models (e.g. Döll and Fiedler 2008) and have proved useful in providing a first estimate of the likely magnitude of groundwater recharge compared to surface water. However, global models have been shown to be unreliable at predicting long-term trends in groundwater storage when compared to variations in terrestrial water storage measured using GRACE (Scanlon *et al* 2018). There is therefore renewed interest in using

ground-based estimates of groundwater recharge to constrain global models (e.g. Mohan *et al* 2017, Moeck *et al* 2020) and to provide an independent estimate of groundwater recharge rates. However, to aggregate and map recharge from a meta-analysis of published, ground-based studies is challenging, as these can feature spatial and temporal biases, duplicate studies, and inappropriate applications of recharge methodologies.

Africa has a long history of groundwater recharge research with three areas particularly well studied. In southern Africa (Xu and Beekman 2003, 2019, Abiye 2017) and particularly the Kalahari desert (the site of several long-term research projects (Verhagen *et al* 1974, de Vries *et al* 2000)), work has focussed on the role of vegetation and rainfall intensity on controlling recharge. The North African sedimentary basins have benefited from many research projects in collaboration with the International Atomic Energy Agency primarily examining paleo recharge during wetter climates (Edmunds and Wright 1979, Guendouz *et al* 2003, Sturchio *et al* 2004) and localised depletion, for example in Morocco (Bouchaou *et al* 2008). Finally, research continues in the Sudano-Sahel of West Africa where research focuses on the impact of land clearing and coupling between groundwater and climate (Edmunds and Gaye 1994, Leduc *et al* 2001, Leblanc *et al* 2008, Favreau *et al* 2009). Recent research, focussed on groundwater-level responses to rainfall, has illustrated the complexity and episodic nature of recharge, and its large year-to-year variability particularly in drylands (Taylor *et al* 2013b, Cuthbert *et al* 2019a). Characterising the resilience of groundwater systems is therefore more meaningful using recharge volumes evaluated over decades, rather than annual, time periods.

Groundwater recharge can occur through diffuse or focused mechanisms (Lerner *et al* 1990, Healy 2010). Diffuse recharge occurs when precipitation infiltrates through the soil to the water table, and is by definition distributed over large areas. Focussed recharge occurs where water leaks from surface water sources (rivers, lakes, wadis, wetlands) or land surface depressions, and generally becomes more dominant with aridity (Scanlon *et al* 2006, Cuthbert *et al* 2019a). Focussed recharge can be widely distributed where ephemeral rivers, depressions or rock fractures are common over a large area and contribute to regional recharge (e.g. parts of the Sahel (Leduc *et al* 2001)) or discrete, where an individual river or water body provides significant local recharge (e.g. the Nile (Aly *et al* 1993)). Groundwater recharge can also be significantly enhanced by returns from irrigation (Scanlon *et al* 2010) or from urban areas (Lapworth *et al* 2017).

Here we quantify long-term (multi-decadal) distributed natural groundwater recharge volumes for Africa for the period 1970–2019 by mapping existing estimates from ground-based studies. We include both diffuse and focussed recharge where this is

widespread, since many methods cannot distinguish which process dominates; estimates of focussed recharge from an identified large discrete feature such as a river or lake are excluded. A quality assurance procedure was used to provide a robust dataset of 134 long-term estimates that minimised duplication. These estimates were then related to a range of climatic and terrestrial parameters to scale across the African continent. The results are used to discuss water security implications for different African countries.

2. Methods

2.1. Collating recharge studies
We developed a database of existing recharge studies for Africa. Recharge studies were compiled using published and grey literature identified from online databases, Google Scholar® and the Africa Groundwater Atlas (accessed May 2020) for the period 1970–2019, supplemented from the authors' personal databases and knowledge. For each study, meta-data including the time period of the recharge estimate, the geographic extent of the study, and an accurate geolocation checked using aerial photography from Google Maps®. Long-term average recharge (LTA recharge) values were recorded for each study area along with the employed methods noting the primary and secondary methods used. Each study was critically reviewed and given a confidence rating based on the number and type of methods applied, the quality of the application of the methods, and the number of sites included in the study (see supplementary data for more information (available online at stacks.iop.org/ERL/16/034012/mmedia)). A range of uncertainty was also included for each study: for studies with many measurements uncertainty was often the quoted standard deviation, interquartile range (IQR), or range; where studies noted uncertainty in input factors (such as specific yield or rainfall chloride) these were included in calculating the uncertainty. Estimates of groundwater recharge are inherently uncertain due to the assumptions made, therefore particular care was taken to exclude studies where the assumptions were invalid, and uncertainty was reduced when multiple independent methods were applied.

Different recharge-estimation methods included: CMB; water-table fluctuation (WTF) methods; environmental tracers (EnTs); WB; calibrated GMs; BF; and soil physics methods. Studies of groundwater recharge explicitly from river or lake infiltration, irrigation returns or urban leakage were excluded, leaving only studies representing distributed recharge from rainfall, which can include both diffuse and distributed focussed pathways. After the database was completed, studies for individual countries were assessed together to identify and remove duplicates; preference was given to syntheses and studies with

higher confidence ratings. Studies with lower confidence were retained if no other study had been repeated at the location. Records in the final dataset had equal weighting in the analysis.

2.2. Sources of additional African data
An analysis in a geographical information system (GIS) was then used to attribute various physical parameters known from previous studies to have an influence on groundwater recharge: long-term (1981–2010) climate data (Harris and Osborn 2020) (LTA rainfall, aridity index, number of wet days in a year, potential evapotranspiration (PET)); aquifer domain (MacDonald *et al* 2012), land cover (Arino *et al* 2007); the reference soil group as mapped in the Soil Atlas of Africa (Jones *et al* 2013), and normalised difference vegetation index (NDVI) (Didan *et al* 2015). Maps of these data are shown in the supplementary material. Each of these parameters were used in the linear mixed model (LMM) described below.

2.3. Statistical analysis
We required a statistical model which used a suitable subset of the measured covariates to predict LTA recharge at unsampled sites so that LTA Recharge could be mapped at continental scale. It was necessary to use an approach that was suitable for data with significant clustering (and therefore not an independent random sample) and that also selected a subset of predictor variables without over-fitting. To achieve this we used an LMM. Technical details are given in supplementary material and by Lark *et al* (2006). In an LMM a variable is modelled as a combination of fixed effects and random effects. The fixed effects define the expected value of the dependent variable given values of covariates (including categorical variables such as aquifer domain or soil group, and continuous ones such as LTA rainfall). The fixed effects therefore constitute a regression-type model.

Random effects in the LMM comprised a spatially dependent Gaussian random variable, and an independent error term (see supplementary material). The spatial term accounts for variability in LTA recharge observations around the fitted value, given that fixed effects are likely to be spatially dependent such that observations at nearby locations are expected to be more similar than those further apart. The independent error term accounts for factors such as error in the processes of estimating LTA recharge at a site, as well as any fine-scale sources of variation in the variable which are not resolved by the spatial distribution of the sample locations.

To fit the LMM, the parameters of the random effects were first estimated by residual maximum likelihood. The parameters of the fixed effects were then estimated by generalised least squares (Lark *et al* 2006). To select the final subset from predictors listed above, we considered predictors sequentially, starting with a simple 'null' model in which the only fixed
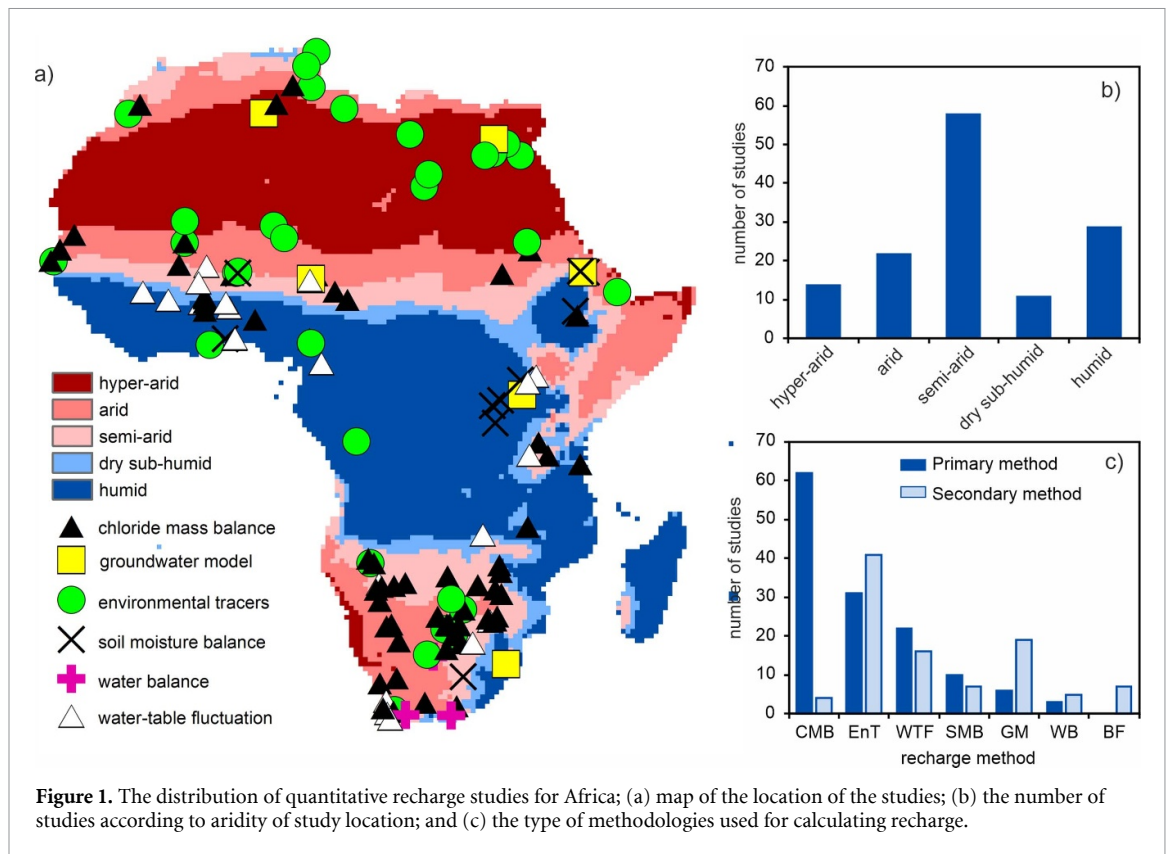
Figure 1. The distribution of quantitative recharge studies for Africa; (a) map of the location of the studies; (b) the number of studies according to aridity of study location; and (c) the type of methodologies used for calculating recharge.

effect was a constant mean value. A model with the first predictor was then fitted, and the strength of evidence that the predictor should be retained was assessed by a log-likelihood ratio (LLR) test following Welham and Thompson (1997). A continuous predictor would appear in the model as a regression-type predictor with an estimated coefficient. A categorical predictor (such as soil group) would appear in the model as a set of different intercept terms for the prediction. If a categorical predictor was accepted by the LLR test, then its interactions with continuous predictors already in the model would be tested next. Once all predictors had been considered, the evidence for each one included was reassessed against a threshold for the *P*-value determined to control the false discovery rate (FDR) over all tests conducted. The FDR is the probability that a predictor which has no relation to the target variable is incorrectly regarded as significant within a set of multiple hypothesis tests. We followed the approach described by Lark (2017) to maximise power to detect meaningful predictors while controlling FDR by ordering the initial sequence of predictors so that those thought most likely to be predictive were considered first.

The final model was then used to compute the empirical best linear unbiased prediction (E-BLUP) of LTA recharge at unsampled sites on a prediction grid. The E-BLUP combines the predicted value from the fixed effects with an interpolation of the random effect by a kriging-type predictor. The E-BLUP thus minimises the expected squared prediction error

(prediction error variance), and computes this value as a measure of uncertainty. After an exploratory least-squares fit of a model with all predictors, and examination of the distribution of residuals, we transformed LTA recharge to natural logarithms to make the assumption of Gaussian errors plausible; continuous predictors were also transformed to logarithms because of their marked skewness. The prediction was back-transformed to the original scales of measurement by exponentiation, which gives a median-unbiased prediction, appropriate for skewed variables.

2.4. Water security analysis

Average decadal groundwater recharge was subsequently calculated for each African country with uncertainty characterised by the prediction error variance of the best linear unbiased predictor. Groundwater recharge was then compared with published estimates of groundwater storage for each country (MacDonald *et al* 2012) to form a basis to discuss water security in terms of a combination of LTA recharge and storage (Foster and MacDonald 2014).

3. Results

3.1. Summary of groundwater recharge data

A total of 134 separate studies with robust quantitative LTA recharge data were identified for Africa. Figure 1 shows their location and the primary method employed in their analysis of recharge (MacDonald *et al* 2020). In arid, semi-arid and dry
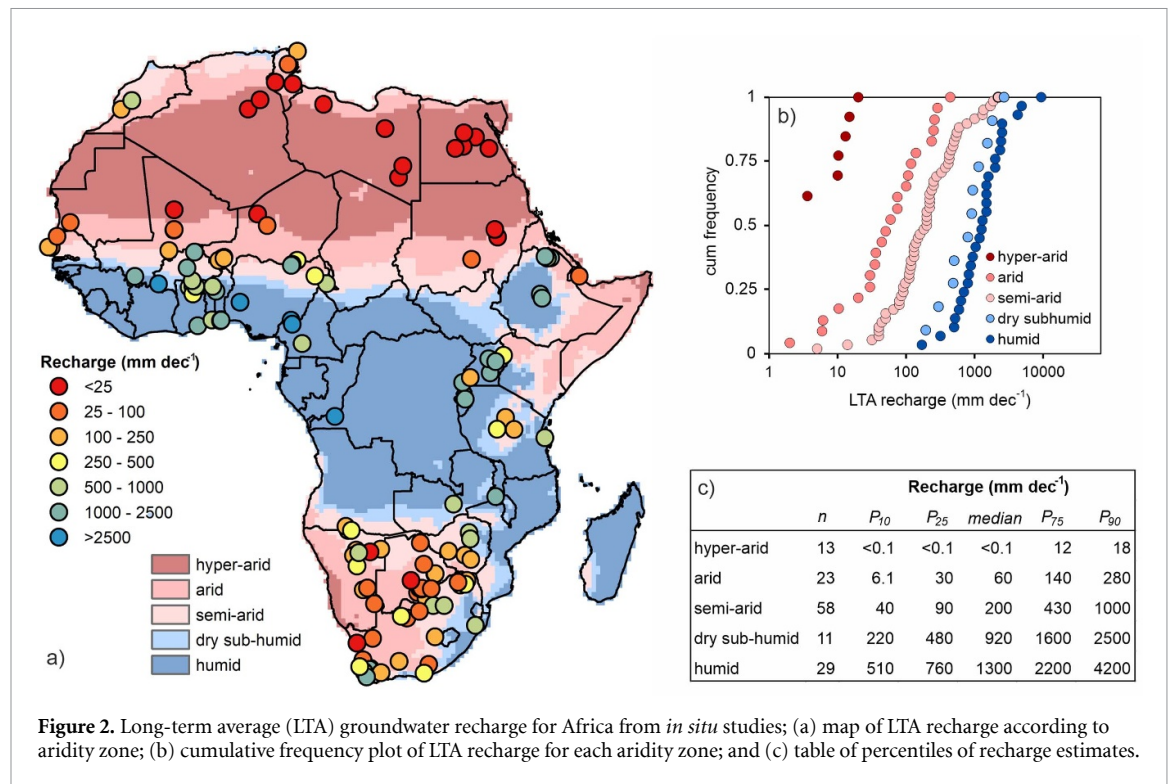
Figure 2. Long-term average (LTA) groundwater recharge for Africa from *in situ* studies; (a) map of LTA recharge according to aridity zone; (b) cumulative frequency plot of LTA recharge for each aridity zone; and (c) table of percentiles of recharge estimates.

Table 1. Sequence of linear mixed models for LTA recharge with log-likelihood ratio (LLR) test and probability (*p*-value) for the addition of each new predictor to a null model.

	Model	Null model	LLR	*P*-value
1	$\log_e$ LTA rainfall	μ	48.20	$\ll$0.0001
2	$\log_e$ LTA rainfall + $\log_e$ LTA PET	$\log_e$ LTA rainfall	1.47	0.225
3	$\log_e$ LTA rainfall + soil group	$\log_e$ LTA rainfall	10.04	0.968
4	$\log_e$ LTA rainfall + aquifer domain	$\log_e$ LTA rainfall	1.05	0.593
5	$\log_e$ LTA rainfall + $\log_e$ NDVI	$\log_e$ LTA rainfall	3.28	0.070
6	$\log_e$ LTA rainfall + $\log_e$ LTA wet days	$\log_e$ LTA rainfall	0.90	0.344
7	$\log$ LTA rainfall + $\log_e$ LTA aridity	$\log_e$ LTA rainfall	1.48	0.224

sub-humid areas, CMB was the most commonly applied method whereas EnT (such as tritium) and WTF methods were the most common methods in arid and humid areas respectively. However, 75% of the studies used two or more methods to estimate recharge, with CMB and EnT representing the most common combination. Studies are generally well distributed across Africa, though there is a relative dearth of studies in humid areas, such as the Congo basin, coastal West Africa, and southeastern Africa including Madagascar. Most arid and semi-arid areas are well represented with the exception of the Horn of Africa (figure 1).

Measurable modern groundwater recharge was found in studies across much of Africa and rates decrease with aridity (figure 2). Although recharge is not detected in the majority of studies in hyper-arid areas, 40% of studies indicated some measurable recharge, and was generally associated with episodic rainfall and wadi infiltration (Edmunds *et al* 1992, Gonçalvès *et al* 2013). In arid and semi-arid climates, some component of modern groundwater

recharge was detected in all studies, with median values of 60 mm (IQR 30–140 mm) and 200 mm (IQR 90–430 mm) respectively decade^{-1}, although recharge rarely occurred every year but was episodic (e.g. Taylor *et al* 2013b). In dry sub humid and humid areas groundwater recharge is significantly higher and recharge is recorded to occur during most years (figure 2): dry sub humid 920 mm (IQR 480–1600 mm) decade^{-1}; humid 1300 mm (IQR 760–2200 mm) decade^{-1}.

3.2. Mapping groundwater recharge across Africa

Table 1 shows the results for successive addition of predictors in the fixed effects of the model. In row one of the table, a model with $\log_e$ LTA rainfall as the only predictor is tested against the null model with the only fixed effect a constant mean (μ). The LLR is a measure of the strength of evidence against the null model, with larger values reflecting stronger evidence. The *P*-value ($\ll$0.0001) indicates the low probability that there is evidence to support the preference of the null model, therefore $\log_e$ LTA rainfall is retained.

Table 2. Parameters for the selected model.

Fixed effects parameters		
Parameter	Estimate	Standard error
β_0	-5.00	0.574
β_1	1.338	0.096

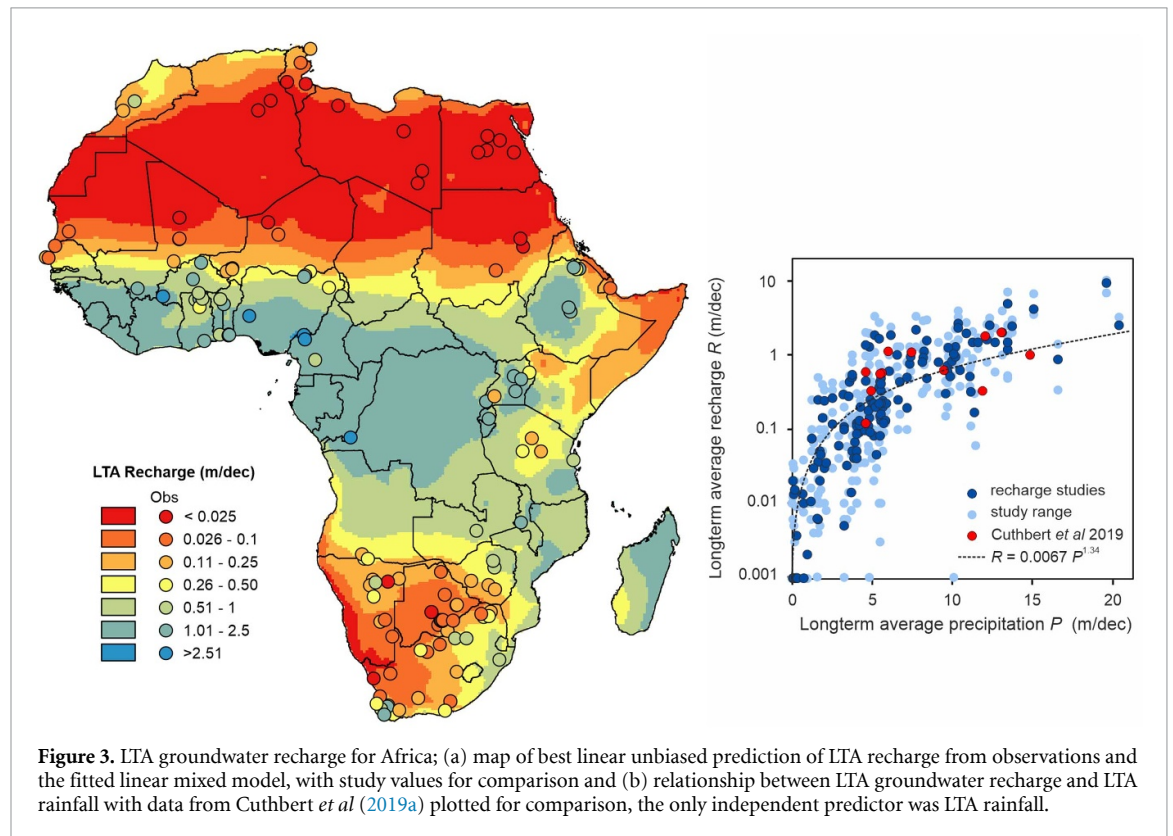| **Random effects parameters**					
Fixed effects	κ	ϕ	c_0	c_1	R^2_{adj}
$\sim\mu$	0.5	2001.1	0.551	6.203	—
$\sim\log_e$ [LTA rainfall]	0.5	288.0	0.759	0.489	0.82

Figure 3. LTA groundwater recharge for Africa; (a) map of best linear unbiased prediction of LTA recharge from observations and the fitted linear mixed model, with study values for comparison and (b) relationship between LTA groundwater recharge and LTA rainfall with data from Cuthbert *et al* (2019a) plotted for comparison, the only independent predictor was LTA rainfall.

In the next row a model in which $\log_e$ PET is added as a second predictor is tested against the alternative model with LTA rainfall only. In this, and for all subsequent predictors considered, the evidence to retain the new predictor is weak. Because none of the categorical predictors were included, their interaction with LTA rainfall was not considered. Applying the FDA control, only LTA rainfall was retained as a predictor in the model. The final fixed effect model therefore takes the form of equation (1):

$$\log_e [\text{LTA recharge}] = \beta_0 + \beta_1 \log_e [\text{LTA rainfall}] \quad (1)$$

where β_0 is -5 and β_1 is 1.388 (table 2). Random effects parameter estimates are also shown for the overall null model where a constant mean is the only fixed effect and for the selected model. Spatially correlated random effects show spatial dependence up to distances approximately three times the distance

parameter, ϕ (see supplementary material). Using a constant mean as the only fixed effect there is spatial dependence in the LTA recharge data at distances up to approximately 6000 km (reflecting the spatial dependence of long-term climatic trends). The spatial dependence of the random variation after including LTA rainfall as a predictor is restricted to a shorter range of 900 km. The term c_1 is the variance of this spatially correlated random effect. Note that c_1 is much reduced on inclusion of rainfall as a fixed effect. The term c_0 is the variance of the uncorrelated random error. The adjusted R^2 for the model, computed from the reduction in random variance on inclusion of the fixed effect, is 0.82. This is the proportion of the variance in $\log_e$ LTA recharge accounted for by including LTA rainfall in the model. The non-linearity in the relationship between LTA rainfall and LTA recharge represented by the model is consistent with ground-based studies highlighting
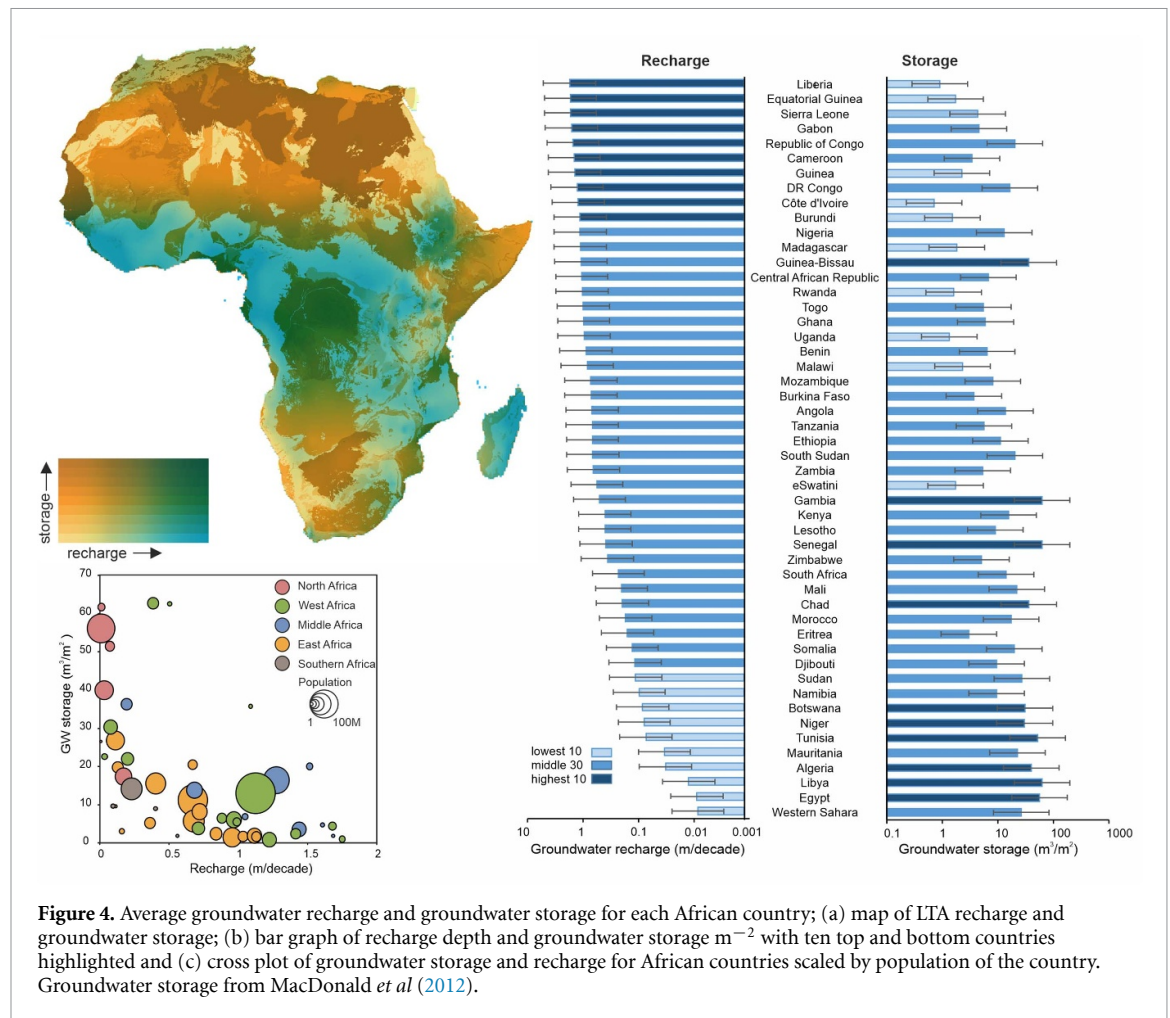
Figure 4. Average groundwater recharge and groundwater storage for each African country; (a) map of LTA recharge and groundwater storage; (b) bar graph of recharge depth and groundwater storage m^{-2} with ten top and bottom countries highlighted and (c) cross plot of groundwater storage and recharge for African countries scaled by population of the country. Groundwater storage from MacDonald *et al* (2012).

the disproportionate contribution of heavy rainfall to groundwater recharge in Africa (e.g. Taylor *et al* 2013b, Cuthbert *et al* 2019a, Banks *et al* 2020).

The LMM was used to produce the map of LTA recharge (figure 3) along with observed data for comparison. The mapped value at any location is obtained as a combination of the predicted value obtained by applying the model in equation (1) to the known LTA rainfall values, and a kriging-type prediction from the residuals for this fit to minimise the expected prediction error variance. Figure 3(b) plots the relationship between LTA recharge and LTA rainfall along with the modelled relationship and data from Cuthbert *et al* (2019a) for comparison. Recharge estimates are more uncertain in the wetter areas of Congo basin, coastal West Africa and Madagascar as there are no recharge observations where LTA rainfall exceeds 2000 mm a^{-1}. Using this method the LTA decadal groundwater recharge for Africa is estimated to be 15 000 km^3 (4900–45 000 km^3). The range is the prediction error variance of E-BLUP.

The countries with the lowest rates of distributed groundwater recharge flux are Western Sahara, Egypt, Libya, Algeria and Mauritania with less than 50 mm decade^{-1}, and the highest groundwater

recharge fluxes (>1500 mm decade^{-1}) are found in Liberia, Equatorial Guinea, Sierra Leone, Gabon and the Republic of Congo. Figure 4 shows the LTA recharge volume for individual countries and table 3 reports the total recharge volume for each country along with the average decadal recharge depth.

3.3. Water security

Combining estimates of LTA recharge with available groundwater storage provides a platform to discuss water security (Foster and MacDonald 2014) and the resilience of aquifer systems to drought (Calow *et al* 2010). This analysis can be undertaken at different scales, from individual aquifers to regions or countries. Figure 4(a) shows a map of combined groundwater recharge fluxes and groundwater storage for Africa and highlights high storage but low recharge in many of the North African sedimentary aquifers, and low storage but high recharge across many crystalline basement aquifers. Figures 4(b) and (c) compare groundwater storage and recharge for individual countries—with a combination of high groundwater storage and recharge giving increased water security. Countries in this situation are rare with only five countries, Guinea Bissau, the Republic of Congo, the

Table 3. Distributed groundwater recharge estimates for each African country, the range is the calculated prediction error variance. Groundwater storage from MacDonald *et al* (2012) is shown for comparison. Average annual recharge and storage per capita is also calculated.

Country	Recharge Volume (km³ decade⁻¹)	Recharge Depth (mm decade⁻¹)	Storage Volume (km³)	Groundwater per capita Annual recharge (m³)	Groundwater per capita Storage (×1000 m³)
Algeria	75 24–220	33 10–96	92 000 56 000–243 000	170	2100
Angola	850 270–2600	680 220–2100	17 000 7800–46 500	2600	520
Benin	99 37–280	880 330–2500	720 320–2000	820	59
Botswana	49 17–140	84 30–240	18 000 9560–58 300	2100	7700
Burkina Faso	190 67–540	710 250–2000	980 319–3330	900	47
Burundi	35 12–100	1100 390–3300	47 8–183	290	3.9
Cameroon	650 220–1900	1400 490–4200	1600 667–4810	2500	59
Cent African Rep	660 210–2100	1100 340–3300	4200 1900–13 100	14 000	880
Chad	250 82–770	200 64–610	46 000 26 600–112 000	1500	2800
Côte d'Ivoire	410 140–1300	1200 400–3700	240 49–1020	1600	9.1
Djibouti	2.1 0.7–5.9	120 39–330	170 35–546	210	170
DR Congo	3000 970–9200	1300 410–3900	38 000 18 600–103 000	3300	430
Egypt	8.8 2.6–24	8.9 2.6–24	55 000 36 000–130 000	8.6	540
Equatorial Guinea	47 15–140	1700 530–4900	48 20–147	3300	34
Eritrea	18 6.3–56	160 56–490	330 94–1120	510	95
eSwatini	7.7 2.8–23	560 200–1700	24 6–104	660	21
Ethiopia	770 260–2200	670 220–2000	13 000 4340–39 300	670	110
Gabon	420 140–1300	1600 520–5000	1200 499–4190	19 000	550
Gambia	6 2.1–19	510 170–1600	750 498–1750	250	310
Ghana	230 80–660	970 340–2800	1400 369–4418	730	45
Guinea	340 110–1000	1400 460–4300	540 133–1935	2600	41
Guinea-Bissau	36 12–110	1100 350–3300	1200 742–2824	1800	600
Kenya	230 78–710	400 140–1200	8800 4090–23 300	430	160
Lesotho	13 4.3–37	400 130–1200	290 78–936	620	140
Liberia	170 55–530	1800 580–5600	86 25–333	3300	17
Libya	20 6.3–58	13 3.9–36	100 000 64 600–234 000	300	15 000
Madagascar	640 200–2000	1100 350–3400	1100 207–4160	2300	38
Malawi	98 33–300	840 280–2500	270 91–885	510	14
Mali	250 86–750	200 69–610	27 000 10 600–87 000	1200	1300
Mauritania	36 12–110	34 12–110	23 000 10 500–67 200	770	5100
Morocco	74 24–220	170 56–500	7400 3970–20 700	200	200
Mozambique	560 180–1700	720 240–2200	6300 2684–20 300	1800	200
Namibia	79 27–220	97 33–270	7700 3520–24 600	3100	3100

(Continued)

Table 3. (Continued).

Country	Recharge		Storage	Groundwater per capita	
	Volume (km³ decade⁻¹)	Depth (mm decade⁻¹)	Volume (km³)	Annual recharge (m³)	Storage (×1000 m³)
Niger	93 (33–300)	79 (28–260)	36 000 (19 000–94 700)	380	1500
Nigeria	1000 (350–3100)	1100 (380–3400)	12 000 (5710–33 600)	500	57
Rep of Congo	510 (170–1600)	1500 (500–4700)	6700 (3 350–18 300)	9300	1200
Rwanda	32 (11–92)	1000 (370–3000)	49 (6–198)	240	3.8
Senegal	77 (26–230)	390 (130–1200)	13 000 (8280–29 100)	460	750
Sierra Leone	130 (42–420)	1700 (550–5500)	330 (160–850)	1600	41
Somalia	81 (27–250)	130 (43–400)	12 000 (5210–34 500)	510	770
South Africa	290 (100–820)	230 (81–660)	17 000 (6400–56 100)	480	290
South Sudan	420 (140–1300)	670 (220–2100)	13 000 (8800–36 200)	3700	1100
Sudan	210 (70–650)	110 (38–350)	50 000 (35 100–143 000)	480	1100
Tanzania	630 (210–1900)	680 (230–2000)	5300 (2040–17 900)	1100	88
Togo	54 (20–150)	990 (360–2800)	300 (102–879)	650	36
Tunisia	11 (3.08–31)	74 (26–210)	7600 (4 910–18 100)	92	640
Uganda	240 (84–690)	960 (330–2800)	340 (73–1270)	530	7.4
Western Sahara	2.2 (0.7–6.6)	8.5 (2.6–26)	6800 (3770–21 400)	370	11 000
Zambia	490 (160–1500)	650 (210–2000)	4000 (1430–12 300)	2700	210
Zimbabwe	140 (50–410)	360 (130–1000)	2000 (906–7230)	960	130
Africa	14 750 (4900–45 000)	490 (160–1500)	0.66 × 10⁶ (0.36–1.8 × 10⁶) km³	1100	490

Democratic Republic of Congo, Nigeria and Angola having both recharge and storage above the median for Africa. Having both low groundwater storage and recharge considerably reduces water security; again countries in this condition are rare with only five, eSwatini, Zambia, Lesotho, Zimbabwe and Eritrea having both recharge and storage below the African median.

The majority of African countries have either high storage, or high groundwater recharge. Where storage is high, but LTA recharge low, groundwater is resilient to short-term change in climate, but prone to long-term depletion. In Africa, six of the countries with least recharge have highest storage: Egypt, Algeria, Libya, Tunisia, Niger and Botswana and represent some of the highest groundwater abstractors in Africa (Wada *et al* 2012). In areas where groundwater storage is low but recharge is high, groundwater supplies are more vulnerable to drought but resilient to long-term irreversible depletion (figure 4). Five of the countries with highest recharge have the least groundwater storage: Liberia, Equatorial Guinea, Guinea, Cote D'Ivoire and Burundi. A similar picture of water security is given by considering the groundwater recharge and storage available per capita (table 3).

4. Discussion

4.1. Recharge and long-term average rainfall
The LMM shows that at the scale of the African continent only LTA rainfall is related to LTA recharge. The inclusion of other factors, PET, NDVI, number of wet days, soil group, aquifer domain and land cover does not improve the model. This outcome contrasts with that of some other large-scale studies (e.g. Mohan *et al* 2017), which required several different climate and land-cover parameters to improve model fitting. The good fit of the model presented here using only LTA rainfall may be due to the extra care taken to geolocate studies and only include studies that passed stringent quality assurance tests to give data that estimate long-term recharge. However, the random effect in the LMM still show spatial dependence (up to 900 km), and local prediction of recharge can be improved by using the BLUP, with its kriging-type component, relative to a prediction from rainfall alone. This spatial dependence reflects the importance of local soil and land use conditions in mediating the relationship between recharge and rainfall as demonstrated by many studies (e.g. Sami and Hughes 1996, Scanlon *et al* 2005, Ibrahim *et al* 2014). However, in modelling LTA recharge across Africa using continental-scale datasets, these parameters do not have a consistent effect, and LTA rainfall dominates the relationship. The scale of these local effects is represented by the variance observed in the relationship between LTA rainfall and recharge (figure 3 and table 3). Therefore, the approach taken

here has most value for estimating recharge at a regional scale.

There is little evidence from the data to support a threshold value of LTA rainfall below which recharge cannot occur. Measurable distributed modern groundwater recharge is found to occur where average annual rainfall is considerably less than 250 mm (figure 2) and even in some hyper-arid areas. This deduction is most likely explained by the increased probability of high rainfall events occurring when observing over several decades and the dominance of convective precipitation in arid areas. For example in the dune covered Stampriet Basin in Namibia where average rainfall is less than 250 mm a^{-1}, rainfall can be as high as 600 mm in some years—leading to significant diffuse recharge events (Stone and Edmunds 2012). Lack of vegetation in some arid and hyper-arid areas can also contribute to diffuse groundwater recharge, as heavy rainfall can infiltrate beneath the shallow zero flux plane (Dincer *et al* 1974, Gates *et al* 2008, Scanlon *et al* 2010). Focussed groundwater recharge is also of increased importance in arid areas (Scanlon *et al* 2006, Cuthbert *et al* 2019a) and can contribute to regional distributed groundwater recharge. In Niger for example, research has demonstrated highly localised redistribution of runoff by vegetation and geomorphology (Bromley *et al* 1997) and more widely distributed recharge through temporary ponds and ephemeral streams (Leduc *et al* 1997). The presence of karst feature can also increase focused recharge in arid regions (Schulz *et al* 2016). This current study examining long-term relationships complements recent findings examining patterns in annual recharge (Taylor *et al* 2013b, Kolusu *et al* 2019. Cuthbert *et al* 2019a), which demonstrate increasing annual variability in recharge with aridity and many years with no measurable observed recharge. These results strongly support measuring and reporting recharge values over decades rather than annually.

4.2. Water security
Most African countries with little groundwater storage have high annual rainfall and therefore regular recharge. Conversely, many African countries with low rainfall, usually considered as water insecure, have considerable groundwater storage which was mostly recharged millennia ago (figure 4). Generally, assessments of water stress and water security ignore groundwater storage (Taylor 2009), but concentrate on annual ratios between renewable water and water use by people and the environment (Vörösmarty *et al* 2010). Even where groundwater is considered, early thinking was dominated by the concept of safe yield and ratios between abstraction and recharge (Zhou 2009). However over the last 2 decades this conceptualisation has evolved beyond simple ratios to broader issues of sustainability

(Morris *et al* 2003, Alley and Leake 2004); and include both the response time of groundwater systems to change (Cuthbert *et al* 2019b) and dynamic groundwater storage (Damkjaer and Taylor 2017, Bierkens and Wada 2019). Sustainability is increasingly being considered as context specific (Gleeson *et al* 2020) with an acknowledgement that countries have different priorities depending on other pressures and aims, such as the Sustainable Development Goals. With increasing calls to draw from groundwater storage in order to stimulate economic growth and improve food security in Africa (Wijnen *et al* 2018, Cobbing 2020) a more nuanced approach to water security is necessary.

Several countries, particularly, (but not exclusively) in North Africa (figure 4(c)) have considerable water security when groundwater storage is taken into consideration. This storage provides a significant buffer before abstraction will impact the regional groundwater system. Since there is little dependency on modern recharge, the supply is secure against current climate variability. Examples from elsewhere, including the High Plains and Californian Central Valley aquifers in the US (Scanlon *et al* 2012), as well as the Indo-Gangetic Basin in northern India and Pakistan (MacDonald *et al* 2016) demonstrate that such abstraction can be continued in large aquifers but not without degradation. Similar degradation occurs in smaller heavily exploited aquifers North Africa, such as the Souss in Morocco (Bouchaou *et al* 2008). In Libya, where groundwater recharge is negligible, groundwater storage was developed as part of the Great Man Made River Project without convincing evidence of its sustainability (Edmunds and Wright 1979, Ahmad 1983). Unsustainable groundwater abstraction increased current water supply considerably but at the expense of water security for future generations. Eventually limits can be reached as abstraction increases and becomes more widespread. As groundwater-levels fall, and groundwater discharge reduces in response to abstraction, ecological consequences can occur and include the destruction of wetlands, reduction of baseflow to rivers, land subsidence and increases in salinity. Equally important is the impact on other groundwater users as shallow wells and boreholes dry up, leaving only those with access to the deepest and most expensive boreholes able to access groundwater.

Countries with low groundwater storage but high groundwater recharge are common in Africa, mainly because of the wide prevalence of crystalline-rock and volcanic aquifers. When abstraction is low (e.g. supporting widespread community hands pumps) the water supply is secure, even through short-term droughts (MacDonald *et al* 2019). Where aquifers are more permeable however, the increase in abstraction (enabled by the geology) for irrigation or urban supply, can quickly deplete storage in dry years—as

shown in the crystalline basement aquifers in Peninsular India (Collins *et al* 2020).

Both these examples above highlight the importance of ongoing dedicated groundwater monitoring to act as an early warning of rapid changes in storage or water quality in response to pumping. Although the use of GRACE has proved useful at scales of >100 000 km^2, it cannot substitute for *in situ* monitoring to capture changes in groundwater levels (Shamsudduha and Taylor 2020), water quality (Lapworth *et al* 2020) and abstraction (Oiro *et al* 2020) to identify threats to water security for individual aquifers, regions or countries.

4.3. Estimating recharge

The three most common methods used to estimate LTA recharge in Africa are CMB, WTF methods and the use of EnTs. The majority of studies used several techniques to assess recharge, and the most reliable studies (those in the Sahel and the Kalahari) have developed understanding and data over decades, with different methods and new techniques used to challenge and refine previous results. There is no evidence of bias in the dataset from the method used (see supplementary material). This observation likely arises, however, from the quality assurance procedure, which eliminated studies where techniques had been applied incorrectly and gave a lower priority to studies where only one technique was applied.

Where correctly applied (e.g. accounting for surface runoff, and constraining rainfall and atmospheric inputs) CMB offers useful insight for integrating recharge over the long-term. Studies where unsaturated zone profiles of chloride concentrations are combined with measurements at the water -table are particularly helpful (e.g. de Vries *et al* 2000, Edmunds *et al* 2002), as are the additional use of EnTs in more arid areas to indicate if recharge has occurred within recent decades (Lapworth *et al* 2013). The WTF method is the only method which directly measures groundwater storage responses and is well suited for examining temporal responses to recharge. However to estimate LTA recharge in more arid areas a sufficiently long record is required to capture important episodic recharge events (Taylor *et al* 2013b, Cuthbert *et al* 2019a) and sufficient local knowledge is needed of the aquifer properties and the groundwater discharge regime (Cuthbert 2010). In humid areas however, where annual recharge is less variable (Cuthbert *et al* 2019a), shorter hydrographs can also provide valuable data particularly when in combination with other methods. In arid and hyper-arid areas, combinations of EnTs are used to estimate the residence times of groundwater, and in particular identify any component of modern recharge.

There are large parts of Africa including 19 countries lacking a reliable recharge study. In humid areas of Central Africa, West Africa and Madagascar, there is a particular dearth of studies, probably

due to high rainfall and limited reliance on groundwater. The limited understanding of recharge process and volumes in these areas has consequences when modelling continental and global processes and constraining terrestrial WBs. In more arid areas, the Horn of Africa is lacking in studies—an area where groundwater is fundamental for buffering drought (MacAllister *et al* 2020).

5. Conclusions

The development of a quantitative map and database of long-term distributed groundwater recharge for Africa from ground-based observations is a useful addition to current knowledge of groundwater resources in Africa. Estimated average decadal recharge is 15 000 km^3 (4900–45 000 km^3) and the statistical model and 134 individual studies can be used to help constrain global and continental models (e.g. Döll and Fiedler 2008). Measurable long-term distributed recharge is found in most environments; average decadal recharge fluxes in arid and semi-arid areas are 60 mm (IQR 30–140 mm) and 200 mm (IQR 90–430 mm), respectively. Recharge occurs episodically in dryland environments so that integrative methods such as CMB, EnTs or multi-decadal hydrographs are required to estimate long-term recharge. As a result, recharge is best reported as decadal rather than annual averages. Average decadal recharge is approximately 2% of estimated groundwater storage across the continent as a whole but with stark variability between the high-storage/low-recharge sedimentary aquifers in North Africa and low-storage/high-recharge crystalline-rock aquifers across much of tropical Africa. African water security is greatly enhance by the distribution of groundwater storage and recharge; many countries that feature low recharge, possess substantial groundwater storage, whereas countries with low storage typically have high, regular recharge.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5285/45d2b71c-d413-44d4-8b4b-6190527912ff.

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