Understanding process controls on groundwater recharge variability across Africa through Recharge Landscapes

Charles West[1], Rafael Rosolem[1,2], Alan M. MacDonald[3], Mark O. Cuthbert[4,5] and Thorsten Wagener[1,6]

1 Civil Engineering, University of Bristol, Bristol, United Kingdom

2 Cabot Institute for the Environment, University of Bristol, Bristol, United Kingdom

3 British Geological Survey, Lyell Centre, Edinburgh EH14 4AP, United Kingdom

4 School of Earth and Environmental Sciences, Cardiff University, Park Place, Cardiff, CF10 3AT, United Kingdom

5 School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia

6 Institute for Environmental Science and Geography, University of Potsdam, 14476 Potsdam, Germany

Abstract

Groundwater is critical in supporting current and future reliable water supply throughout Africa. Although continental maps of groundwater storage and recharge have been developed, we currently lack a clear understanding on how the controls on groundwater recharge vary across the entire continent. Reviewing the existing literature, we synthesize information on reported groundwater recharge controls in Africa. We find that 15 out of 22 of these controls can be characterised using global datasets. We develop 11 descriptors of climatic, topographic, vegetation, soil and geologic properties using global datasets, to characterise groundwater recharge controls in Africa. These descriptors cluster Africa into 15 Recharge Landscape Units for which we expect recharge controls to be similar. Over 80% of the continents land area is organized by just nine of these units. We also find that aggregating the Units by similarity into four broader Recharge Landscapes (Desert, Dryland, Wet tropical and Wet tropical forest) provides a suitable level of landscape organisation to explain differences in ground-based long-term mean annual recharge and recharge ratio (annual recharge / annual precipitation) estimates. Furthermore, wetter Recharge Landscapes are more efficient in converting rainfall to recharge than drier Recharge Landscapes as well as having higher annual recharge rates. In Dryland Recharge Landscapes, we found that annual recharge rates largely varied according to mean annual precipitation, whereas recharge ratio estimates increase with increasing monthly variability in P-PET. However, we were unable to explain why ground-based estimates of recharge signatures vary across other Recharge Landscapes, in which there are fewer ground-based recharge estimates, using global datasets alone. Even in dryland regions, there is still considerable unexplained variability in the estimates of annual recharge and recharge ratio, stressing the limitations of global datasets for investigating ground-based information.

Keywords: Groundwater recharge, Africa, recharge controls, ground-based estimates, landscapes, comparative hydrology

1 Introduction

With an estimated storage of 0.66 million km^3, groundwater is the largest store of freshwater in Africa, exceeding annual volumes of streamflow by a factor of 100, and its development is fundamental for securing current and future water supply (MacDonald et al., 2012). Understandably it is often regarded as important for both urban (Foster et al. 2020; Oiro et al. 2020) and rural (Calow et al. 1997; Lapworth et al. 2013; MacDonald and Calow 2009)communities, though quantifying its role in water supply remains challenging for many parts of the continent (Chávez García Silva et al. 2020). In Northern Africa, groundwater irrigation practices (Siebert et al. 2010) have potentially led to the depletion of groundwater resources (Aeschbach-Hertig and Gleeson 2012; Rodell et al. 2018). In contrast, groundwater use in sub-Saharan Africa is primarily for domestic supply and sanitation services (Braune and Xu 2010) and is potentially being under-utilized for crop production (Giordano 2006; Siebert et al. 2010). In dryland river basins, securing water supply from surface water is challenging due to the high inter-annual variability of streamflow and persistent dry periods

(Conway et al. 2009; Siam and Eltahir 2017; Sidibe et al. 2019). Therefore increasing groundwater abstraction for more conjunctive use of surface water and groundwater could reduce vulnerability to climate driven surface water shortages, particularly in rural communities (Calow et al., 1997; Lapworth et al., 2013; MacDonald & Calow, 2009) and generally improve water accessibility (Robins et al., 2006). In the future, rapid population growth (Gerland et al. 2014; Parnell and Walawege 2011) and climate change could further enhance the value of African groundwater resources (Taylor et al. 2013).

Yet, our understanding of the spatial variability of groundwater recharge processes across Africa remains limited, constraining our ability to plan for the sustainable use of this resource (MacDonald et al., 2021), though recharge rates should not be regarded as a safe-yield for groundwater use (Aeschbach-Hertig and Gleeson 2012). Recent studies have tried to overcome this problem in multiple ways: [1] Scaling up knowledge from a limited number of detailed local studies. Cuthbert *et al.* (2019b) used multi-decadal groundwater level timeseries in conjunction with local knowledge to develop site specific conceptual models which allowed the authors to highlight a relationship between climate and recharge frequency, sensitivity to precipitation and dominant recharge mechanisms. However, this approach relies heavily upon rare long-term data as well as local knowledge and therefore it is challenging to transfer findings to larger scales or different regions. [2] Recently, MacDonald et al. (2021) used 134 ground-based annual recharge estimates compiled from the literature along with global datasets to develop a continental statistical model. This model enabled them to estimate long-term groundwater recharge rates across Africa using mean annual precipitation without qualitative inclusion of different recharge processes. [3] Most studies have based their continental scale estimates on process-based models. Global scale hydrological models and land surface models can estimate groundwater recharge rates across large spatial domains (Reinecke et al. 2021). However, recharge outputs from these models have not yet been thoroughly evaluated (Bierkens, 2015; Telteu *et al.*, 2021; Wagener *et al.*, 2021). Furthermore, global models thus far only include a limited number of process representations and neglect regionally dominant controls which could be important for Africa, such as karst (Hartmann et al., 2015; Hartmann et al., 2014) or dryland-specific hydrological processes (Quichimbo et al. 2021). This is likely because most (if not all) available continental to global scale models available to estimate recharge have their origin from regions outside of Africa.

In this study we want to take a step back to review what dominant controls should be present in a model across Africa and investigate how well we can quanitfy these process controls given the available data. In doing so, We specifically aim to answer three questions: (i) What are the dominant controls on groundwater recharge already identified across Africa in previous studies? (ii) Using global datasets only, what descriptors of controlling processes can we define, and which regions of Africa should have similar recharge controls when clustered using these descriptors? (iii) How do these regions for which we expect similar controls compare to ground-based recharge observations? Due to the limited amount of ground-based data on groundwater recharge in Africa, we adopt an approach which builds strongly on our a priori understanding of recharge controls in Africa identified from the literature. In doing so we build on previous efforts by Scanlon et al. (2006) who synthesized qualitative local knowledge of recharge processes for the world's dry regions. In keeping with the database compiled by (MacDonald et al., 2021), we only review the controls on recharge which is distributed throughout the landscape. MacDonald et al. (2021) define distributed recharge as both diffuse and focussed recharge but exclude focussed recharge from large discrete features such as rivers or lakes. Where focussed recharge is widely distributed through ephemeral rivers, depressions or rock fractures which are common over a large area and contribute to regional recharge, they include this in their definition of distributed recharge which we use. We follow the ideas of Winter's concept of hydrological landscapes (Winter 2001) and define Recharge Landscape Units to represent areas for which we expect similar recharge controls. We then compare these areas against an openly available, comprehensive and thoroughly quality assured dataset of ground-based recharge estimates in Africa, recently published by MacDonald et al. (2021). Although we use their database in our analysis, this work has some key differences to the previous work by MacDonald et al. (2021). Firstly, we attempt to explicitly link our analysis to both the qualitative (understanding of recharge controls) and quantitative (i.e., ground-based recharge estimates) findings in the literature, whereas MacDonald et al. (2021) only investigate the quantitative data. Furthermore, our classification approach allows us to explore whether relationships between environmental controls and recharge signatures vary between different environmental settings. In contrast, the statistical approach taken by MacDonald et al. (2021) only allowed them to investigate relationships which applied to the whole continent. Finally, we investigate both long-term mean annual recharge rates of groundwater recharge and recharge ratios. This allows us to understand how different recharge signatures vary and interact in space, furthering our understanding of groundwater recharge beyond just looking at annual rates.

2. Review of process controls on groundwater recharge across Africa

Most of the existing knowledge base on groundwater recharge processes, controls and rates in Africa comes from a relatively small number of case studies investigating recharge at the field, catchment, or sometimes regional scale. These studies use a wide range of methods to understand recharge processes throughout the continent, with approaches often varying according to environmental setting, data availability and the objective of the individual studies (MacDonald et al. 2021). Details of the strengths and weaknesses of the different methods can be found in Scanlon et al. (2002) and Healy (2010). We organize the review of controls into four domains: climate and weather, topography, landcover/use, and soils and geology. The aim of this review is firstly to identify dominant controls on groundwater recharge, and secondly to understand whether these controls have clear positive or negative relationships with groundwater recharge, or if their relationship with recharge is ambiguous. We are considering processes that govern the potential recharge of an aquifer, which can be more than the actual recharge due to interflow processes or if the potential recharge rate is so large that it exceeds the rate at which water can flow laterally through the aquifer (Theis 1940). In the latter case, the aquifer can become over-full such that available recharge is rejected. We show a summary of this review in Figure 1. An extended version of the review can be found in the supplemental information.

Climate and weather

Annual scale components of the water-energy balance are a first order control on the spatial variability of groundwater recharge (Kim and Jackson, 2012; Mohan *et al.*, 2018; Cuthbert *et al.*, 2019b; MacDonald *et al.*, 2021), as they control the quantity of water available to be partitioned into groundwater recharge, as well as the energy available to partially control atmospheric losses (Budyko, 1974). Hence studies in Africa show variability of annual recharge rates along a climate gradient, largely defined by precipitation due to the generally high levels of energy available (MacDonald et al. 2021). In an upland catchment of Cameroon where rainfall exceeds 3000 mm/year, estimated recharge rates exceed 900 mm/year (Kamtchueng et al. 2015), in comparison to recharge rates between 160 mm/year and 330 mm/year in the Ethiopian Highlands where annual rainfall is approximately 1300 mm/year (Azagegn et al. 2015; Banks et al. 2021; Demlie 2015). Groundwater resources throughout the deserts, which receive very little annual rainfall (Nicholson 2000), are recharged at rates below 5 mm/year (Foster et al., 1982; Dabous and Osmond, 2001; Zouari et al., 2011), or may not even be actively recharged (Befus et al. 2017). In these regions deep ‘fossil’ groundwaters recharged prior to the Holocene dominate aquifer stores (Sturchio et al., 2004; Guendouz et al., 2006; Abotalib et al., 2016; Jasechko et al., 2017).

Groundwater recharge volumes are often biased towards the rainy season as elevated rainfall is required to overcome high rates of evapotranspiration (Bromley *et al.*, 1997; Demlie *et al.*, 2007; Walraevens *et al.*, 2009; Mechal et al., 2015), and greater monthly and daily precipitation intensity leads to a more efficient conversion of rainfall to recharge (Jasechko and Taylor 2015; Owor et al. 2009; Taylor and Howard 1996). Groundwater level observations in the Makutapora wellfield, Tanzania, suggest that recharge is dependent upon months with the most extreme (> 95^{th} percentile) rainfall (Taylor, Todd, et al. 2013) often enhanced by the El Nino Southern Oscillation and the Indian Ocean Dipole. However, the multiple climate oscillations known to affect climate patterns in Africa (Brown et al., 2010) can have opposing effects in different parts of the continent (Nicholson and Kim 1997). Nonetheless, wetting and drying cycles are being reflected in observed groundwater hydrographs throughout Africa (Taylor *et al.*, 2013; Cuthbert *et al.*, 2019b; Kolusu *et al.*, 2019), showing both seasonally extreme recharge events as well as recharge events which are more episodic in nature.

Episodic rainfall events are particularly important in arid landscapes where recharge often depends upon a small number of days of intense rainfall (Vogel and Van Urk, 1975; Mazor *et al.*, 1977; Van Tonder and Kirchner, 1990; Nkotagu, 1996; De Vries et al., 2000; Xu and Beekman, 2003; Wanke et al., 2008). Döll and Fiedler (2008) stressed the importance of heavy rainfall events in semi-arid and arid regions as they modelled groundwater recharge globally, applying a rainfall threshold of 10 mm/day to drylands, below which they assumed recharge would not occur. They identified this threshold via an independent analysis of 25 chloride profile estimates of annual recharge distributed throughout the world as well as regional model estimates of recharge in Death Valley, California.

In summary, annual and seasonal precipitation as well as heavy rainfall events have a positive relationship with groundwater recharge in Africa – largely driving inter- and intra-annual recharge variability, while the amount of energy available from radiation has a negative relationship with groundwater recharge. However, the influence of large-scale climate oscillations on groundwater recharge in Africa is less clear as their effect on climate patterns vary regionally.

Topography

Topographic slope controls the movement of water across the land surface and therefore controls water infiltration into the subsurface and groundwater recharge, with gentler slopes promoting more recharge than steeper slopes (Simmers 1990). The role of slope in controlling groundwater recharge has been discussed throughout many different regions of Africa, including Ethiopia (Gebreyohannes et al. 2013), Nigeria (Abdullateef et al. 2021; Fashae et al. 2014), Botswana (Lentswe and Molwalefhe 2020) and Algeria (Boufekane et al., 2020). Yet interestingly, McKenna and Sala (2018) found that recharge beneath flat playas in the south-western United States is greater when they are surrounded by steeper slopes which promote greater run-on onto the playa.

In dry regions, intense rainfall events are important drivers of focused recharge through flash flooding (Sultan et al. 2000) and the formation of ephemeral water bodies and depression storage (Lehner and Döll, 2004) , i.e. in areas where water accumulates on the land surface. In Africa's dry regions, alluvial aquifers underlying dry riverbeds are recharged episodically or perhaps seasonally by river transmission losses following heavy rainfall (Tantawi, El-Sayed and Awad, 1998; Sultan *et al.*, 2000; Gheith and Sultan, 2002; Benito *et al.*, 2010;

Walker et al., 2019; Seddon *et al.*, 2021). These storms can activate focused recharge mechanisms despite negligible diffuse recharge in interfluve regions due to high evaporation (Favreau et al. 2009). In endoreic arid basins, surface water can also accumulate in salt pans which typically occupy topographic depressions (Lehner and Döll 2004). (De Vries et al., 2000) use chloride profiles to show that in the eastern fringes of the Kalahari Desert, recharge is enhanced under these pans, with estimated annual rates of 50mm in comparison to 7mm for the surrounding landscape.

Therefore, slope generally has a negative relationship with groundwater recharge since it will provide an easier flow path for water to move downhill, whereas topographic depressions have a positive relationship with (focused) groundwater recharge because they allow water to accumulate.

Landcover/use

Landcover and use varies considerably across the African continent. Bare soils (33% of Africa's land area) occupy most of northern Africa as well as parts of southern and eastern Africa, whilst grasslands (15.4%), shrublands (13.4%) and agriculture (11.6%) are largely distributed throughout the Sahel and Southern and Eastern Africa, and forests and woodland (26%) spread across western, central and south-eastern regions (Mayaux *et al.*, 2004; Tsendbazar et al., 2017; Xiong *et al.*, 2017). These vegetation patterns influence the spatial variability of groundwater recharge (Kim and Jackson 2012) through their control over transpiration, interception and soil evaporation fluxes (Gordon *et al.*, 2005; Schlesinger and Jasechko, 2014; Good et al., 2015).

An estimated 7% of the continent's precipitation returns to the atmosphere via interception evaporation, mostly occurring in the densely forested regions of Central Africa where this flux can exceed 10% of the precipitation input (Miralles et al. 2010; Zhang et al. 2016; Zheng et al. 2017). Globally, we could not find any studies directly discussing the relationship between rainfall interception and groundwater recharge. However, it seems reasonable to assume that by limiting the amount of precipitation reaching the land surface, interception consequently reduces groundwater recharge.

An estimated 49% and 21% of precipitation over Africa returns to the atmosphere via transpiration and bare soil evaporation, respectively (Zhang et al. 2016). The bulk of continental transpiration is associated with the tropical forests (Gordon *et al.*, 2005; Good et al., 2015), where tall vegetation with deep rooting systems increases the capacity of root-zone moisture storage (Nijzink et al. 2016) and the access to deeper groundwater (Barbeta and Peñuelas 2017). When investigating groundwater recharge at regional and catchment scales, studies often find that recharge rates are lower in areas which are forested than in areas which are unforested or have bare soils (Gebreyohannes et al. 2013; Houston 1982; Howard and Karundu 1992; Stone and Edmunds 2012). Furthermore, the presence of woodland or forest can restrict groundwater recharge to years of particularly high rainfall, even when recharge in grass, crop or unvegetated parts of the catchment occurs annually (Houston 1982; Howard and Karundu 1992). In the Kalahari Desert, dense bush and tree savannah is believed to transpire much of the annual rainfall during the long dry season, leading to very little recharge (De Vries et al., 2000; Sibanda et al., 2009). Similarly, chloride profiles in Senegal, suggest that groundwater recharge rates decline as vegetation density increases (Edmunds and Gaye 1994). Land clearing, often for agricultural expansion, can also enhance groundwater recharge rates by reducing evapotranspiration (Taylor and Howard 1996; Været et al. 2009).

Land clearing for agriculture does not only affect recharge through changes to evapotranspiration, it can also alter the mechanisms through which recharge occurs, by altering soil surface properties (Wirmvem et al. 2015) as well as runoff run-on processes

(Leduc et al., 2001; Leblanc *et al.*, 2008; Favreau *et al.*, 2009; Ibrahim *et al.*, 2014; Wirmvem *et al.*, 2015). Agricultural land adjacent to many of Africa's largest lakes and rivers is regularly equipped for irrigation (Siebert et al. 2015). Excess irrigation water can infiltrate into the soil and percolate to the aquifer, increasing groundwater recharge rates (Bouimouass et al. 2020; Scanlon et al. 2007). Nonetheless, as irrigation technologies become more efficient, recharge via irrigation excesses is expected to decline (Scanlon et al. 2007).

Urban settings only account for less than 0.01% of the African landscape (Zhou et al. 2015). Although, urbanisation is typically perceived as reducing groundwater recharge by reducing the permeable surface area, recharge rates in urban areas can be as high as or even higher than nearby rural areas (Lerner 2002; Sharp 2010). Urbanization can dampen existing recharge mechanisms, but it can also introduce new mechanisms such as localised recharge where there is little drainage infrastructure (Lerner 2002; Sharp 2010), as well as leakages from on-site sanitation (Foster et al., 1999; Diouf, 2012; Lapworth *et al.*, 2017) and piped distribution networks if such water supply is available.

In short, we find that the transpiration and canopy storage controls of different landcovers show a negative relationship with groundwater recharge, whereas the additional supply of water to agricultural land through irrigation has a positive relationship with recharge. Effects of urbanisation on groundwater recharge on the other hand are more ambiguous.

Soils and Geology

Soils with larger sand fractions are more permeable and support higher recharge rates than finer clay soils. In a global scale meta-analysis of recharge estimates, Kim and Jackson (2012) show that on average sandy soils are 50% more efficient in converting water input into groundwater recharge. Similar results are found at regional and catchment scales in Senegal, Sudan and Zimbabwe, whereby higher recharge rates are estimated in areas where the sand fraction is a more dominant component of the soil (Abdalla 2009; Butterworth et al. 1999; Edmunds and Gaye 1994). Lower recharge rates are found in clayey soils as the vertical percolation of water through the soil profile is restricted (Attandoh et al. 2013; Edmunds et al. 1992) and soil moisture is more exposed to evapotranspiration (Mensah et al, 2014; Yidana and Koffie, 2014; Kotchoni et al., 2018).

However, soil texture alone fails to recognise structural soil properties which enable infiltration via preferential flow paths which bypass the soil matrix (Beven and Germann 1982). Macropores in the soil structure allow infiltration to bypass vegetation rooting zones and impermeable soil layers (De Vries et al., 2000; Mazor, 1982; Van Tonder & Kirchner, 1990; Xu & Beekman, 2003) and facilitate recharge in conditions which would otherwise be prohibitive. These preferential flow paths are an important mechanism for groundwater recharge across a range of contrasting environmental settings. In the Botswanan Kalahari Desert, semi-arid Tanzania and the tropical highlands of Ethiopia, the contribution of preferential flows to groundwater recharge is approximately 24%, 60% and 36%, respectively (Demlie et al. 2007; Nkotagu 1996; de Vries and Gieske 1990).

Rock fracturing (Nkotagu, 1996; Xu and Beekman, 2003; Adams et al., 2004; Kebede *et al.*, 2005; Kamtchueng *et al.*, 2015) and vertical conduits in karstic rock (Farid *et al.*, 2014; Hartmann *et al.*, 2014, 2017; Chemseddine et al., 2015; Ayadi *et al.*, 2018; Leketa *et al.*, 2019) also provide preferential flow paths for groundwater recharge. In dry landscapes such as the Kalahari Desert, rock fracturing at bedrock outcrops and isolated rock formations called inselbergs (Burke 2003) can locally enhance groundwater rates (Mazor, 1982; Butterworth *et al.*, 1999; Brunner *et al.*, 2004; Wanke et al., 2008). The distribution and geometry of the superficial geology can also have a marked impact on recharge pathways and rates in conjunction with the underlying bedrock and distribution of stream networks (Zarate et al. 2021). Similar observations have been made regarding focused recharge opportunities for water in karstic regions (Hartmann et al. 2017).

Soil perturbations such as crusting, cementation, compaction, weathering, and tillage can also have a significant impact on recharge rates. Whilst studies mostly find that soil crusting (Favreau et al. 2009; Jacks and Traoré 2014; Wakindiki and Ben-Hur 2002), cementation (Nash et al., 1994; De Vries et al., 2000; Xu and Beekman, 2003; Francis *et al.*, 2007) and compaction (Hamza and Anderson, 2005; du Toit et al., 2009) reduce the permeability of soil layers and hence reduce groundwater recharge, the effects of deeply weathered soils known as laterites (Bromley *et al.*, 1997; Rueedi *et al.*, 2005; Cuthbert and Tindimugaya, 2010; Bonsor et al., 2014) and agricultural tilling practices (Abu-Hamdeh, 2004; Osunbitan et al., 2005; Spaan et al., 2005; Strudley et al., 2008; Thierfelder and Wall, 2009; Abidela Hussein *et al.*, 2019) on recharge are much less clear.

Therefore, in summation we find that, soil grain sizes, bedrock outcrops and properties which promote preferential flow paths, such as soil macropores, rock fractures and karst geology, have a positive relationship with groundwater recharge. Some soil perturbations such as compaction, cementation and crusting have a negative relationship with groundwater recharge, whereas others, including tilling and soil laterization, have a less clear relationship with recharge.

Interactions between controls

Up to now we have largely looked at landscape properties and their control over recharge processes independently, in reality, groundwater recharge is a function of the interactions between these controls. Hence at the continental scale, we would typically expect to find some of the lowest recharge rates in areas with the most freely draining soils, as these regions also have the lowest precipitation volumes. By identifying patterns in the landscape, i.e.

climate, topography, vegetation, soils and geology, we can begin to conceptualise recharge processes of different environmental settings found in Africa. We can find these patterns as landscapes are continuously co-evolving (Troch et al. 2013) via an array of physical and biological processes which effect the uplift and deformation of bedrock and the erosion, transportation and deposition of sediments (Dietrich and Perron 2006; Reinhardt et al. 2010). This co-evolution, explains why we typically expect to find certain landscapes throughout the continent, including rainforests, tropical woodlands and savannas and deserts.

We often regard climate as an external force driving the hydrological system, but it also controls the spatial and temporal patterns of landcover (Zhou et al., 2014; Hawinkel et al., 2016; Bouvet et al., 2018; Measho et al., 2019; Ndehedehe et al., 2019) and soils (Jenny 1941; Towett et al. 2015). Climate and vegetation patterns as well as soil properties are also strongly affected by local topography. In mountainous areas we see vegetation becoming shorter and less dense above the treeline, as temperatures decline and thinning soils make ground conditions less stable (Harsch et al., 2009; Egli and Poulenard, 2016). Increased precipitation and runoff due to orographic forcing as well as steeper slopes, promote more active erosion and sediment transport fluxes at elevation and therefore prevents the accumulation of soils (Acosta et al. 2015). In contrast, at lower elevations, vegetation can assist the accumulation of soils by reducing surface water erosion and promoting infiltration (Acosta et al. 2015; Descheemaeker et al. 2006; Descroix et al. 2009; Thompson et al. 2010). In water limited regions, vegetation density often increases in topographic depressions such as ephemeral streams, as accessibility to groundwater may be locally improved (Morin et al., 2009; Steward et al., 2012; Ndehedehe et al., 2019; Grodek et al., 2020).

Summary

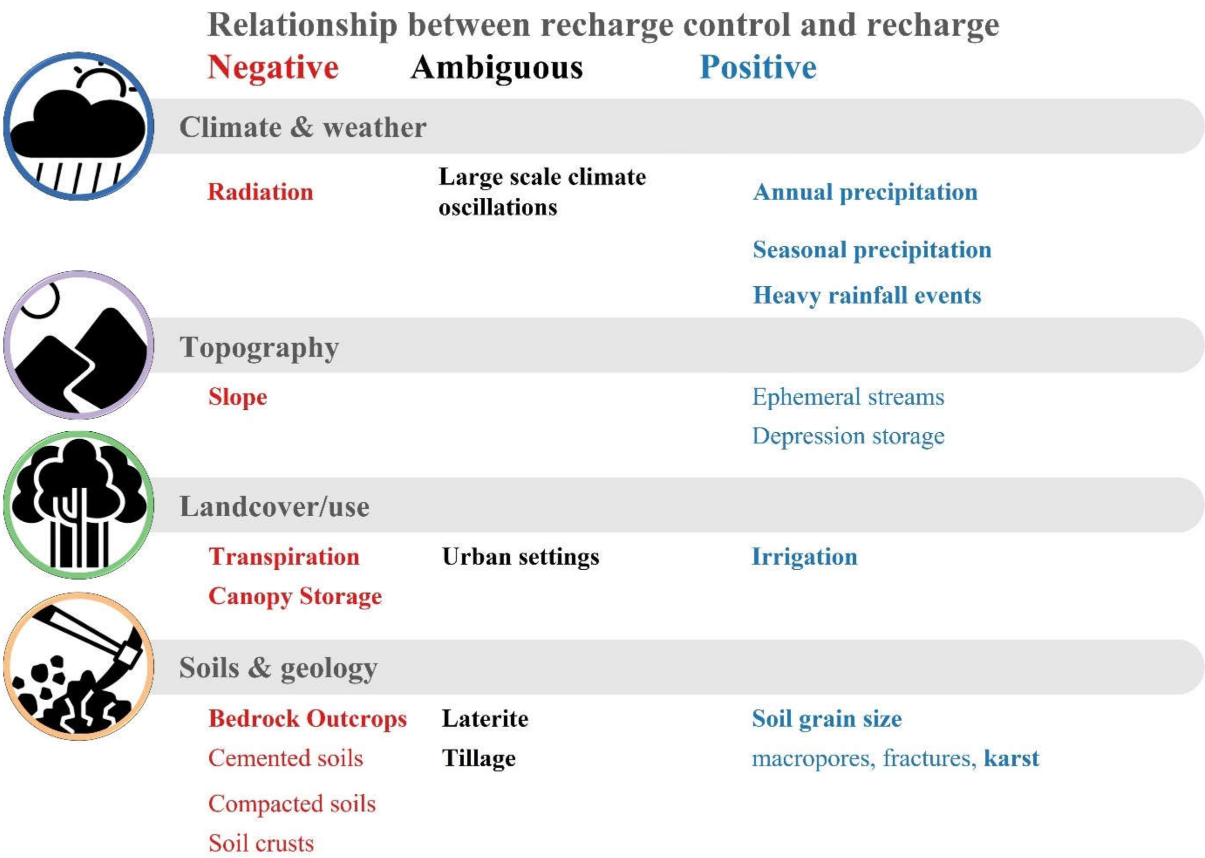

Figure 1. Summary of groundwater recharge controls for Africa identified in the literature. Controls are colour coded according to their relationship with recharge with red and blue representing negative and positive relationships, respectively. Bold font highlights controls which we can characterise using global datasets.

3. Materials and methods

To consolidate our understanding of groundwater recharge controls taken from reviewing the literature, we take a classification approach which we can then use as a tool to investigate why ground-based estimates of groundwater recharge vary spatially across the continent. We acknowledge their will be uncertainty in the classification due to the limitations of our own understanding and of global datasets. However, we aim to connect the qualitative and quantitative information obtained from local/regional findings to large scale regionalization approaches.

3.1 Global Datasets

We used nine global datasets to characterize the previously identified groundwater recharge controls. Furthermore, controls were only integrated into our classification if the literature indicated it had a clear positive or negative relationship with groundwater recharge and it could be characterized using global datasets. The datasets used and the indices calculated are summarized in Table 1.

Indices describing annual and seasonal climate attributes mostly characterise first-order estimates of the water potentially available for groundwater recharge (P-PET) annually and seasonally as well as its variability. This also builds on previous work by Wolock et al. (2004) who used P-PET as the climatic index to delineate hydrological landscapes in the United States. We characterised heavy rainfall across Africa using a threshold of 10 mm/day. Several studies in Africa (Döll and Fiedler 2008; Owor et al. 2009; Taylor and Howard 1996) have found annual recharge has a stronger correlation with the average volume of rainfall per year on days with at least 10 mm of rain, than with mean annual precipitation and hence we selected this as threshold for heavy rainfall in Africa. Though we acknowledge the rainfall threshold for recharge occurrence likely varies across the continent. We characterized the influence of landcover on groundwater recharge via transpiration and canopy storage processes, by attributing vegetation specific transpiration coefficients to a landcover dataset and by looking at the Leaf Area Index, respectively. This approach is also often taken when parameterizing these processes in continental scale hydrological modelling (Telteu *et al.*, 2021). To avoid having multiple indices to describe soil textures we instead calculated the ratio of soils which promote infiltration (i.e., sand) to those which restrict infiltration (i.e., silt and clay) (Saxton *et al.*, 1986; Wösten et al., 2001). We used the depth to bedrock dataset of (Pelletier et al. 2016) to highlight bedrock outcrop regions and the world map of carbonate rock outcrops (Williams and Ford 2006) to highlight the extent of carbonate rock outcrops.

Table 1. Details of the recharge control indices we defined to characterise recharge controls across Africa and the global datasets we used to calculate them.

Attribute	Description	Units	Period	Data source	Reference
Climate attributes					
P-PET	Mean annual precipitation minus mean annual PET.	mm/year	1979-2015	1. MSWEP v1.2 (Precipitation) Spatial res.: 0.25° Temporal res.: Daily 2. CRU v4 (PET) Spatial res.: 0.5° Temporal res.: Monthly	1. (Beck et al. 2017) 2. (Harris et al., 2020)
P-PET in season	Mean annual volume of precipitation in excess to PET in months considered in-season. A month is considered in-season when P exceeds PET.	mm/year	1979-2015		
σ(P-PET)	The standard deviation of monthly P-PET	mm/month	1979-2015		
P10	The average volume of rainfall per year on days with at least 10 mm of rain.	mm/year	1979-2015		
Topography attributes					
Slope	Geodesic slope of the DEM using a 3 by 3 moving window.	Degrees	-(Lehner, Verdin, and Jarvis 2013)	HydroSHEDS Spatial res.: 15 arc seconds	(Lehner et al., 2013)
Landcover/use					
Kveg	Vegetation coefficient related to transpiration. Vegetation-specific annual values (L. J. Gordon et al. 2005) applied to a landcover classification. Mean value from 1992-2005.	-	1992-2015	ESA-CCI v2.0.7 Spatial res.: 300m Temporal res.: Yearly	(Defourny et al. 2017)
LAI	Mean leaf area index (based on 12 monthly means from 1981-2015)	-	1981-2015	GIMMS-LAI3g v2 Spatial res.: 0.25° Temporal res.: Monthly	(Mao and Yan. 2019)
Irrigation	Area equipped for irrigation multiplied by the fractional area actually irrigated.	km^2	2005	Global Map of Irrigation Areas Spatial res.: 5 arc minutes	(Siebert et al., 2013)
Soil attributes					
Sand / (Clay + Silt)	The ratio of sand (>0.05mm) to silt (0.002-0.05mm) and clay (<0.002mm) in the fine earth fraction of the top 2m of the	-	-	SoilGrids250m Spatial res.: 250m	(Hengl et al. 2017)

	soil profile. Proportions of each soil texture are by weight. Take the depth weighted harmonic mean across intervals of 0-5cm, 5-15cm, 15-30cm, 30cm-60cm, 60-100cm, 100-200cm.				
Geology attributes					
Depth to bedrock	Average soil and sedimentary deposit thickness. Maximum of 50m.	m	-	Gridded Thickness of Soil, Regolith and Sedimentary Deposit Layers Spatial res.: 30 arc seconds	(Pelletier et al. 2016)
Karst	Extent of carbonate rock outcrop areas.	-	-	World Map of Carbonate Rock Outcrops V3.0	(Williams and Ford 2006)

3.2 Ground-based annual recharge and recharge ratio estimates

We used the database compiled by MacDonald et al. (2021) of long-term mean annual recharge estimates compiled from case studies in the literature. We selected this database above other meta-datasets (Moeck et al. 2020; Mohan et al. 2018) because of its focus on Africa, the thorough quality assurance conducted throughout its compilation, and the additional meta-data provided, such as recharge estimate uncertainty ranges. Through quality assurance steps, MacDonald et al. (2021) removed 182 datapoints (from an initial 316), due to duplicative studies in the same location and findings which were solely dependent upon hydrological modelling. Additional screening removed data points where the site co-ordinates and date of the study period were not provided. Finally, we removed estimates dated prior to 1979 or after 2015, as they would not correspond to the timing of the climate datasets we used. Ultimately, we were left with 129 ground-based estimates of annual groundwater recharge distributed across Africa. 111 of these sites/studies also reported corresponding mean annual precipitation rates, so we could estimate long-term mean recharge ratios at these locations (Figure 2). Spatially, 31 of these estimates reflect recharge rates over spatial scales less than 100 km^2, a further 41, 29, and 28 are for spatial scales of 100-2500 km^2, 2500-62500 km^2 and greater than 62500 km^2, respectively.

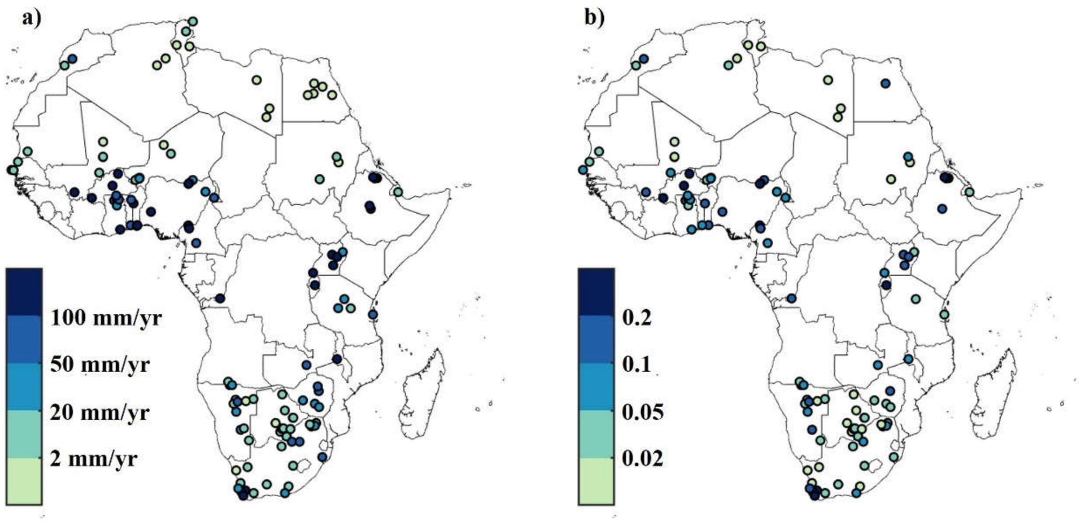

Figure 2. The remaining annual recharge and recharge ratio estimates collected from case studies in the literature by MacDonald et al. (2021), after initial screening of the data. The recharge ratio is defined as the fraction of precipitation being converted to recharge (recharge / precipitation).

3.3 Clustering

To delineate regions with expected similar recharge control indices (i.e., Recharge Landscape Units) we use a fuzzy c-means clustering algorithm (Bezdec 1981). This fuzzy clustering algorithm allows for pixels to belong to multiple units simultaneously, albeit with varying degrees of membership, thus enabling us to study the gradual transition between units (e.g., reflecting different landscapes). The degree of overlap in membership allowed us to determine the uniqueness of each delineated Recharge Landscape Unit. The degree of membership is dependent upon how close in value each pixel's recharge control indices are to the centroid of each unit, which is regarded as being representative for a unit. Membership scores vary from 0 to 1, with 0 representing no similarity and 1 suggesting the pixel's recharge control indices are equal to the values of the unit's centroid. Further details on the algorithm and on application details are provided in the supplemental material. Ultimately, we attributed each pixel to the unit with which it has the highest degree of membership, which we refer to as its primary unit.

3.4 Random Forests

We used classification-based Random Forests to expand our classification for recharge controls in Africa to the rest of the world. Random Forests is a machine learning algorithm which combines multiple trees to produce an ensemble of predictions (Breiman 2001; Breiman et al. 1984), which link predictor variables (recharge control indices) to a response (Recharge Landscape Units). Each individual tree develops rules for predicting responses which are structured as a binary decision tree composing of nodes and branches. At each node a conditional binary split is applied to one of the predictor variables. The split forms two branches which link to nodes in the overlying stratum. This splitting continues until the terminal node (the leaf) is met and the outcome is predicted. Each classification tree in the ensemble model is trained on observations (Pixels of classification for recharge controls in Africa) which were randomly selected with replacement from a sub-sample of 70% of the total observations ('in-bag' observations). The random forest model consists of 25 trees each with a maximum of 400 decision splits. Increasing the number of trees or decision splits did not significantly improve model performance. Addor et al., (2018) previously used Random Forests to predict observed streamflow signatures across the USA and Stein et al., (2021) used random forests to explore how climate and catchment attributes influence flood generating processes.

4 Results

4.1 Recharge Landscape Units outline regions with similar recharge controls in Africa

Based on our review in section 2, we defined and calculated 11 indices to characterise the different controls on distributed groundwater recharge we identified in our review (Figure 1). To avoid using redundant information for each control, we checked the correlations between each of the indices initially considered and removed indices such that none of the indices for a given control had Pearson correlation coefficients greater than or equal to 0.7 with one another (see supplemental information) (Dormann et al. 2013).

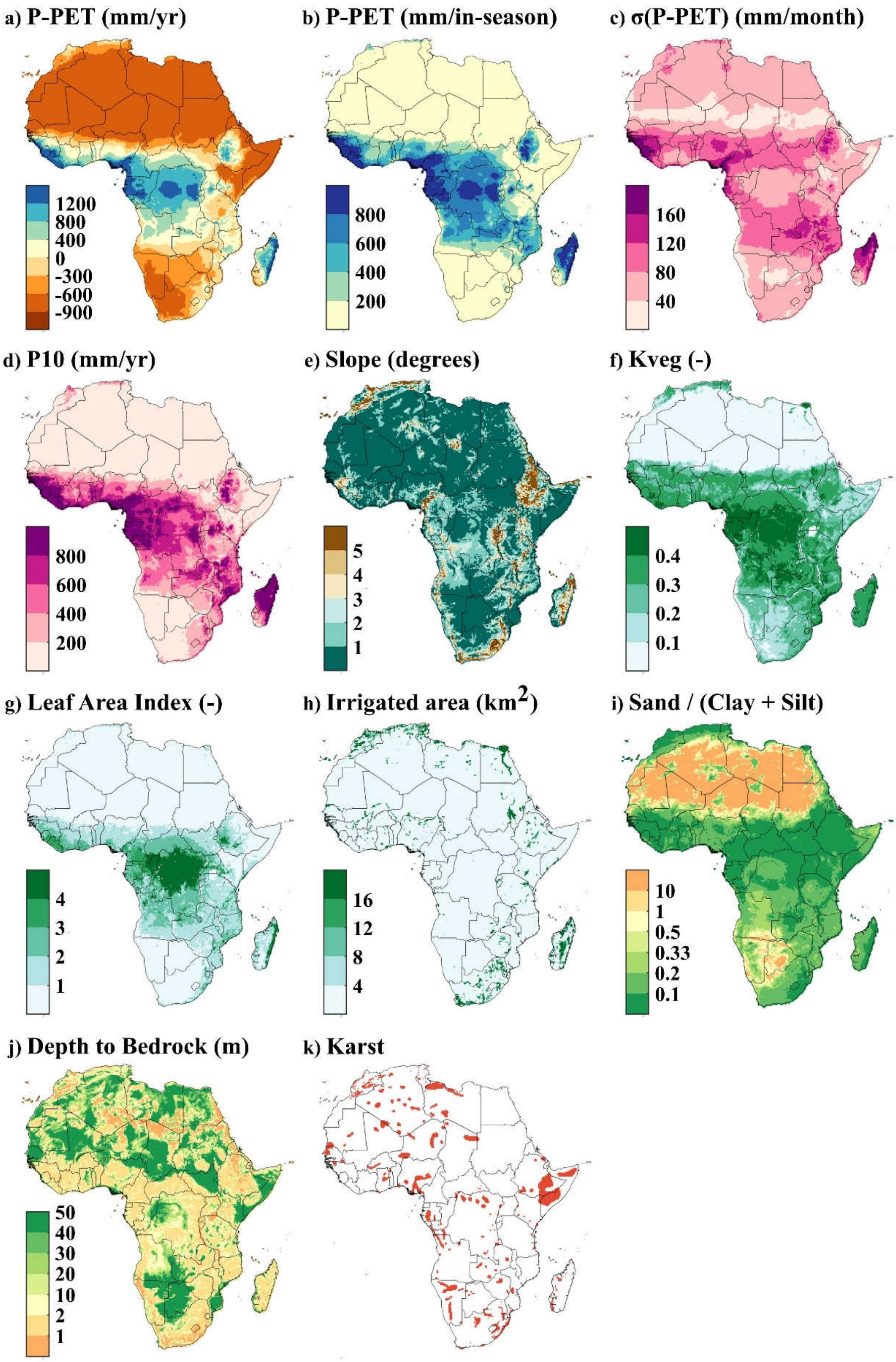

Figure 3. 11 recharge control indices characterising controls identified in the literature using global datasets. a) P-PET; b) P-PET in-season; c) σ(P-PET); d) P10; e) Slope; f) Kveg; e) Leaf Area Index; h) Irrigated area; i) Sand / (Clay + Silt); j) Depth to bedrock; k) Karst. The definitions of each index the datasets used for their characterisation are stated in Table 1.

The cluster analysis combines the 11 indices into 15 Recharge Landscape Units with similar recharge control indices of which 9 cover over 80% of the African land area (Figure 4). We initially identified 14 units using fuzzy clustering, as additional units did not greatly reduce the dissimilarity within individual units. The 15th unit which delineates potential karst regions was manually superimposed. Even though we expect recharge to vary significantly between the different settings in which karst is found, we delineate the group as a whole, because we expect the recharge mechanism associated to karst environments to be a dominant control on recharge processes. We can see the continent has been roughly organised into very dry regions in the north and south of the continent and wetter regions spanning from West Africa down through Central Africa towards Mozambique and Madagascar. Even though the spatial organisation of the units suggest proximity is a reasonable indicator for similarity, we do find regions with similar recharge control indices which are also far away from each other. For example, hyper arid regions with shallow soils can be found along Namibia's coastline as well as the coastlines of Egypt and Sudan and throughout the Sahara Desert (unit 5) and extremely wet regions can be found on the coast of West Africa and eastern Madagascar (unit 7). Likewise dry highland regions with high slope can be found in South Africa, the East African Rift, Ethiopian Highlands and in the Atlas Mountains (unit 4) and flat regions with thick soil profiles can be found throughout the Sahel, South Sudan and the Kalahari basin (unit 13). In contrast, we also find Recharge Landscape Units which appear to represent unique and spatially concentrated areas, such as the Congo Basin Rainforest (units 9 and 14), as well as regions where properties appear more diverse with multiple units appearing within smaller areas, such as Madagascar and Ethiopia.

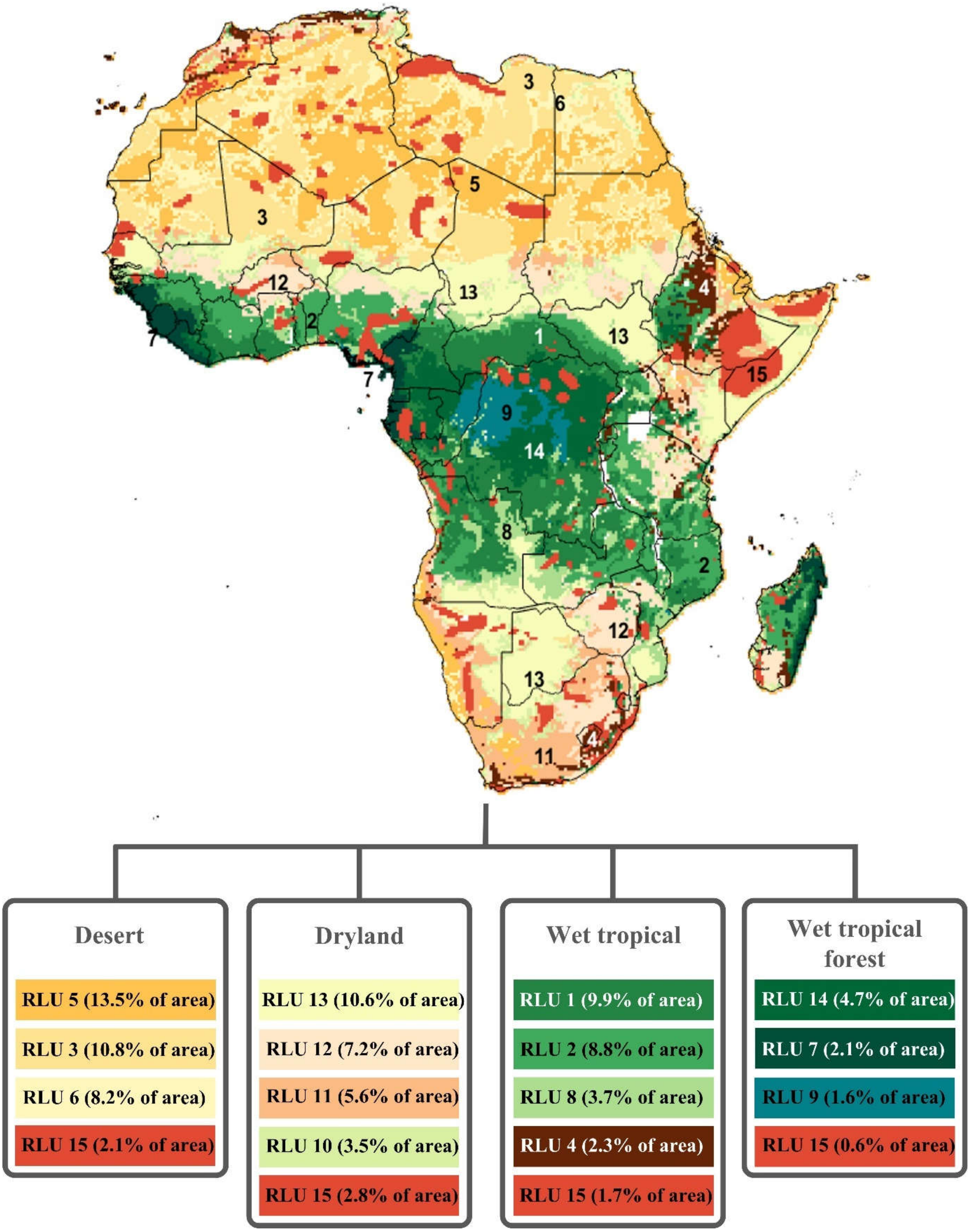

Figure 4. Map of the 15 Recharge Landscape Units of our classification for a priori understanding of recharge controls in Africa. We group the Recharge Landscape Units into broader groups of similar units which we call Recharge Landscapes.

We found that grouping Recharge Landscape Units into broader Recharge Landscapes suitably organises the African landscape into regions with noticeably different distributions of long-term average annual recharge and recharge ratio (Figure 6). Further disaggregation of the landscape did not allow us to explain any further variability in the ground-based estimates of recharge signatures when using global datasets. These broader Recharge Landscapes also aggregate Recharge Landscape Units with similar recharge control indices, as shown by the boxplots in Figure 5. For each index, boxplots are organized by the median values of each unit, ordered from left to right in descending order. In Dryland and Wet tropical Recharge Landscapes, we see that climate and weather, landcover and soil texture indices transition smoothly across all units. Units within Wet tropical forest Recharge Landscape are typically associated to high Kveg and Leaf Area index values and fine soil textures, whilst units of the Desert Recharge Landscape have low Kveg and Leaf Area values as well as predominantly sandy soils. Similarly, most units have similar topographic slopes except for unit 3, 4 and 13 which represent highland and flat plain regions. There is a clear divide in the depth of soils in each of the units, with six of the units showing deeper soil profiles and 8 showing a tendency towards shallow soils. We can see that unit 15 which represents karst regions occurs in a wide range of different climate, topographical, landcover and soil settings. Irrigated areas do not contribute to large areas of any of our Recharge Landscape Units.

Desert Recharge Landscapes could only be further differentiated by their depth to bedrock, while other landscape types were dis-aggregated by climate seasonality, slope, landcover and slope, as well as the depth to bedrock. Desert Recharge Landscape Units are differentiated according to where depth to bedrock is less than 13.5 m (unit 5), where the bedrock depth is between 13.5 m and 33.9 m (unit 6) and where the depth to bedrock is greater than 33.9 m (unit 3). This reflects differences in topography throughout Desert Recharge Landscapes, as mountainous Desert Recharge Landscapes with greater slopes also have smaller bedrock depths. Dryland Recharge Landscapes are also largely dis-aggregated according to the depth to bedrock, with unit 13 representing where bedrock depth is greater than 37m, unit 10 where bedrock depth is between 16.3m and 37m and units 11 and 12 where the bedrock depth is less than 16m.

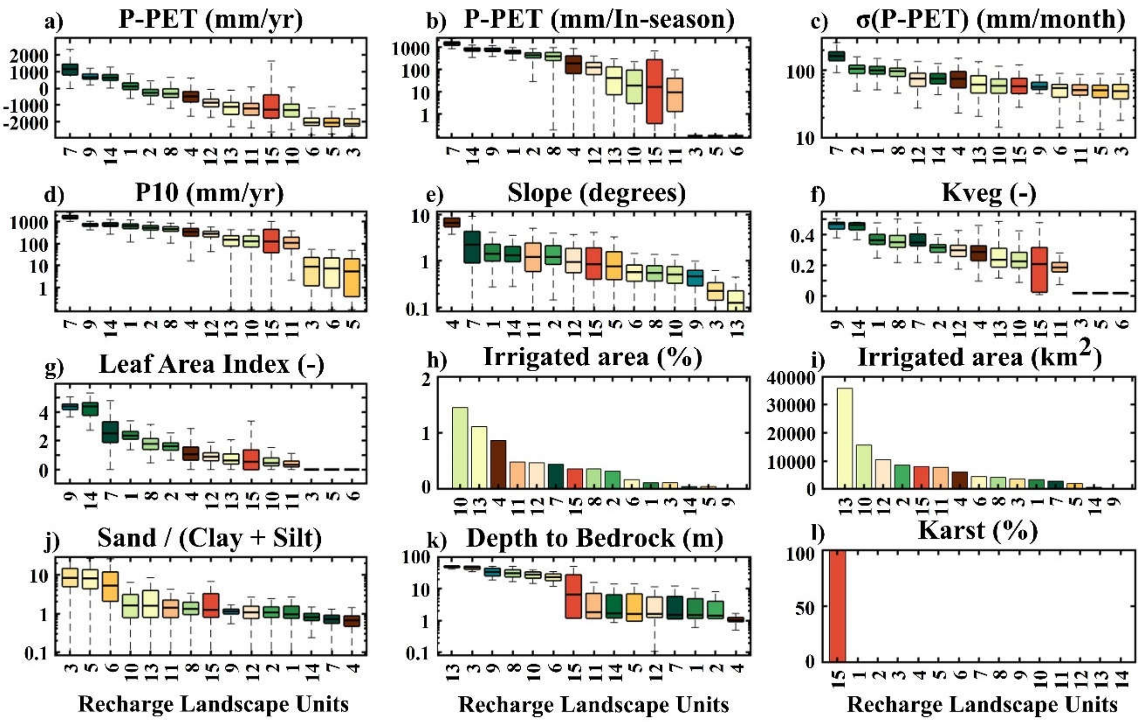

Figure 5. Boxplots showing the index values in each of the Recharge Landscape Units we identified. Boxplots are organised from left to right in descending order of the median values in each unit. We show irrigated area as both the total area irrigated within the Recharge Landscape Units (h) and as a percentage of the areas for each Recharge Landscape Unit (i).

Ground-based estimates of annual recharge (recharge ratio) are bias towards drier settings with 20 (15), 66 (58), 28 (25) and 3 (3) data points in Desert, Dryland, Wet tropical and Wet tropical forest Recharge Landscapes, respectively. Recharge Landscapes which have high annual recharge rates also have higher recharge ratios suggesting that as well as being generally wetter, they are more efficient in converting that rainfall into recharge (Figure 6). The variability of ground-based annual recharge estimates within Landscapes is greatest in wetter settings, as shown by standard deviations of 5.6 mm/year, 66.0 mm/year, 84.0 mm/year and 400.1 mm/year for Desert, Dryland, Wet tropical and Wet tropical forest Recharge Landscapes, respectively. The standard deviation between the mean annual recharge estimates of each Recharge Landscape is 217.2 mm/year in contrast to a standard deviation of 113.7 mm/year when looking across the whole dataset population. Similarly for ground-based estimates of recharge ratio, the standard deviations within Desert, Dryland, Wet tropical and Wet tropical forest Recharge Landscapes are, 0.033, 0.059, 0.070 and 0.092, respectively. Again, standard deviation between the mean recharge ratio estimates of each Recharge Landscape is greater than across the whole population, each being 0.079 and 0.072 respectively.

We also investigated the possible influence of the different groundwater recharge estimation methods to see whether this explained any of the variability in annual recharge and recharge ratio estimates within the individual spatial units (see supplemental information). However, in agreement with (MacDonald et al. 2021) we did not find a relationship between the estimation methods used and the recharge signatures. Additionally, one of the benefits of the database compiled by MacDonald et al. (2021) is that they provide uncertainty ranges for each of their ground-based estimates. Although figure 6 does not show these uncertainty ranges, we found that these uncertainty ranges were lowest for both annual recharge and recharge ratio in Desert Recharge Landscapes and were largest in Wet tropical and Wet tropical forest Recharge Landscapes (see supplemental). However, uncertainty ranges relative to the ground-based estimates were largest in Desert Recharge Landscapes and lowest in Wet tropical forest Recharge Landscapes. Below we discuss the larger Recharge Landscapes.

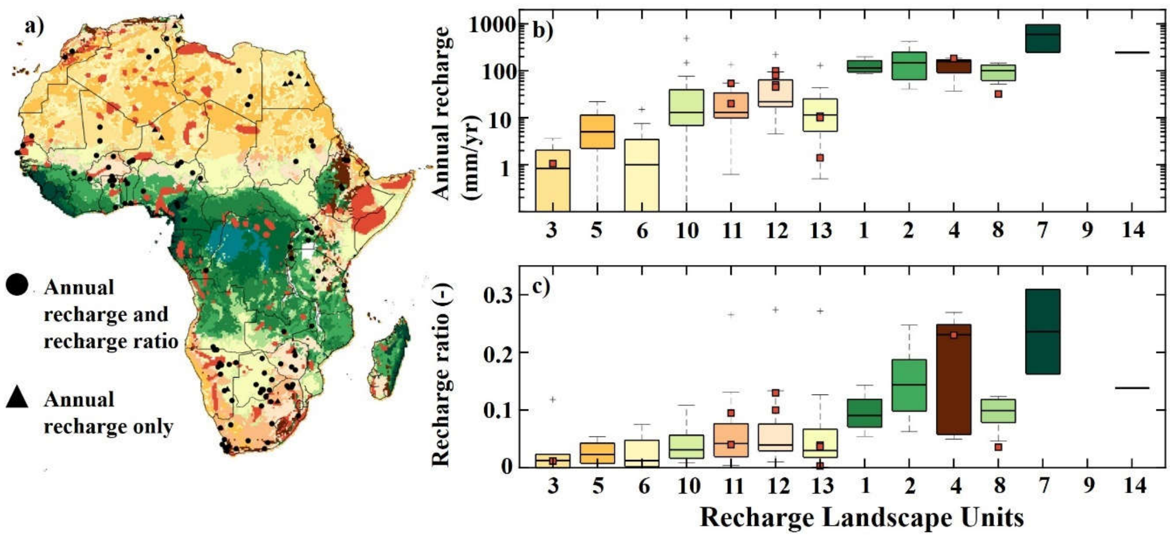

Figure 6. a) Map of ground-based estimate data points distributed across the Classification of recharge controls in Africa. Boxplots of the ground-based estimates of long-term mean annual recharge (b) and recharge ratio (c) found in each of the Recharge Landscape Units. No data points are located within Unit 9 and hence it is not shown. Only one data point is located within Unit 14. Unit 15 representing karst does not have its own boxplot. Instead, we have superimposed (red dots) these data points above the units which they would have otherwise been attributed to. For this plot we simply use the average ground-based estimates of annual recharge and recharge ratio at each data point and ignore the uncertainty ranges.

Desert (RLU 3, 5, 6)

Desert Recharge Landscapes are characterised by low moisture availability (P-PET), low vegetation cover (kveg) and very high sand content in its soils (Figure 5). These properties lead to the lowest annual recharge and recharge ratio estimates occurring in Africa, as 80% of annual recharge (recharge ratio) estimates in Desert Recharge Landscapes are below 5mm/year (4%). Low recharge ratios suggest that even when rain does fall, only a small fraction is converted to recharge, despite the sandy soils, owing to the very high potential evapotranspiration demand. In these regions evapotranspiration can draw on moisture from substantial depths which prohibits the downward flux of moisture towards to water table (Lehmann et al. 2019; Scanlon et al. 2006). We also find ground-based recharge estimates in Desert Recharge Landscapes show very little variability. Although we find marginally greater annual recharge rates and recharge ratios in unit 5, we cannot explain why, and differences may not be significant as there are only 20 data points across this region.

Dryland (10, 11, 12, 13)

About 51% of the 129 ground-based estimates are sited in Dryland Recharge Landscapes where water is generally only available for recharge seasonally (units 10, 11, 12 and 13). 70% of these sites have annual recharge rates between 3-30 mm/year and a further 18% of these sites have rates between 30-100 mm/year. Typically, in these regions less than 10% of rainfall is converted to recharge, with only 9 of the 58 sites recording higher recharge ratios. In this Recharge Landscape, we find that long-term estimates of annual recharge vary according to mean annual precipitation, whereas recharge ratios are greater at sites with greater monthly variability in P-PET (Figure 7).

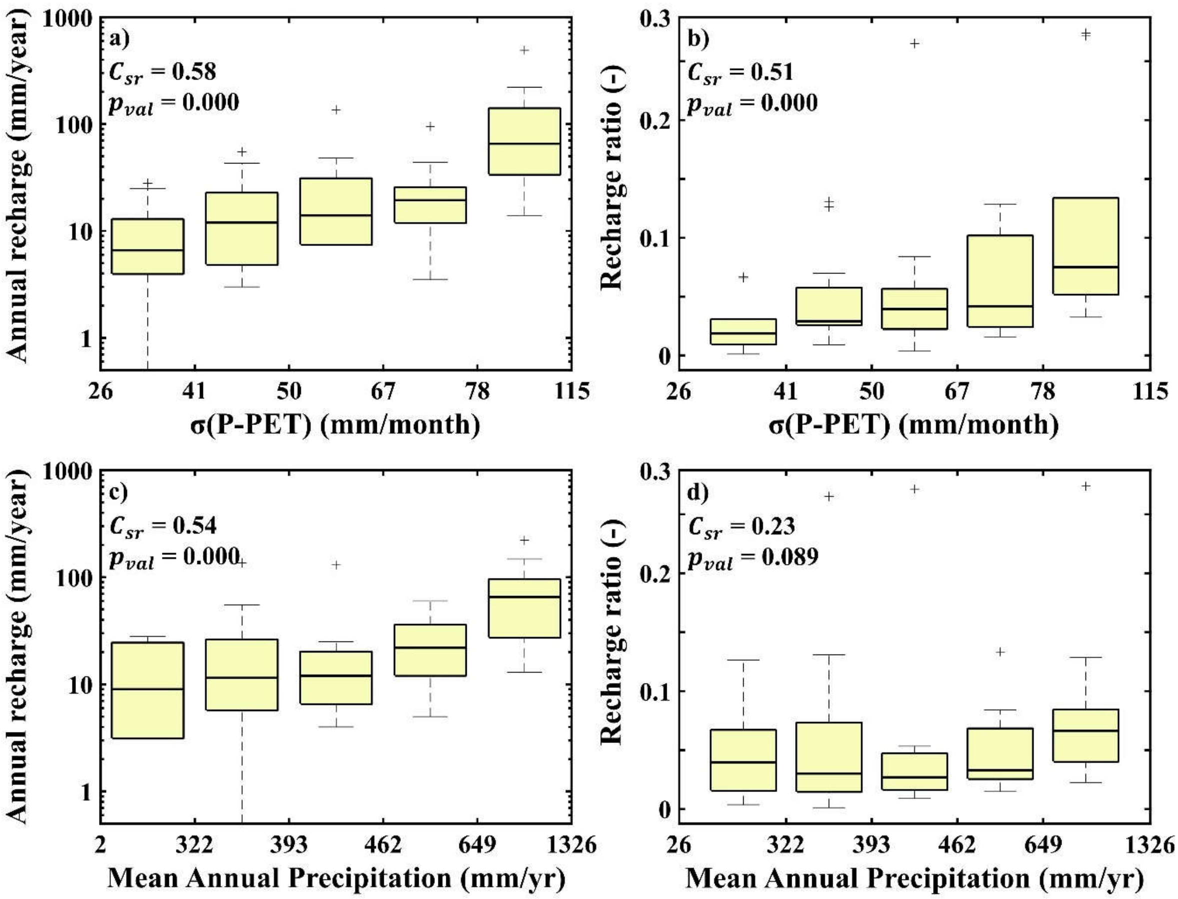

Figure 7. Boxplots showing how ground-based estimates of mean annual recharge (a, c) and recharge ratio (b, d) vary according to monthly variability of P-PET and Mean Annual Precipitation in Dryland Recharge Landscapes. Recharge signatures are binned according to percentiles (0-20; 20-40; 40-60; 60-80; 80-100) of the controlling variable. In the top left corner of each sub-plot, we show the spearman rank correlation and the p-value for testing the hypothesis of no correlation.

Wet tropical (1, 2, 4, 8)

18 (26) out of 28 annual recharge estimates in the Wet tropical landscapes (units 1, 2, 7, 8) exceed 100mm/year (50mm/year). These sites are also the more efficient in converting rainfall to recharge with 56% (92%) of them having recharge ratios greater than 10% (5%). The wetter conditions as well as seasonal periods of heavy monsoon rain allows deeper drainage, despite increased partitioning of rainfall at the land surface by vegetation, steeper terrain, and less permeable soils. Most of the variability between and within Wet tropical landscape units is attributed to differences in annual and seasonal scale water excess (P-PET) and heavy rainfall events (P10).

Differences in annual recharge and recharge ratio estimates of units 1 (median annual recharge 115mm/year; median recharge ratio 9%) and 2 (median annual recharge 148mm/year; median recharge ratio 14%) could be attributed to greater LAI and Kveg properties in unit 2. However, when comparing the properties of the individual sites we do not find this relationship. Highland areas (unit 4) show a particularly large variability in the fraction of precipitation being converted to recharge. This perhaps reflects the high degree of variability we can expect in highland regions depending upon landscape positioning.

Wet tropical forest (7, 9, 14)

These areas are characterised by the highest vegetation cover (LAI) and moisture availability (P-PET). We only have three ground-based estimates of annual recharge and recharge ratio within this Recharge Landscape: two in unit 7 and one in 14. The highest annual recharge estimate in our database is located in unit 7, with 31% of rainfall being converted to recharge to allow a rate of 941 mm/yr. Referring to existing literature, we find that in addition to high annual precipitation rates (3050 mm/yr) extensive bedrock fracturing near the land surface enables rapid infiltration and recharge (Kamtchueng et al. 2015).

Karst – present across the other Landscapes (15)

We do not find a clear pattern whereby the presence of karst at a site indicates higher annual recharge rates or recharge ratios than other sites within a similar setting (Figure 6). When investigating the individual studies, some studies reported karst despite not being identified as such by the global dataset, and vice versa Within settings defined as karst by global datasets, annual recharge rates and recharge ratios increase with increasing annual scale P-PET (see supplemental information).

5 Discussion

5.1 Which regions of Africa show similar recharge controls when clustered using descriptors derived from global datasets?

We find 15 Recharge Landscape Units within which we expect recharge processes to be similar, according to our clustering result. Only 9 Recharge Landscape Units are needed to characterize over 80% of the continent's land area. Although we initially wanted to investigate the potential membership of pixels to multiple Recharge Landscape Units, more than 80% of pixels have a membership greater than 0.8 to their primary unit (please see supplemental information). This is likely due to the high dimensionality of the dataset we are using in the cluster analysis. In light of this, and because we further aggregated our 14 (out of 15) Recharge Landscape Units into broader Recharge Landscapes (largely according to climate), we simply used the primary unit membership. The Recharge Landscapes we identify are Desert, Dryland, Wet tropical and Wet tropical forest, which account for 32.5%, 26.9%, 24.6% and 8.4% of Africa's land area respectively (total of 92.4%). An additional 7.25% of the continent's land area is defined by its geology (i.e. karst) and can be found distributed across each of the four previously mentioned Recharge Landscapes (as we would expect according to previous studies, e.g. Hartmann *et al.*, 2017). At the resolution of our classification, climate indices have strong positive correlations with landcover indices (pearson correlation coefficient > 0.7). It is not surprising that our Recharge Landscapes strongly resemble previous climate classifications (Peel et al., 2007; Knoben et al., 2018), because climate is a dominant control on the long-term evolution of land surface and near surface landscape characteristics including topography (Chen et al. 2019), soils and vegetation (Pelletier et al. 2013). It is important to recognise that the classification of places may vary temporally (Aleman et al. 2020; Tierney et al. 2017), however as existing continental scale datasets for ground-based recharge estimates only provide long-term mean annual rates, we were not currently able to investigate the temporal variability of groundwater recharge and how this relates to changing landscape classification (Sawicz et al. 2014). Furthermore, we regard the classification as a tool for analysis rather than something unchanging in time.

Our Recharge Landscapes broadly resemble the ecozones in classifications by Olson *et al.* (2001) and Jasechko *et al.* (2014), which identify five and three different regions across Africa respectively. They are also similar to the five regions delineated by MacDonald *et al.* (2021) when using aridity classes to investigate the spatial variability of recharge across Africa. Unlike Olson *et al.* (2001) and Jasechko *et al.* (2014) we do not aggregate deserts and xeric shrublands, which we instead include in our Dryland Recharge Landscapes. Hence our Desert Recharge Landscapes more closely align with the hyper-arid regions delineated by MacDonald *et al.* (2021), whilst our Dryland Recharge Landscapes also align with their arid and semi-arid regions. By separating dry systems according to the occurrence of vegetation, we differentiate between regions where transpiration has a greater effect on recharge processes (Scott *et al.*, 2006; Cavanaugh et al., 2011; Gebreyohannes *et al.*, 2013). Consequently, we organise the Kalahari Desert as a Dryland, as it is affected by transpiration (Foster et al. 1982). Our Dryland Recharge Landscapes can be found throughout the desert, shrubland and tropical biomes of classifications by Olson *et al.* (2001) and Jasechko *et al.* (2014). Thus, previous ecozone classifications may have delineated these regions too broadly. We also see that by identifying Dryland Recharge Landscapes with low slope and high bedrock depths (RLU 13), we identified a landscape unit where large seasonal wetlands are likely to occur (Olson et al. 2001). These wetlands include the Okavango delta, the Kafue and Barotse floodplains in Southern Africa; the Sudd Swamps in Eastern Africa; and the inland Niger delta, Hadejia-Nguru wetlands and wetlands of Southern Chad in the Sahel. Such wetlands can be significant sources of annually occurring focused groundwater recharge, given soil conditions do not restrict infiltration (Edmunds et al., 1999; Wolski et al., 2006). Unlike the classifications of Olson et al. (2001), Jasechko et al. (2014) and MacDonald *et al.* (2021), we further disaggregate Desert Recharge Landscapes according to depth to bedrock. In Desert Recharge Landscapes, shallow bedrock depths largely align with mountainous regions, which are often regarded as important recharge zones for current episodic recharge events (Gheith and Sultan 2002; Sultan et al. 2007) and more regular recharge events in previous paleoclimate periods (Sturchio et al. 2004). Our Wet tropical forest Recharge Landscapes largely align with the tropical and subtropical moist forests shown in Olson *et al.* (2001). Though further disaggregation into units identifies unique regions such as the Swamp forests of the Congo Basin and regions with extreme monsoonal rainfall in the Gulf of Guinea. In contrast, neither Jasechko *et al.* (2014) nor MacDonald *et al.* (2021) identify the forested regions of their tropical and humid classes, respectively.

5.2 How do regions with similar controls compare to ground-based recharge estimates?

In Africa, Recharge Landscapes with greater long-term mean annual recharge rates are also more efficient in converting precipitation to recharge, as shown by the higher long-term mean recharge ratio estimates. We do not know whether this relationship is found across other continents or regions as previous studies investigating the controls on ground-based recharge estimates across large spatial scales assess the spatial variability of annual recharge rates only (Moon et al., 2004; Mohan *et al.*, 2018; Moeck *et al.*, 2020; MacDonald *et al.*, 2021). Investigating how recharge signatures interact in space allowed us to advance our conceptualisations of recharge processes across Africa. Though comparative hydrology is only just starting to be recognised by observational investigations within the groundwater community (Haaf et al. 2020; Heudorfer et al. 2019), it is well established within the surface water community (Addor et al. 2018; Sawicz et al. 2011, 2014) and has already been used in global scale groundwater investigations using global scale modelling products (Cuthbert *et al.*, 2019a).

Even though we can explain the variability of ground-based estimates of annual recharge and recharge ratio between different Recharge Landscapes, we have very limited ability to explain why they vary within Recharge Landscapes using global datasets. Wet tropical and Wet tropical forest Recharge Landscapes receive higher rates of annual recharge and are also more efficient in converting precipitation to recharge than Dryland and Desert Recharge Landscapes, as shown by the higher recharge ratio estimates in these places. This is not surprising, as heavy seasonal, monthly and daily rainfall is already known to be important for recharge processes in both tropical and dry regions of Africa (Döll and Fiedler 2008; Jasechko and Taylor 2015; Owor et al. 2009; Taylor, Todd, et al. 2013). Furthermore, in agreement with Taylor *et al.* (2013), we find that mean annual recharge ratios in Dryland Recharge Landscapes, increase with monthly variability in P-PET. However, interactions with other large-scale physical or biological indices offer little further explanation for why ground-based estimates of annual recharge and recharge ratio vary within individual Recharge Landscapes. For the most part, our inability to explain the spatial variability of ground-based recharge estimates within Recharge Landscapes stresses the limitations of global datasets for describing the complex interactions between landscape properties and how they control more local recharge processes. It could also be attributed to the scale differences in the resolution of our classification and the representative areas of each of our ground-based estimates. Previous studies trying explain the spatial variability of recharge processes at continental and global scales also mostly establish relationships with broad climate and eco-hydrological patterns (Jasechko *et al.*, 2014; Cuthbert *et al.*, 2019b; MacDonald *et al.*, 2021). Furthermore, MacDonald *et al.* (2021) were also unable to explain the more regional/local spatial variability in ground-based estimates of recharge using global datasets. More specifically, they found that there are spatial correlations in long-term average recharge rates across Africa up to distances of 900 km, which cannot yet be explained by environmental properties. Ultimately, this suggests a gap between what we can learn from local insight and from large scale regionalization, regarding the interaction of environmental properties and their control over recharge processes. This potentially has wider implications as global-scale models which are frequently used to estimate groundwater recharge at these scales (Döll and Fiedler 2008; Wada et al. 2010), typically rely upon assimilating global datasets for climate forcing, characterising the land surface and model parameterisations (Telteu et al. 2021). Nonetheless, understanding which recharge controls are currently identifiable using these methods could help guide the evaluation and future development of continental scale models (Gleeson et al. 2021). For example, recharge ratio estimates across the Sahara from PCR-GLOBWB are typically greater than 0.2 (Jasechko et al. 2014), whilst our analysis shows they are mostly below 0.04.

5.3 Looking ahead

Given the limited explanatory power of global datasets as shown in our and other previous studies, it is likely that continental and global scale modelling of groundwater recharge can benefit from the implementation of landscape-based conceptualisations of recharge processes and controls (Gao et al. 2018). Hartmann et al. (2015) showed (for carbonate rock regions across Europe and Northern Africa) that even relatively simple process conceptualizations capture main differences in recharge dynamics between different large landscape groups. Such conceptual models characterize largely our prior understanding of groundwater recharge in different landscapes. This is likely to be particularly important in data sparse regions where we cannot reasonably rely upon model parameterisation schemes that rely heavily on the reliability of soils and other data (Wagener et al. 2021). Adding information through the definition of simple system conceptualizations, would enable us to further combine expected hydrologic behaviour of the landscape with widely available datasets (e.g. Cuthbert *et al.*, 2019b). By focussing on regionally dominant recharge controls, we can develop more parsimonious mathematical models that are also more appropriate for the data scarcity found in many places (Sarrazin *et al.*, 2018), or specific hydrologic processes of most relevance (Quichimbo et al. 2021).

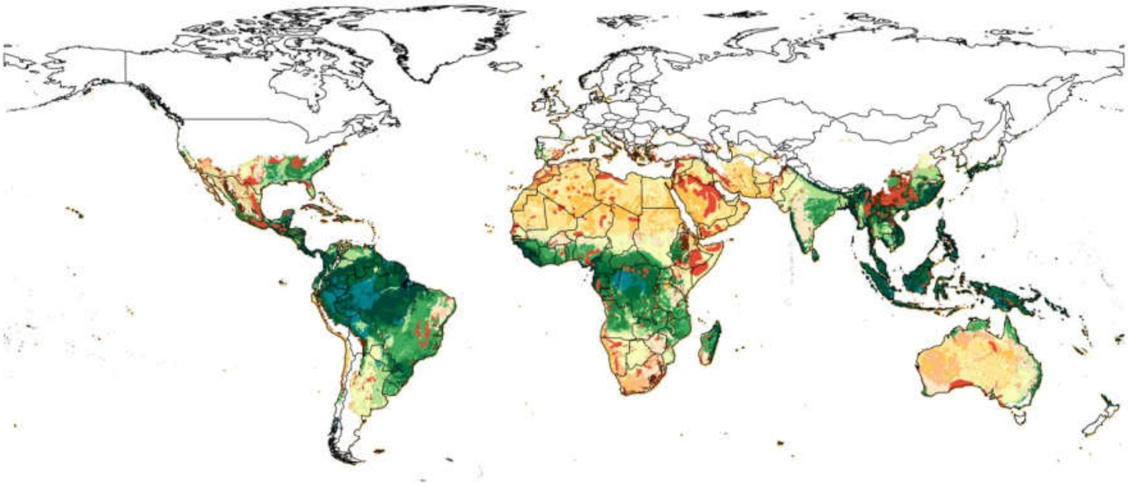

Figure 8. Application of the recharge landscape classification framework to domains outside of the study region. We used a random forest to transfer our Recharge Landscape Units across the rest of the world, with the previously discussed recharge control indices acting as predictor variables. The random forest model is an ensemble of 25 classification trees each with a maximum of 400 decision splits. The model was trained on data points in Africa which were randomly selected with replacement from a sub-sample of 70% of the Africa data points ('in-bag'). Model testing on 'out of bag' data points found a misclassification rate of just 4%. Areas shown in white are significantly dissimilar to the study region. The criterion for this separation was having mean temperatures below 13.5˚C or above 35.5˚C and snow fractions above 0.1. We estimated snow fractions by using a simple temperature threshold. Precipitation on days with an average temperature below 1˚C is regarded as entirely snowfall whereas it is entirely rainfall on days with an average temperature above 1˚C (Berghuijs et al., 2014).

We use a global gridded dataset of daily temperature provided by the Climate Prediction Center, NOAA (NOAA/OAR/ESRL PSD). Further details are provided in the supplemental information.

The value of comparative hydrology in this context could lie in identifying regions of similarity beyond the direct study domain. As discussed here, specific studies with ground-based estimates of groundwater recharge are rare – certainly across Africa. Figure 8 shows how the classification approach introduced here would classify other regions of the world if applied globally. All areas shown in white are significantly dissimilar to our study domain and hence unsuitable for comparison. However, areas in colour map onto some areas in our domain and thus offer the potential for transferability of knowledge gained from outside our direct study domain. For example, studies in karst regions (shown in red) might complement the rather sparse ground-based measurements available inside Africa, thus offering an opportunity to expand on existing datasets like that compiled by MacDonald et al. (2021).

6 Conclusions

We set out to study the variability of groundwater recharge across Africa through the use of a classification of groundwater recharge controls as landscape elements, utilising global datasets to characterize our *a priori* understanding following an extensive literature review. Our final classification consists of 15 recharge landscape units which are similar across the 11 indices we used to describe recharge controls across the continent. We aggregated these Recharge Landscape Units into four larger Recharge Landscapes, including Desert, Dryland, Wet tropical, and Wet tropical forest, which broadly agrees with classifications by Olson *et al.* (2001) and Jasechko *et al.* (2014). Karstic environments are treated separately, scattered across each of the Recharge Landscapes we have found.

A classification approach has allowed us to consolidate most of the findings from previous studies into a spatial representation of expected recharge controls across the African continent. Much of our previous understanding of recharge processes in Africa was point or plot based, originating from the case studies which have assessed recharge processes and controls throughout the region. We hypothesize that the small number of Recharge Landscapes needed to characterize the broader recharge controls of the African landscape, is explained by the dominance of climatic controls, likely connected with the co-evolution of vegetation, soils, and topography. These Recharge Landscapes were useful in organising ground-based estimates of annual recharge and recharge ratio. Yet, in exception of Dryland Recharge Landscapes, we were not able to explain the variability of estimated recharge signatures within each of the Recharge Landscapes using global datasets alone.

There is still considerable variability in ground-based estimates of groundwater recharge which cannot yet be explained using global datasets. This result highlights the limits of using global datasets to decipher the complex interactions of landscape properties in controlling recharge processes. Nonetheless, future data-based modelling of groundwater recharge at continental scales could be advanced by using methods which explore the relationships between controls and recharge within regions of similarity, instead of across the entire continent (MacDonald et al. 2021). Further advancement is also likely to come from the development of system conceptualizations which allow us to add more information than that embedded in global datasets (Wagener et al. 2021). This would lead to a convergence of top-down strategies (such as classification) with other more bottom-up approaches like the one taken by Cuthbert *et al.* (2019b). Further expanding the study domain using similarity principles might offer a strategy for expanding existing strategies. Furthermore, considering the co-evolution of multiple landscape properties could help further separate the hydrologically relevant behaviour of different places (Troch et al. 2013), which in turn could help the predictive ability of global datasets used in model parameterisations. Currently such expected hydrologic behaviour (derived from literature reviews), is only considered through the definition of appropriate predictor variables.

Finally, as meta-analysis databases become more common in continental and global scale hydrological studies (Moeck et al. 2020; Wang et al. 2020), we would like to stress the importance of thorough quality assurance in their initial development. Our findings from these studies depend upon strong underlying datasets and it is unlikely future studies will assess the quality of these datasets when investigating or expanding upon them. For the same reasons, the initial development of these databases should also ensure that additional meta-information is comprehensive.

Acknowledgements

CW is funded as part of the WISE CDT under a grant from the Engineering and Physical Sciences Research Council (EPSRC), grant EP/L016214/1. MOC gratefully acknowledges funding for an Independent Research Fellowship from the UK Natural Environment Research Council (NE/P017819/1).

References

Abdalla, Osman A. E. 2009. “Groundwater Recharge/Discharge in Semi-Arid Regions Interpreted from Isotope and Chloride Concentrations in North White Nile Rift, Sudan.” *Hydrogeology Journal* 17(3):679–92. doi: 10.1007/s10040-008-0388-9.

Abdullateef, Lawal, Moshood N. Tijani, Nabage A. Nuru, Shirputda John, and Aliyu Mustapha. 2021. “Assessment of Groundwater Recharge Potential in a Typical Geological Transition Zone in Bauchi, NE-Nigeria Using Remote Sensing/GIS and MCDA Approaches.” *Heliyon* 7(4):e06762. doi: 10.1016/j.heliyon.2021.e06762.

Abidela Hussein, Misbah, Habtamu Muche, Petra Schmitter, Prossie Nakawuka, Seifu A. Tilahun, Simon Langan, Jennie Barron, and Tammo S. Steenhuis. 2019. “Deep Tillage Improves Degraded Soils in the (Sub) Humid Ethiopian Highlands.” *Land* 8(11):159. doi: 10.3390/land8110159.

Abotalib, Abotalib Z., Mohamed Sultan, and Racha Elkadiri. 2016. “Groundwater Processes in Saharan Africa: Implications for Landscape Evolution in Arid Environments.” *Earth-Science Reviews* 156:108–36.

Abu-Hamdeh, N. H. 2004. “The Effect of Tillage Treatments on Soil Water Holding Capacity and on Soil Physical Properties.” *13th International Soil Conservation Organisation Conference* (669):1–6.

Acosta, Verónica Torres, Taylor F. Schildgen, Brian A. Clarke, Dirk Scherler, Bodo Bookhagen, Hella Wittmann, Friedhelm Von Blanckenburg, and Manfred R. Strecker. 2015. “Effect of Vegetation Cover on Millennial-Scale Landscape Denudation Rates in East Africa.” *Lithosphere* 7(4):408–20. doi: 10.1130/L402.1.

Adams, S., R. Titus, and Y. Xu. 2004. *Groundwater Recharge Assessment of the Basement Aquifers of Central Namaqualand*. Vol. No. 1093/1.

Addor, N., G. Nearing, C. Prieto, A. J. Newman, N. Le Vine, and M. P. Clark. 2018. “A Ranking of Hydrological Signatures Based on Their Predictability in Space.” *Water Resources Research*, 8792–8812.

Aeschbach-Hertig, Werner, and Tom Gleeson. 2012. “Regional Strategies for the Accelerating Global Problem of Groundwater Depletion.” *Nature Geoscience* 5(12):853–61.

Aleman, Julie C., Marta A. Jarzyna, and A. Carla Staver. 2018. “Forest Extent and Deforestation in Tropical Africa Since.” *Nature Ecology and Evolution* 2(1):26–33. doi: 10.1038/s41559-017-0406-1.

Attandoh, Nelson, Sandow Mark Yidana, Aliou Abdul-Samed, Patrick Asamoah Sakyi, Bruce Banoeng-Yakubo, and Prosper M. Nude. 2013. “Conceptualization of the Hydrogeological System of Some Sedimentary Aquifers in Savelugu-Nanton and Surrounding Areas, Northern Ghana.” *Hydrological Processes* 27(11):1664–76. doi: 10.1002/hyp.9308.

Ayadi, Yosra, Naziha Mokadem, Houda Besser, Faten Khelifi, Samia Harabi, Amor Hamad, Adrian Boyce, Rabah Laouar, and Younes Hamed. 2018. “Hydrochemistry and Stable Isotopes (Δ18O and Δ2H) Tools Applied to the Study of Karst Aquifers in Southern Mediterranean Basin (Teboursouk Area, NW Tunisia).” *Journal of African Earth Sciences* 137:208–17. doi: 10.1016/j.jafrearsci.2017.10.018.

Azagegn, Tilahun, Asfawossen Asrat, Tenalem Ayenew, and Seifu Kebede. 2015. “Litho-Structural Control on Interbasin Groundwater Transfer in Central Ethiopia.” *Journal of African Earth Sciences* 101:383–95. doi: 10.1016/j.jafrearsci.2014.10.008.

Azare, I. M., M. S. Abdullahi, A. A. Adebayo, I. J. Dantata, and T. Duala. 2020. “Deforestation, Desert Encroachment, Climate Change and Agricultural Production in the Sudano-Sahelian Region of Nigeria.” *Journal of Applied Sciences and Environmental Management* 24(1):127. doi: 10.4314/jasem.v24i1.18.

Banks, Eddie W., Peter G. Cook, Michael Owor, Joseph Okullo, Seifu Kebede, Dessie Nedaw, Prince Mleta, Helen Fallas, Daren Gooddy, Donald John MacAllister, Theresa Mkandawire, Patrick Makuluni, Chikondi E. Shaba, and Alan M. MacDonald. 2021. “Environmental Tracers to Evaluate Groundwater Residence Times and Water Quality Risk in Shallow Unconfined Aquifers in Sub Saharan Africa.” *Journal of Hydrology* 598. doi: 10.1016/j.jhydrol.2020.125753.

Barbeta, Adrià, and Josep Peñuelas. 2017. “Relative Contribution of Groundwater to Plant Transpiration Estimated with Stable Isotopes.” *Scientific Reports* 7(1):1–10. doi: 10.1038/s41598-017-09643-x.

Beck, Hylke E., Albert I. J. M. Van Dijk, Vincenzo Levizzani, Jaap Schellekens, Diego G. Miralles, Brecht Martens, and Ad De Roo. 2017. “MSWEP: 3-Hourly 0.25° Global Gridded Precipitation (1979-2015) by Merging Gauge, Satellite, and Reanalysis Data.” *Hydrology and Earth System Sciences* 21(1):589–615. doi: 10.5194/hess-21-589-2017.

Befus, Kevin M., Scott Jasechko, Elco Luijendijk, Tom Gleeson, and M. Bayani Cardenas. 2017. “The Rapid yet Uneven Turnover of Earth’s Groundwater.” *Geophysical Research Letters* 44(11):5511–20. doi: 10.1002/2017GL073322.

Benito, Gerardo, Rick Rohde, Mary Seely, Christoph Külls, Ofer Dahan, Yehouda Enzel, Simon

Todd, Blanca Botero, Efrat Morin, Tamir Grodek, and Carole Roberts. 2010. "Management of Alluvial Aquifers in Two Southern African Ephemeral Rivers: Implications for IWRM." *Water Resources Management* 24(4):641–67. doi: 10.1007/s11269-009-9463-9.

Berghuijs, W. R., R. A. Woods, and M. Hrachowitz. 2014. "A Precipitation Shift from Snow towards Rain Leads to a Decrease in Streamflow." *Nature Climate Change* 4(7):583–86. doi: 10.1038/nclimate2246.

Beven, Keith, and Peter Germann. 1982. "Macropores and Water Flow in Soils." *Water Resources Research* 18(5):1311–25. doi: 10.1029/WR018i005p01311.

Bierkens, Marc F. P. 2015. "Global Hydrology 2015: State, Trends, and Directions." *Water Resources Research* 51(7):4923–47. doi: 10.1002/2015WR017173.

Bonsor, H. C., A. M. Macdonald, and J. Davies. 2014. "Evidence for Extreme Variations in the Permeability of Laterite from a Detailed Analysis of Well Behaviour in Nigeria." *Hydrological Processes* 28(10):3563–73. doi: 10.1002/hyp.9871.

Boufekane, Abdelmadjid, Hind Meddi, and Mohamed Meddi. 2020. "Delineation of Groundwater Recharge Zones in the Mitidja Plain, North Algeria, Using Multi-Criteria Analysis." *Journal of Hydroinformatics* 22(6):1468–84. doi: 10.2166/HYDRO.2020.082.

Bouimouass, Houssne, Younes Fakir, Sarah Tweed, and Marc Leblanc. 2020. "Groundwater Recharge Sources in Semiarid Irrigated Mountain Fronts." *Hydrological Processes* 34(7):1598–1615. doi: 10.1002/hyp.13685.

Bouvet, Alexandre, Stéphane Mermoz, Thuy Le Toan, Ludovic Villard, Renaud Mathieu, Laven Naidoo, and Gregory P. Asner. 2018. "An Above-Ground Biomass Map of African Savannahs and Woodlands at 25 m Resolution Derived from ALOS PALSAR." *Remote Sensing of Environment* 206:156–73. doi: 10.1016/j.rse.2017.12.030.

Braune, Eberhard, and Yongxin Xu. 2010. "The Role of Ground Water in Sub-Saharan Africa." *Ground Water* 48(2):229–38. doi: 10.1111/j.1745-6584.2009.00557.x.

Breiman, L. 2001. "Random Forests." *Machine Learning* 45:5–32.

Breiman, L., J. H. Friedman, R. A. Olshen, and C. J. Stone. 1984. *Classification and Regression Trees*. 1st ed. Chapman and Hall/CRC.

Bromley, J., W. M. Edmunds, E. Fellman, J. Brouwer, S. R. Gaze, J. Sudlow, and J. D. Taupin. 1997. "Estimation of Rainfall Inputs and Direct Recharge to the Deep Unsaturated Zone of Southern Niger Using the Chloride Profile Method." *Journal of Hydrology* 188–189(1–4):139–54. doi: 10.1016/S0022-1694(96)03157-5.

Brown, Molly E., Kirsten de Beurs, and Anton Vrieling. 2010. "The Response of African Land Surface Phenology to Large Scale Climate Oscillations." *Remote Sensing of Environment* 114(10):2286–96. doi: 10.1016/j.rse.2010.05.005.

Brunner, Philip, Peter Bauer, Martin Eugster, and Wolfgang Kinzelbach. 2004. "Using Remote Sensing to Regionalize Local Precipitation Recharge Rates Obtained from the Chloride Method." *Journal of Hydrology* 294(4):241–50. doi: 10.1016/j.jhydrol.2004.02.023.

Burke, Antje. 2003. "Inselbergs in a Changing World - Global Trends." *Diversity and Distributions* 9(5):375–83. doi: 10.1046/j.1472-4642.2003.00035.x.

Butterworth, J. A., D. M. J. Macdonald, J. Bromley, L. P. Simmonds, C. J. Lovell, and F. Mugabe. 1999. "Hydrological Processes and Water Resources Management in a Dryland Environment III: Groundwater Recharge and Recession in a Shallow Weathered Aquifer." *Hydrology and Earth System Sciences* 3(3):345–51. doi: 10.5194/hess-3-345-1999.

Calow, R. C., N. S. Robins, A. M. Macdonald, D. M. J. Macdonald, B. R. Gibbs, W. R. G. Orpen, P.

Mtembezeka, A. J. Andrews, and S. O. Appiah. 1997. “Groundwater Management in Drought-Prone Areas of Africa.” *International Journal of Water Resources Development* 13(2):241–61. doi: 10.1080/07900629749863.

Cavanaugh, Michelle L., Shirley A. Kurc, and Russell L. Scott. 2011. “Evapotranspiration Partitioning in Semiarid Shrubland Ecosystems: A Two-Site Evaluation of Soil Moisture Control on Transpiration.” *Ecohydrology* 4(5):671–81. doi: 10.1002/eco.157.

Chávez García Silva, Rafael, Jenny Grönwall, Johannes Van Der Kwast, Kerstin Danert, and Jan Willem Foppen. 2020. “Estimating Domestic Self-Supply Groundwater Use in Urban Continental Africa.” *Environmental Research Letters* 15(10). doi: 10.1088/1748-9326/ab9af9.

Chemseddine, Fehdi, Belfar Dalila, and Baali Fethi. 2015. “Characterization of the Main Karst Aquifers of the Tezbent Plateau, Tebessa Region, Northeast of Algeria, Based on Hydrogeochemical and Isotopic Data.” *Environmental Earth Sciences* 74(1):241–50. doi: 10.1007/s12665-015-4480-x.

Chen, Shiuan An, Katerina Michaelides, Stuart W. D. Grieve, and Michael Bliss Singer. 2019. “Aridity Is Expressed in River Topography Globally.” *Nature* 573(7775):573–77. doi: 10.1038/s41586-019-1558-8.

Conway, Declan, Aurelie Pereschino, Sandra Ardoin-Bardin, Hamisai Hamandawana, Claudin Dieulin, and Gil Mahé. 2009. “Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century.” *Journal of Hydrometeorology* 10(1):41–59. doi: 10.1175/2008JHM1004.1.

Cuthbert, M. O., T. Gleeson, N. Moosdorf, K. M. Befus, A. Schneider, J. Hartmann, and B. Lehner. 2019. “Global Patterns and Dynamics of Climate–Groundwater Interactions.” *Nature Climate Change* 9(2):137–41.

Cuthbert, M. O., and C. Tindimugaya. 2010. “The Importance of Preferential Flow in Controlling Groundwater Recharge in Tropical Africa and Implications for Modelling the Impact of Climate Change on Groundwater Resources.” *Journal of Water and Climate Change* 1(4):234–45. doi: 10.2166/wcc.2010.040.

Cuthbert, Mark O., Richard G. Taylor, Guillaume Favreau, Martin C. Todd, Mohammad Shamsudduha, Karen G. Villholth, Alan M. MacDonald, Bridget R. Scanlon, D. O. Valerie Kotchoni, Jean-Michel Vouillamoz, Fabrice M. A. Lawson, Philippe Armand Adjomayi, Japhet Kashaigili, David Seddon, James P. R. Sorensen, Girma Yimer Ebrahim, Michael Owor, Philip M. Nyenje, Yahaya Nazoumou, Ibrahim Goni, Boukari Issoufou Ousmane, Tenant Sibanda, Matthew J. Ascott, David M. J. Macdonald, William Agyekum, Youssouf Koussoubé, Heike Wanke, Hyungjun Kim, Yoshihide Wada, Min-Hui Lo, Taikan Oki, and Neno Kukuric. 2019. “Observed Controls on Resilience of Groundwater to Climate Variability in Sub-Saharan Africa.” *Nature* 572(7768):230–34. doi: 10.1038/s41586-019-1441-7.

Dabous, A. A., and J. K. Osmond. 2001. “Uranium Isotopic Study of Artesian and Pluvial Contributions to the Nubian Aquifer, Western Desert, Egypt.” *Journal of Hydrology* 243(3–4):242–53. doi: 10.1016/S0022-1694(00)00417-0.

Defourny, P., S. Bontemps, C. Lamarche, C. Brockmann, M. Boettcher, J. Wevers, G. Kirches, and M. Santoro. 2017. “Land Cover CCI Product User Guide - Version 2.0.” *ESA* 1–105.

Demlie, Molla. 2015. “Assessment and Estimation of Groundwater Recharge for a Catchment Located in Highland Tropical Climate in Central Ethiopia Using Catchment Soil–Water Balance (SWB) and Chloride Mass Balance (CMB) Techniques.” *Environmental Earth Sciences* 74(2):1137–50. doi: 10.1007/s12665-015-4099-y.

Demlie, Molla, Stefan Wohnlich, Birhanu Gizaw, and Willibald Stichler. 2007. “Groundwater Recharge in the Akaki Catchment, Central Ethiopia: Evidence from Environmental Isotopes

(Δ18O, Δ2H And3H) and Chloride Mass Balance.” *Hydrological Processes* 21(6):807–18. doi: 10.1002/hyp.6273.

Descheemaeker, Katrien, Jan Nyssen, Jean Poesen, Dirk Raes, Mitiku Haile, Bart Muys, and Seppe Deckers. 2006. “Runoff on Slopes with Restoring Vegetation: A Case Study from the Tigray Highlands, Ethiopia.” *Journal of Hydrology* 331(1–2):219–41. doi: 10.1016/j.jhydrol.2006.05.015.

Descroix, L., G. Mahé, T. Lebel, G. Favreau, S. Galle, E. Gautier, J. C. Olivry, J. Albergel, O. Amogu, B. Cappelaere, R. Dessouassi, A. Diedhiou, E. Le Breton, I. Mamadou, and D. Sighomnou. 2009. “Spatio-Temporal Variability of Hydrological Regimes around the Boundaries between Sahelian and Sudanian Areas of West Africa: A Synthesis.” *Journal of Hydrology* 375(1–2):90–102. doi: 10.1016/j.jhydrol.2008.12.012.

Dietrich, William E., and J. Taylor Perron. 2006. “The Search for a Topographic Signature of Life.” *Nature* 439(7075):411–18.

Diouf, Coly. 2012. “Combined Uses of Water-Table Fluctuation (WTF), Chloride Mass Balance (CMB) and Environmental Isotopes Methods to Investigate Groundwater Recharge in the Thiaroye Sandy Aquifer (Dakar, Senegal).” *African Journal of Environmental Science and Technology* 6(11):425–37. doi: 10.5897/ajest12.100.

Döll, P., and K. Fiedler. 2008. “Global-Scale Modeling of Groundwater Recharge.” *Hydrology and Earth System Sciences* 12(3):863–85. doi: 10.5194/hess-12-863-2008.

Dormann, Carsten F., Jane Elith, Sven Bacher, Carsten Buchmann, Gudrun Carl, Gabriel Carré, Jaime R. Garcí. Marquéz, Bernd Gruber, Bruno Lafourcade, Pedro J. Leitão, Tamara Münkemüller, Colin Mcclean, Patrick E. Osborne, Björn Reineking, Boris Schröder, Andrew K. Skidmore, Damaris Zurell, and Sven Lautenbach. 2013. “Collinearity: A Review of Methods to Deal with It and a Simulation Study Evaluating Their Performance.” *Ecography* 36(1):027–046. doi: 10.1111/j.1600-0587.2012.07348.x.

Edmunds, W. M., W. G. Darling, D. G. Kinniburgh, S. Kotoub, and S. Mahgoub. 1992. “Sources of Recharge at Abu Delaig, Sudan.” *Journal of Hydrology* 131(1–4):1–24. doi: 10.1016/0022-1694(92)90211-D.

Edmunds, W. M., E. Fellman, and I. B. Goni. 1999. “Lakes, Groundwater and Palaeohydrology in the Sahel of NE Nigeria: Evidence from Hydrogeochemistry.” *Journal of the Geological Society* 156(2):345–55. doi: 10.1144/gsjgs.156.2.0345.

Edmunds, W. M., and C. B. Gaye. 1994. “Estimating the Spatial Variability of Groundwater Recharge in the Sahel Using Chloride.” *Journal of Hydrology* 156(1–4):47–59. doi: 10.1016/0022-1694(94)90070-1.

Egli, Markus, and Jérôme Poulenard. 2016. “Soils of Mountainous Landscapes.” Pp. 1–10 in *International Encyclopedia of Geography: People, the Earth, Environment and Technology*.

Farid, Intissar, Kamel Zouari, Rim Trabelsi, and Abd Rahmen Kallali. 2014. “Application of Environmental Tracers to Study Groundwater Recharge in a Semi-Arid Area of Central Tunisia.” *Hydrological Sciences Journal* 59(11):2072–85. doi: 10.1080/02626667.2013.863424.

Fashae, Olutoyin A., Moshood N. Tijani, Abel O. Talabi, and Oluwatola I. Adedeji. 2014. “Delineation of Groundwater Potential Zones in the Crystalline Basement Terrain of SW-Nigeria: An Integrated GIS and Remote Sensing Approach.” *Applied Water Science* 4(1):19–38. doi: 10.1007/s13201-013-0127-9.

Favreau, G., B. Cappelaere, S. Massuel, M. Leblanc, M. Boucher, N. Boulain, and C. Leduc. 2009. “Land Clearing, Climate Variability, and Water Resources Increase in Semiarid Southwest Niger: A Review.” *Water Resources Research* 45(7):W00A16. doi: 10.1029/2007WR006785.

Foster, S. S. D., A. H. Bath, J. L. Farr, and W. J. Lewis. 1982. “The Likelihood of Active Groundwater Recharge in the Botswana Kalahari.” *Journal of Hydrology* 55(1–4):113–36. doi: 10.1016/0022-1694(82)90123-8.

Foster, S. S. D., B. L. Morris, and P. J. Chilton. 1999. “Groundwater in Urban Development-a Review of Linkages and Concerns.” *IAHS-AISH Publication* (259):3–12.

Foster, Stephen, Michael Eichholz, Bertil Nlend, and Julia Gathu. 2020. “Securing the Critical Role of Groundwater for the Resilient Water-Supply of Urban Africa.” *Water Policy* 22(1):121–32. doi: 10.2166/wp.2020.177.

Francis, M. L., M. V. Fey, H. P. Prinsloo, F. Ellis, A. J. Mills, and T. V. Medinski. 2007. “Soils of Namaqualand: Compensations for Aridity.” *Journal of Arid Environments* 70(4):588–603. doi: 10.1016/j.jaridenv.2006.12.028.

Gao, Hongkai, John L. Sabo, Xiaohong Chen, Zhiyong Liu, Zongji Yang, Ze Ren, and Min Liu. 2018. “Landscape Heterogeneity and Hydrological Processes: A Review of Landscape-Based Hydrological Models.” *Landscape Ecology* 33(9):1461–80.

Gebreyohannes, Tesfamichael, Florimond De Smedt, Kristine Walraevens, Solomon Gebresilassie, Abdelwasie Hussien, Miruts Hagos, Kasa Amare, Jozef Deckers, and Kindeya Gebrehiwot. 2013. “Application of a Spatially Distributed Water Balance Model for Assessing Surface Water and Groundwater Resources in the Geba Basin, Tigray, Ethiopia.” *Journal of Hydrology* 499:110–23. doi: 10.1016/j.jhydrol.2013.06.026.

Gerland, Patrick, Adrian E. Raftery, Hana Ševčíková, Nan Li, Danan Gu, Thomas Spoorenberg, Leontine Alkema, Bailey K. Fosdick, Jennifer Chunn, Nevena Lalic, Guiomar Bay, Thomas Buettner, Gerhard K. Heilig, and John Wilmoth. 2014. “World Population Stabilization Unlikely This Century.” *Science* 346(6206):234–37. doi: 10.1126/science.1257469.

Gheith, Hazem, and Mohamed Sultan. 2002. “Construction of a Hydrologic Model for Estimating Wadi Runoff and Groundwater Recharge in the Eastern Desert, Egypt.” *Journal of Hydrology* 263(1–4):36–55. doi: 10.1016/S0022-1694(02)00027-6.

Giordano, Mark. 2006. “Agricultural Groundwater Use and Rural Livelihoods in Sub-Saharan Africa: A First-Cut Assessment.” *Hydrogeology Journal* 14(3):310–18. doi: 10.1007/s10040-005-0479-9.

Gleeson, Tom, Thorsten Wagener, P. Doll, Charles West, Yoshihide Wada, Richard G. Taylor, Bridget Scanlon, Rafael Rosolem, Mostaquimur Rahman, Nurudeen Oshinlaja, Reed Maxwell, Min-Hui Lo, Hyungjun Kim, Mary Hill, Andreas Hartmann, Graham Fogg, James S. Famiglietti, Agnes Ducharne, Inge E. M. de Graaf, Mark O. Cuthbert, Laura E. Condon, Etienne Bresciani, and Marc F. P. Bierkens. 2021. “GMD Perspective: The Quest to Improve the Evaluation of Groundwater Representation in Continental-to Global-Scale Models.” *Geoscientific Model Development* 14(12):7545–71.

Good, Stephen P., David Noone, and Gabriel Bowen. 2015. “Hydrologic Connectivity Constrains Partitioning of Global Terrestrial Water Fluxes.” *Science* 349(6244):175–77. doi: 10.1126/science.aaa5931.

Gordon, L. J., W. Steffen, B. F. Jonsson, C. Folke, M. Falkenmark, and A. Johannessen. 2005. “Human Modification of Global Water Vapor Flows from the Land Surface.” *Proceedings of the National Academy of Sciences* 102(21):7612–17. doi: 10.1073/pnas.0500208102.

Gordon, Line J., Will Steffen, Bror F. Jönsson, Carl Folke, Malin Falkenmark, and Åse Johannessen. 2005. “Human Modification of Global Water Vapor Flows from the Land Surface.” *Proceedings of the National Academy of Sciences of the United States of America* 102(21):7612–17. doi: 10.1073/pnas.0500208102.

Grodek, Tamir, Efrat Morin, David Helman, Itamar Lensky, Ofer Dahan, Mary Seely, Gerardo Benito, and Yehouda Enzel. 2020. “Eco-Hydrology and Geomorphology of the Largest Floods along the Hyperarid Kuiseb River, Namibia.” *Journal of Hydrology* 582(124450). doi: 10.1016/j.jhydrol.2019.124450.

Guendouz, A., A. S. Moulla, B. Remini, and J. L. Michelot. 2006. “Hydrochemical and Isotopic Behaviour of a Saharan Phreatic Aquifer Suffering Severe Natural and Anthropic Constraints (Case of Oued-Souf Region, Algeria).” *Hydrogeology Journal* 14(6):955–68. doi: 10.1007/s10040-005-0020-1.

Haaf, Ezra, Markus Giese, Benedikt Heudorfer, Kerstin Stahl, and Roland Barthel. 2020. “Physiographic and Climatic Controls on Regional Groundwater Dynamics.” *Water Resources Research* 56(10):1–20. doi: 10.1029/2019wr026545.

Hamza, M. A., and W. K. Anderson. 2005. “Soil Compaction in Cropping Systems: A Review of the Nature, Causes and Possible Solutions.” *Soil and Tillage Research* 82(2):121–45.

Harris, Ian, Timothy J. Osborn, Phil Jones, and David Lister. 2020. “Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset.” *Scientific Data* 7(1):1–18. doi: 10.1038/s41597-020-0453-3.

Hartmann, A., T. Gleeson, R. Rosolem, F. Pianosi, Y. Wada, and T. Wagener. 2015. “A Large-Scale Simulation Model to Assess Karstic Groundwater Recharge over Europe and the Mediterranean.” *Geoscientific Model Development* 8(6):1729–46. doi: 10.5194/gmd-8-1729-2015.

Hartmann, A., N. Goldscheider, T. Wagener, J. Lange, and M. Weiler. 2014. “Karst Water Resources in a Changing World: Review of Hydrological Modeling Approaches.” *Reviews of Geophysics* 52(3):218–42.

Hartmann, Andreas, Tom Gleeson, Yoshihide Wada, and Thorsten Wagener. 2017. “Enhanced Groundwater Recharge Rates and Altered Recharge Sensitivity to Climate Variability through Subsurface Heterogeneity.” *Proceedings of the National Academy of Sciences* 114(11):2842–47. doi: 10.1073/pnas.1614941114.

Hawinkel, P., W. Thiery, S. Lhermitte, E. Swinnen, B. Verbist, J. Van Orshoven, and B. Muys. 2016. “Vegetation Response to Precipitation Variability in East Africa Controlled by Biogeographical Factors.” *Journal of Geophysical Research: Biogeosciences* 121(9):2422–44. doi: 10.1002/2016JG003436.

Healy, Richard W. 2010. *Estimating Groundwater Recharge*. Cambridge: Cambridge University Press.

Hengl, Tomislav, Jorge Mendes De Jesus, Gerard B. M. Heuvelink, Maria Ruiperez Gonzalez, Milan Kilibarda, Aleksandar Blagotić, Wei Shangguan, Marvin N. Wright, Xiaoyuan Geng, Bernhard Bauer-Marschallinger, Mario Antonio Guevara, Rodrigo Vargas, Robert A. MacMillan, Niels H. Batjes, Johan G. B. Leenaars, Eloi Ribeiro, Ichsani Wheeler, Stephan Mantel, and Bas Kempen. 2017. “SoilGrids250m: Global Gridded Soil Information Based on Machine Learning.” *PLoS ONE* 12(2):e0169748. doi: 10.1371/journal.pone.0169748.

Heudorfer, B., E. Haaf, K. Stahl, and R. Barthel. 2019. “Index-Based Characterization and Quantification of Groundwater Dynamics.” *Water Resources Research* 55(7):5575–92. doi: 10.1029/2018WR024418.

Houston, J. F. T. 1982. “Rainfall and Recharge to a Dolomite Aquifer in a Semi-Arid Climate at Kabwe, Zambia.” *Journal of Hydrology* 59(1–2):173–87. doi: 10.1016/0022-1694(82)90010-5.

Howard, Ken W. F., and John Karundu. 1992. “Constraints on the Exploitation of Basement Aquifers in East Africa - Water Balance Implications and the Role of the Regolith.” *Journal of Hydrology*

139(1–4):183–96. doi: 10.1016/0022-1694(92)90201-6.

Ibrahim, Maïmouna, Guillaume Favreau, Bridget R. Scanlon, Jean Luc Seidel, Mathieu Le Coz, Jérôme Demarty, and Bernard Cappelaere. 2014. “Long-Term Increase in Diffuse Groundwater Recharge Following Expansion of Rainfed Cultivation in the Sahel, West Africa.” *Hydrogeology Journal* 22(6):1293–1305. doi: 10.1007/s10040-014-1143-z.

Jacks, Gunnar, and Matallah S. Traoré. 2014. “Mechanisms and Rates of Groundwater Recharge at Timbuktu, Republic of Mali.” *Journal of Hydrologic Engineering* 19(2):422–27. doi: 10.1061/(ASCE)HE.1943-5584.0000801.

Jasechko, Scott, S. Jean Birks, Tom Gleeson, Yoshihide Wada, Peter J. Fawcett, Zachary D. Sharp, Jeffrey J. McDonnell, and Jeffrey M. Welker. 2014. “The Pronounced Seasonality of Global Groundwater Recharge.” *Water Resources Research* 50(11):8845–67. doi: 10.1002/2014WR015809.

Jasechko, Scott, Debra Perrone, Kevin M. Befus, M. Bayani Cardenas, Grant Ferguson, Tom Gleeson, Elco Luijendijk, Jeffrey J. McDonnell, Richard G. Taylor, Yoshihide Wada, and James W. Kirchner. 2017. “Global Aquifers Dominated by Fossil Groundwaters but Wells Vulnerable to Modern Contamination.” *Nature Geoscience* 10(6):425–29. doi: 10.1038/ngeo2943.

Jasechko, Scott, and Richard G. Taylor. 2015. “Intensive Rainfall Recharges Tropical Groundwaters.” *Environmental Research Letters* 10(12):124015. doi: 10.1088/1748-9326/10/12/124015.

Jenny, Hans. 1941. *Factors of Soil Formation. A System of Quantitative Pedology, Soil Science.*

Kamtchueng, Brice Tchakam, Wilson Yetoh Fantong, Mengnjo Jude Wirmvem, Rosine Edwige Tiodjio, Alain Fouépé Takounjou, Kazuyoshi Asai, Serges L. Bopda Djomou, Minoru Kusakabe, Takeshi Ohba, Gregory Tanyileke, Joseph Victor Hell, and Akira Ueda. 2015. “A Multi-Tracer Approach for Assessing the Origin, Apparent Age and Recharge Mechanism of Shallow Groundwater in the Lake Nyos Catchment, Northwest, Cameroon.” *Journal of Hydrology* 523:790–803. doi: 10.1016/j.jhydrol.2015.02.008.

Kebede, Seifu, Yves Travi, Tamiru Alemayehu, and Tenalem Ayenew. 2005. “Groundwater Recharge, Circulation and Geochemical Evolution in the Source Region of the Blue Nile River, Ethiopia.” *Applied Geochemistry* 20(9):1658–76. doi: 10.1016/j.apgeochem.2005.04.016.

Kim, John H., and Robert B. Jackson. 2012. “A Global Analysis of Groundwater Recharge for Vegetation, Climate, and Soils.” *Vadose Zone Journal* 11(1). doi: 10.2136/vzj2011.0021RA.

Knoben, Wouter J. M., Ross A. Woods, and Jim E. Freer. 2018. “A Quantitative Hydrological Climate Classification Evaluated With Independent Streamflow Data.” *Water Resources Research* 54(7):5088–5109. doi: 10.1029/2018WR022913.

Kotchoni, D. O. Valeri., Jean Michel Vouillamoz, Fabrice M. A. Lawson, Philippe Adjomayi, Moussa Boukari, and Richard G. Taylor. 2018. “Relationships between Rainfall and Groundwater Recharge in Seasonally Humid Benin: A Comparative Analysis of Long-Term Hydrographs in Sedimentary and Crystalline Aquifers.” *Hydrogeology Journal* 27:447–457. doi: 10.1007/s10040-018-1806-2.

Lapworth, D. J., A. M. MacDonald, M. N. Tijani, W. G. Darling, D. C. Gooddy, H. C. Bonsor, and L. J. Araguás-Araguás. 2013. “Residence Times of Shallow Groundwater in West Africa: Implications for Hydrogeology and Resilience to Future Changes in Climate.” *Hydrogeology Journal* 21:673–686. doi: 10.1007/s10040-012-0925-4.

Lapworth, D. J., D. C. W. Nkhuwa, J. Okotto-Okotto, S. Pedley, M. E. Stuart, M. N. Tijani, and J. Wright. 2017. “Urban Groundwater Quality in Sub-Saharan Africa: Current Status and Implications for Water Security and Public Health.” *Hydrogeology Journal* 25:1093–1116. doi: 10.1007/s10040-016-1516-6.

Leblanc, Marc J., Guillaume Favreau, Sylvain Massuel, Sarah O. Tweed, Maud Loireau, and Bernard Cappelaere. 2008. "Land Clearance and Hydrological Change in the Sahel: SW Niger." *Global and Planetary Change* 61(3–4):135–50. doi: 10.1016/j.gloplacha.2007.08.011.

Leduc, C., G. Favreau, and P. Schroeter. 2001. "Long-Term Rise in a Sahelian Water-Table: The Continental Terminal in South-West Niger." *Journal of Hydrology* 243(1):43–54. doi: 10.1016/S0022-1694(00)00403-0.

Lehmann, Peter, Markus Berli, Jeremy E. Koonce, and Dani Or. 2019. "Surface Evaporation in Arid Regions: Insights From Lysimeter Decadal Record and Global Application of a Surface Evaporation Capacitor (SEC) Model." *Geophysical Research Letters* 46(16):9648–57. doi: 10.1029/2019GL083932.

Lehner, B., K. Verdin, and A. Jarvis. 2013. "HydroSHEDS Technical Documentation Version 1.2." *EOS Transactions* 89(10):26.

Lehner, Bernhard, and Petra Döll. 2004. "Development and Validation of a Global Database of Lakes, Reservoirs and Wetlands." *Journal of Hydrology* 296(1–4):1–22. doi: 10.1016/j.jhydrol.2004.03.028.

Leketa, Khahliso, Tamiru Abiye, Silindile Zondi, and Michael Butler. 2019. "Assessing Groundwater Recharge in Crystalline and Karstic Aquifers of the Upper Crocodile River Basin, Johannesburg, South Africa." *Groundwater for Sustainable Development* 8:31–40. doi: 10.1016/j.gsd.2018.08.002.

Lentswe, Gaolatlhe Bhutto, and Loago Molwalefhe. 2020. "Delineation of Potential Groundwater Recharge Zones Using Analytic Hierarchy Process-Guided GIS in the Semi-Arid Motloutse Watershed, Eastern Botswana." *Journal of Hydrology: Regional Studies* 28. doi: 10.1016/j.ejrh.2020.100674.

Lerner, David N. 2002. "Identifying and Quantifying Urban Recharge: A Review." *Hydrogeology Journal* 10(1):143–52. doi: 10.1007/s10040-001-0177-1.

M.I, Budyko. 1974. *Climate and Life*. Academic Press, New York.

MacDonald, A. M., H. C. Bonsor, B. É. Ó. Dochartaigh, and R. G. Taylor. 2012. "Quantitative Maps of Groundwater Resources in Africa." *Environmental Research Letters* 7(024009). doi: 10.1088/1748-9326/7/2/024009.

MacDonald, A. M., and R. C. Calow. 2009. "Developing Groundwater for Secure Rural Water Supplies in Africa." *Desalination* 248(1–3):546–56. doi: 10.1016/j.desal.2008.05.100.

MacDonald, Alan M., R. Murray Lark, Richard G. Taylor, Tamiru Abiye, Helen C. Fallas, Guillaume Favreau, Ibrahim B. Goni, Seifu Kebede, Bridget Scanlon, James P. R. Sorensen, Moshood Tijani, Kirsty A. Upton, and Charles West. 2021. "Mapping Groundwater Recharge in Africa from Ground Observations and Implications for Water Security." *Environmental Research Letters* 16(034012). doi: 10.1088/1748-9326/abd661.

Mao, J., and B. Yan. 2019. "Global Monthly Mean Leaf Area Index Climatology, 1981-2015." *ORNL DAAC, Oak Ridge, Tennessee, USA*. Retrieved (https://daac.ornl.gov/VEGETATION/guides/Mean_Seasonal_LAI.html).

Mayaux, Philippe, Etienne Bartholomé, Steffen Fritz, and Alan Belward. 2004. "A New Land-Cover Map of Africa for the Year 2000." *Journal of Biogeography* 31(6):861–77. doi: 10.1111/j.1365-2699.2004.01073.x.

Mazor, E., B. Th Verhagen, J. P. F. Sellschop, M. T. Jones, N. E. Robins, L. Hutton, and C. M. H. Jennings. 1977. "Northern Kalahari Groundwaters: Hydrologic, Istopic and Chemical Studies at Orapa, Botswana." *Journal of Hydrology* 34(3–4):203–34. doi: 10.1016/0022-1694(77)90132-9.

Mazor, Emanuel. 1982. “Rain Recharge in the Kalahari - A Note on Some Approaches to the Problem.” *Journal of Hydrology* 55(1–4):137–44. doi: 10.1016/0022-1694(82)90124-X.

McKenna, Owen P., and Osvaldo E. Sala. 2018. “Groundwater Recharge in Desert Playas: Current Rates and Future Effects of Climate Change.” *Environmental Research Letters* 13(1):014025. doi: 10.1088/1748-9326/aa9eb6.

Measho, Simon, Baozhang Chen, Yongyut Trisurat, Petri Pellikka, Lifeng Guo, Sunsanee Arunyawat, Venus Tuankrua, Woldeselassie Ogbazghi, and Tecle Yemane. 2019. “Spatio-Temporal Analysis of Vegetation Dynamics as a Response to Climate Variability and Drought Patterns in the Semiarid Region, Eritrea.” *Remote Sensing* 11(6). doi: 10.3390/RS11060724.

Mechal, Abraham, Thomas Wagner, and Steffen Birk. 2015. “Recharge Variability and Sensitivity to Climate: The Example of Gidabo River Basin, Main Ethiopian Rift.” *Journal of Hydrology: Regional Studies* 4(B):644–60. doi: 10.1016/j.ejrh.2015.09.001.

Melanie A. Harsch, Philip E. Hulme, Matt S. McGlone, and Richard P. Duncan. 2009. “Are Treelines Advancing? A Global Meta-Analysis of Treeline Response to Climate Warming.” *Ecology Letters* 12(10):1040–49.

Miralles, Diego G., John H. Gash, Thomas R. H. Holmes, Richard A. M. De Jeu, and A. J. Dolman. 2010. “Global Canopy Interception from Satellite Observations.” *Journal of Geophysical Research Atmospheres* 115(D16122). doi: 10.1029/2009JD013530.

Moeck, Christian, Nicolas Grech-Cumbo, Joel Podgorski, Anja Bretzler, Jason J. Gurdak, Michael Berg, and Mario Schirmer. 2020. “A Global-Scale Dataset of Direct Natural Groundwater Recharge Rates: A Review of Variables, Processes and Relationships.” *Science of the Total Environment* 717(137042). doi: 10.1016/j.scitotenv.2020.137042.

Mohan, Chinchu, Andrew W. Western, Yongping Wei, and Margarita Saft. 2018. “Predicting Groundwater Recharge for Varying Land Cover and Climate Conditions-a Global Meta-Study.” *Hydrology and Earth System Sciences* 22(5):2689–2703. doi: 10.5194/hess-22-2689-2018.

Moon, Sang Ki, Nam C. Woo, and Kwang S. Lee. 2004. “Statistical Analysis of Hydrographs and Water-Table Fluctuation to Estimate Groundwater Recharge.” *Journal of Hydrology* 292(1–4):198–209. doi: 10.1016/j.jhydrol.2003.12.030.

Morin, Efrat, Tamir Grodek, Ofer Dahan, Gerardo Benito, Christoph Kulls, Yael Jacoby, Guido Van Langenhove, Mary Seely, and Yehouda Enzel. 2009. “Flood Routing and Alluvial Aquifer Recharge along the Ephemeral Arid Kuiseb River, Namibia.” *Journal of Hydrology* 368(1–4):262–75. doi: 10.1016/j.jhydrol.2009.02.015.

Nash, David J., Paul A. Shaw, and David S. G. Thomas. 1994. “Duricrust Development and Valley Evolution: Process–Landform Links in the Kalahari.” *Earth Surface Processes and Landforms* 19(4):299–317. doi: 10.1002/esp.3290190403.

Ndehedehe, Christopher E., Vagner G. Ferreira, and Nathan O. Agutu. 2019. “Hydrological Controls on Surface Vegetation Dynamics over West and Central Africa.” *Ecological Indicators* 103:494–508. doi: 10.1016/j.ecolind.2019.04.032.

Nicholson, S. E. 2000. “The Nature of Rainfall Variability over Africa on Time Scales of Decades to Millenia.” *Global and Planetary Change* 26(1–3):137–58. doi: 10.1016/S0921-8181(00)00040-0.

Nicholson, Sharon E., and Jeeyoung Kim. 1997. “The Relationship of the El MNO-Southern Oscillation to African Rainfall.” *International Journal of Climatology* 17(2):117–35. doi: 10.1002/(SICI)1097-0088(199702)17:2<117::AID-JOC84>3.0.CO;2-O.

Nijzink, Remko, Christopher Hutton, Ilias Pechlivanidis, René Capell, Berit Arheimer, Jim Freer, Dawei Han, Thorsten Wagener, Kevin McGuire, Hubert Savenije, and Markus Hrachowitz.

2016. “The Evolution of Root-Zone Moisture Capacities after Deforestation: A Step towards Hydrological Predictions under Change?” *Hydrology and Earth System Sciences* 20(12):4775–99. doi: 10.5194/hess-20-4775-2016.

Nkotagu, Hudson. 1996. “Application of Environmental Isotopes to Groundwater Recharge Studies in a Semi-Arid Fractured Crystalline Basement Area of Dodoma, Tanzania.” *Journal of African Earth Sciences* 22(4):443–57. doi: 10.1016/0899-5362(96)00022-X.

NOAA/OAR/ESRL PSD. n.d. “CPC Global Temperature Data.” Retrieved June 10, 2020 (https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html).

Oiro, Samson, Jean Christophe Comte, Chris Soulsby, Alan MacDonald, and Canute Mwakamba. 2020. “Depletion of Groundwater Resources under Rapid Urbanisation in Africa: Recent and Future Trends in the Nairobi Aquifer System, Kenya.” *Hydrogeology Journal* 28(8):2635–56. doi: 10.1007/s10040-020-02236-5.

Olson, D. M., Thomas F. Allnutt, Taylor H. Ricketts, Y. U. M. I. K. O. Kura, John F. Lamoreux, W. Wesley, Prashant Hedao, and Kenneth R. Kassem. 2001. “Terrestrial Ecoregions of the World: A New Map of Life on Earth.” *BioScience* 51(11):933–38.

Osunbitan, J. A., D. J. Oyedele, and K. O. Adekalu. 2005. “Tillage Effects on Bulk Density, Hydraulic Conductivity and Strength of a Loamy Sand Soil in Southwestern Nigeria.” *Soil and Tillage Research* 82(1):57–64. doi: 10.1016/j.still.2004.05.007.

Oteng Mensah, Felix, Clement Alo, and Sandow Mark Yidana. 2014. “Evaluation of Groundwater Recharge Estimates in a Partially Metamorphosed Sedimentary Basin in a Tropical Environment: Application of Natural Tracers.” *The Scientific World Journal* 2014(419508). doi: 10.1155/2014/419508.

Owor, M., R. G. Taylor, C. Tindimugaya, and D. Mwesigwa. 2009. “Rainfall Intensity and Groundwater Recharge: Empirical Evidence from the Upper Nile Basin.” *Environmental Research Letters* 4(035009). doi: 10.1088/1748-9326/4/3/035009.

Parnell, Susan, and Ruwani Walawege. 2011. “Sub-Saharan African Urbanisation and Global Environmental Change.” *Global Environmental Change* 21(SUPPL. 1):S12–20. doi: 10.1016/j.gloenvcha.2011.09.014.

Peel, M. C., B. L. Finlayson, and T. A. McMahon. 2007. “Updated World Map of the Köppen-Geiger Climate Classification.” *Hydrology and Earth System Sciences* 11(5):1633–44. doi: 10.5194/hess-11-1633-2007.

Pelletier, Jon D., Greg A. Barron-Gafford, David D. Breshears, Paul D. Brooks, Jon Chorover, Matej Durcik, Ciaran J. Harman, Travis E. Huxman, Kathleen A. Lohse, Rebecca Lybrand, Tom Meixner, Jennifer C. McIntosh, Shirley A. Papuga, Craig Rasmussen, Marcel Schaap, Tyson L. Swetnam, and Peter A. Troch. 2013. “Coevolution of Nonlinear Trends in Vegetation, Soils, and Topography with Elevation and Slope Aspect: A Case Study in the Sky Islands of Southern Arizona.” *Journal of Geophysical Research: Earth Surface* 118(2):741–58. doi: 10.1002/jgrf.20046.

Pelletier, Jon D., Patrick D. Broxton, Pieter Hazenberg, Xubin Zeng, Peter A. Troch, Guo Yue Niu, Zachary Williams, Michael A. Brunke, and David Gochis. 2016. “A Gridded Global Data Set of Soil, Intact Regolith, and Sedimentary Deposit Thicknesses for Regional and Global Land Surface Modeling.” *Journal of Advances in Modeling Earth Systems* 8(1):41–65. doi: 10.1002/2015MS000526.

Quichimbo, E. Andres, Michael Bliss Singer, Katerina Michaelides, D. Hobley, Rosolem, Rafael, and M. O. Cuthbert. 2021. “DRYP 1.0: A Parsimonious Hydrological Model of DRYland Partitioning of the Water Balance.” *Geoscientific Model Development* 14(11):6893–6917.

Rao Kolusu, Seshagiri, Mohammad Shamsudduha, Martin C. Todd, Richard G. Taylor, David Seddon, Japhet J. Kashaigili, Girma Y. Ebrahim, Mark O. Cuthbert, James P. R. Sorensen, Karen G. Villholth, Alan M. Macdonald, and Dave A. Macleod. 2019. "The El Niño Event of 2015-2016: Climate Anomalies and Their Impact on Groundwater Resources in East and Southern Africa." *Hydrology and Earth System Sciences* 23(3):1751–62. doi: 10.5194/hess-23-1751-2019.

Reinecke, Robert, Hannes Müller Schmied, Tim Trautmann, Lauren Seaby Andersen, Peter Burek, Martina Flörke, Simon N. Gosling, Manolis Grillakis, Naota Hanasaki, Aristeidis Koutroulis, Yadu Pokhrel, Wim Thiery, Yoshihide Wada, Satoh Yusuke, and Petra Döll. 2021. "Uncertainty of Simulated Groundwater Recharge at Different Global Warming Levels: A Global-Scale Multi-Model Ensemble Study." *Hydrology and Earth System Sciences* 25(2):787–810. doi: 10.5194/hess-25-787-2021.

Reinhardt, Liam, Douglas Jerolmack, Brad J. Cardinale, Veerle Vanacker, and Justin Wright. 2010. "Dynamic Interactions of Life and Its Landscape: Feedbacks at the Interface of Geomorphology and Ecology." *Earth Surface Processes and Landforms* 35(1):78–101. doi: 10.1002/esp.1912.

Robins, N. S., J. Davies, J. L. Farr, and R. C. Calow. 2006. "The Changing Role of Hydrogeology in Semi-Arid Southern and Eastern Africa." *Hydrogeology Journal* 14:1483–1492. doi: 10.1007/s10040-006-0056-x.

Rodell, M., J. S. Famiglietti, D. N. Wiese, J. T. Reager, H. K. Beaudoing, F. W. Landerer, and M. H. Lo. 2018. "Emerging Trends in Global Freshwater Availability." *Nature* 557:651–659. doi: 10.1038/s41586-018-0123-1.

Rueedi, J., M. S. Brennwald, R. Purtschert, U. Beyerle, M. Hofer, and R. Kipfer. 2005. "Estimating Amount and Spatial Distribution of Groundwater Recharge in the Lullemmeden Basin (Niger) Based on 3H, 3He and CFC-11 Measurements." *Hydrological Processes* 19(17):3285–98. doi: 10.1002/hyp.5970.

Sarrazin, Fanny, Andreas Hartmann, Francesca Pianosi, Rafael Rosolem, and Thorsten Wagener. 2018. "V2Karst V1.1: A Parsimonious Large-Scale Integrated Vegetation-Recharge Model to Simulate the Impact of Climate and Land Cover Change in Karst Regions." *Geoscientific Model Development* 11(12):4933–64. doi: 10.5194/gmd-11-4933-2018.

Sawicz, K. A., C. Kelleher, T. Wagener, P. Troch, M. Sivapalan, and G. Carrillo. 2014. "Characterizing Hydrologic Change through Catchment Classification." *Hydrology and Earth System Sciences* 18(1):273–285. doi: 10.5194/hess-18-273-2014.

Sawicz, K., T. Wagener, M. Sivapalan, P. A. Troch, and G. Carrillo. 2011. "Catchment Classification: Empirical Analysis of Hydrologic Similarity Based on Catchment Function in the Eastern USA." *Hydrology and Earth System Sciences* 15(9):2895–2911. doi: 10.5194/hess-15-2895-2011.

Saxton, K. E., W. J. Rawls, J. S. Romberger, and R. I. Papendick. 1986. "Estimating Generalized Soil-Water Characteristics from Texture." *Soil Science Society of America Journal* 50(4):1031–36. doi: 10.2136/sssaj1986.03615995005000040039x.

Scanlon, Bridget R., Richard W. Healy, and Peter G. Cook. 2002. "Choosing Appropriate Techniques for Quantifying Groundwater Recharge." *Hydrogeology Journal* 10:18–39. doi: 10.1007/s10040-001-0176-2.

Scanlon, Bridget R., Ian Jolly, Marios Sophocleous, and Lu Zhang. 2007. "Global Impacts of Conversions from Natural to Agricultural Ecosystems on Water Resources: Quantity versus Quality." *Water Resources Research* 43(3). doi: 10.1029/2006WR005486.

Scanlon, Bridget R., Kelley E. Keese, Alan L. Flint, Lorraine E. Flint, Cheikh B. Gaye, W. Michael Edmunds, and Ian Simmers. 2006. "Global Synthesis of Groundwater Recharge in Semiarid and

Arid Regions." *Hydrological Processes* 20(15):3335–70. doi: 10.1002/hyp.6335.

Schlesinger, William H., and Scott Jasechko. 2014. "Transpiration in the Global Water Cycle." *Agricultural and Forest Meteorology* 189–190:115–17. doi: 10.1016/j.agrformet.2014.01.011.

Scott, Russell L., Travis E. Huxman, William L. Cable, and William E. Emmerich. 2006. "Partitioning of Evapotranspiration and Its Relation to Carbon Dioxide Exchange in a Chihuahuan Desert Shrubland." *Hydrological Processes* 20(15):3227–43. doi: 10.1002/hyp.6329.

Seddon, David, Japhet J. Kashaigili, Richard G. Taylor, Mark O. Cuthbert, Catherine Mwihumbo, and Alan M. MacDonald. 2021. "Focused Groundwater Recharge in a Tropical Dryland: Empirical Evidence from Central, Semi-Arid Tanzania." *Journal of Hydrology: Regional Studies* 37. doi: 10.1016/j.ejrh.2021.100919.

Sharp, John M. 2010. "The Impacts of Urbanization on Groundwater Systems and Recharge." *Aquamundi* 1(may):51–56. doi: 10.4409/Am-004-10-0008.

Siam, Mohamed S., and Elfatih A. B. Eltahir. 2017. "Climate Change Enhances Interannual Variability of the Nile River Flow." *Nature Climate Change* 7(5):350–54. doi: 10.1038/nclimate3273.

Sibanda, Tenant, Johannes C. Nonner, and Stefan Uhlenbrook. 2009. "Comparison of Groundwater Recharge Estimation Methods for the Semi-Arid Nyamandhlovu Area, Zimbabwe." *Hydrogeology Journal* 17(6):1427–41. doi: 10.1007/s10040-009-0445-z.

Sidibe, Moussa, Bastien Dieppois, Jonathan Eden, Gil Mahé, Jean Emmanuel Paturel, Ernest Amoussou, Babatunde Anifowose, and Damian Lawler. 2019. "Interannual to Multi-Decadal Streamflow Variability in West and Central Africa: Interactions with Catchment Properties and Large-Scale Climate Variability." *Global and Planetary Change* 177:141–56. doi: 10.1016/j.gloplacha.2019.04.003.

Siebert, S., Döll, P., Feick, S., Frenken, K., Hoogeveen, J. 2013. *Global Map of Irrigation Areas Version 5*. Rome. doi: 10.13140/2.1.2660.6728.

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll, and F. T. Portmann. 2010. "Groundwater Use for Irrigation - A Global Inventory." *Hydrology and Earth System Sciences* 14(10):1863–1880. doi: 10.5194/hess-14-1863-2010.

Siebert, S., M. Kummu, M. Porkka, P. Döll, N. Ramankutty, and B. R. Scanlon. 2015. "A Global Data Set of the Extent of Irrigated Land from 1900 to 2005." *Hydrology and Earth System Sciences* 19(3):1521–45. doi: 10.5194/hess-19-1521-2015.

Simmers, I. 1990. "Aridity, Groundwater Recharge and Water Resources Management." Pp. 1–20 in *Groundwater recharge: a Guide to Recharge Measurement in Arid and Semiarid Regionsunderstanding and estimating natural recharge*.

Spaan, W. P., A. F. S. Sikking, and W. B. Hoogmoed. 2005. "Vegetation Barrier and Tillage Effects on Runoff and Sediment in an Alley Crop System on a Luvisol in Burkina Faso." *Soil and Tillage Research* 83(2):194–203. doi: 10.1016/j.still.2004.07.016.

Stein, L., M. P. Clark, W. J. M. Knoben, F. Pianosi, and R. A. Woods. 2021. "How Do Climate and Catchment Attributes Influence Flood Generating Processes? A Large-Sample Study for 671 Catchments Across the Contiguous USA." *Water Resources Research* 57(4):e2020WR028300. doi: 10.1029/2020wr028300.

Steward, Alisha L., Daniel Von Schiller, Klement Tockner, Jonathan C. Marshall, and Stuart E. Bunn. 2012. "When the River Runs Dry: Human and Ecological Values of Dry Riverbeds." *Frontiers in Ecology and the Environment* 10(4):202–9. doi: 10.1890/110136.

Stone, A. E. C., and W. M. Edmunds. 2012. "Sand, Salt and Water in the Stampriet Basin, Namibia: Calculating Unsaturated Zone (Kalahari Dunefield) Recharge Using the Chloride Mass Balance Approach." *Water SA* 38(3):367–78. doi: 10.4314/wsa.v38i3.2.

Strudley, Mark W., Timothy R. Green, and James C. Ascough. 2008. "Tillage Effects on Soil Hydraulic Properties in Space and Time: State of the Science." *Soil and Tillage Research* 99(1):4–48. doi: 10.1016/j.still.2008.01.007.

Sturchio, N. C., X. Du, R. Purtschert, B. E. Lehmann, M. Sultan, L. J. Patterson, Z. T. Lu, P. Müller, T. Bigler, K. Bailey, T. P. O'Connor, L. Young, R. Lorenzo, R. Becker, Z. El Alfy, B. El Kaliouby, Y. Dawood, and A. M. A. Abdallah. 2004. "One Million Year Old Groundwater in the Sahara Revealed by Krypton-81 and Chlorine-36." *Geophysical Research Letters* 31(L05503). doi: 10.1029/2003gl019234.

Sultan, M., N. C. Sturchio, H. Gheith, Y. Abdel Hady, and M. El Anbeawy. 2000. "Chemical and Isotopic Constraints on the Origin of Wadi El-Tarfa Ground Water, Eastern Desert, Egypt." *Ground Water* 38(5):743–51. doi: 10.1111/j.1745-6584.2000.tb02710.x.

Sultan, M., E. Yan, N. Sturchio, A. Wagdy, K. Abdel Gelil, R. Becker, N. Manocha, and A. Milewski. 2007. "Natural Discharge: A Key to Sustainable Utilization of Fossil Groundwater." *Journal of Hydrology* 335(1–2):25–36. doi: 10.1016/j.jhydrol.2006.10.034.

Tantawi, M. A., E. El-Sayed, and M. A. Awad. 1998. "Hydrochemical and Stable Isotope Study of Groundwater in the Saint Catherine-Wadi Feiran Area, South Sinai, Egypt." *Journal of African Earth Sciences* 26(2):277–84. doi: 10.1016/S0899-5362(98)00010-4.

Taylor, Richard G., and Ken W. F. Howard. 1996. "Groundwater Recharge in the Victoria Nile Basin of East Africa: Support for the Soil Moisture Balance Approach Using Stable Isotope Tracers and Flow Modelling." *Journal of Hydrology* 180(1–4):31–53. doi: 10.1016/0022-1694(95)02899-4.

Taylor, Richard G., Bridget Scanlon, Petra Döll, Matt Rodell, Rens Van Beek, Yoshihide Wada, Laurent Longuevergne, Marc Leblanc, James S. Famiglietti, Mike Edmunds, Leonard Konikow, Timothy R. Green, Jianyao Chen, Makoto Taniguchi, Marc F. P. Bierkens, Alan Macdonald, Ying Fan, Reed M. Maxwell, Yossi Yechieli, Jason J. Gurdak, Diana M. Allen, Mohammad Shamsudduha, Kevin Hiscock, Pat J. F. Yeh, Ian Holman, and Holger Treidel. 2013. "Ground Water and Climate Change." *Nature Climate Change* 3(4):322–29. doi: 10.1038/nclimate1744.

Taylor, Richard G., Martin C. Todd, Lister Kongola, Louise Maurice, Emmanuel Nahozya, Hosea Sanga, and Alan M. Macdonald. 2013. "Evidence of the Dependence of Groundwater Resources on Extreme Rainfall in East Africa." *Nature Climate Change* 3:374–378. doi: 10.1038/nclimate1731.

Telteu, Camelia-Eliza, Hannes Müller Schmied, Wim Thiery, Guoyong Leng, Peter Burek, Xingcai Liu, Julien Eric Stanislas Boulange, Lauren Seaby Andersen, Manolis Grillakis, Simon Newland Gosling, Yusuke Satoh, Oldrich Rakovec, Tobias Stacke, Jinfeng Chang, Niko Wanders, Harsh Lovekumar Shah, Tim Trautmann, Ganquan Mao, Naota Hanasaki, Aristeidis Koutroulis, Yadu Pokhrel, Luis Samaniego, Yoshihide Wada, Vimal Mishra, Junguo Liu, Petra Döll, Fang Zhao, Anne Gädeke, Sam Rabin, and Florian Herz. 2021. "Understanding Each Other's Models: A Standard Representation of Global Water Models to Support Improvement, Intercomparison, and Communication." *Geoscientific Model Development Discussions* 1–56. doi: 10.5194/gmd-2020-367.

Telteu, Camelia Eliza, Hannes Müller Schmied, Wim Thiery, Guoyong Leng, Peter Burek, Xingcai Liu, Julien Eric Stanislas Boulange, Lauren Seaby Andersen, Manolis Grillakis, Simon Newland Gosling, Yusuke Satoh, Oldrich Rakovec, Tobias Stacke, Jinfeng Chang, Niko Wanders, Harsh Lovekumar Shah, Tim Trautmann, Ganquan Mao, Naota Hanasaki, Aristeidis Koutroulis, Yadu Pokhrel, Luis Samaniego, Yoshihide Wada, Vimal Mishra, Junguo Liu, Petra Döll, Fang Zhao, Anne Gädeke, Sam S. Rabin, and Florian Herz. 2021. “Understanding Each Other’s Models An Introduction and a Standard Representation of 16 Global Water Models to Support Intercomparison, Improvement, and Communication.” *Geoscientific Model Development* 14(6):3843–78.

Theis, Charles V. 1940. “The Source of Water Derived from Wells.” *Civil Engineering* 10(5):277–80.

Thierfelder, Christian, and Patrick C. Wall. 2009. “Effects of Conservation Agriculture Techniques on Infiltration and Soil Water Content in Zambia and Zimbabwe.” *Soil and Tillage Research* 105(2):217–27. doi: 10.1016/j.still.2009.07.007.

Thompson, S. E., C. J. Harman, P. Heine, and G. G. Katul. 2010. “Vegetation-Infiltration Relationships across Climatic and Soil Type Gradients.” *Journal of Geophysical Research: Biogeosciences* 115(G02023). doi: 10.1029/2009jg001134.

Tierney, Jessica E., Francesco S. R. Pausata, and Peter B. De Menocal. 2017. “Rainfall Regimes of the Green Sahara.” *Science Advances* 3(1). doi: 10.1126/sciadv.1601503.

du Toit, G. van N., H. A. Snyman, and P. J. Malan. 2009. “Physical Impact of Grazing by Sheep on Soil Parameters in the Nama Karoo Subshrub/Grass Rangeland of South Africa.” *Journal of Arid Environments* 73(9):804–10. doi: 10.1016/j.jaridenv.2009.03.013.

Van Tonder, G. J., and J. Kirchner. 1990. “Estimation of Natural Groundwater Recharge in the Karoo Aquifers of South Africa.” *Journal of Hydrology* 121(1–4):395–419. doi: 10.1016/0022-1694(90)90243-Q.

Towett, Erick K., Keith D. Shepherd, Jerome E. Tondoh, Leigh A. Winowiecki, Tamene Lulseged, Mercy Nyambura, Andrew Sila, Tor G. Vågen, and Georg Cadisch. 2015. “Total Elemental Composition of Soils in Sub-Saharan Africa and Relationship with Soil Forming Factors.” *Geoderma Regional* 5:157–68. doi: 10.1016/j.geodrs.2015.06.002.

Troch, P. A., G. Carrillo, M. Sivapalan, T. Wagener, and K. Sawicz. 2013. “Climate-Vegetation-Soil Interactions and Long-Term Hydrologic Partitioning: Signatures of Catchment Co-Evolution.” *Hydrology and Earth System Sciences* 17(6):2209–17. doi: 10.5194/hess-17-2209-2013.

Tsendbazar, Nandin Erdene, Sytze de Bruin, and Martin Herold. 2017. “Integrating Global Land Cover Datasets for Deriving User-Specific Maps.” *International Journal of Digital Earth* 10(3):219–37. doi: 10.1080/17538947.2016.1217942.

Været, Lars, Bruce Kelbe, Sylvi Haldorsen, and Richard H. Taylor. 2009. “A Modelling Study of the Effects of Land Management and Climatic Variations on Groundwater Inflow to Lake St Lucia, South Africa.” *Hydrogeology Journal* 17(8):1949–67. doi: 10.1007/s10040-009-0476-5.

Vogel, J. C., and H. Van Urk. 1975. “Isotopic Composition of Groundwater in Semi-Arid Regions of Southern Africa.” *Journal of Hydrology* 25(1–2):23–36. doi: 10.1016/0022-1694(75)90036-0.

de Vries, J., and A. Gieske. 1990. “A Simple Chloride Balance Routing Method to Regionalize Groundwater Recharge: A Case Study in Semiarid Botswana.” Pp. 81–89 in *Regionalization in Hydrolo*. he Ljubljan: IAHS Publ. no. 191.

De Vries, J. J., E. T. Selaolo, and H. E. Beekman. 2000. “Groundwater Recharge in the Kalahari, with Reference to Paleo-Hydrologic Conditions.” *Journal of Hydrology* 238(1–2):110–23. doi: 10.1016/S0022-1694(00)00325-5.

Wada, Yoshihide, Ludovicus P. H. Van Beek, Cheryl M. Van Kempen, Josef W. T. M. Reckman, Slavek Vasak, and Marc F. P. Bierkens. 2010. “Global Depletion of Groundwater Resources.” *Geophysical Research Letters* 37(20):L20402. doi: 10.1029/2010GL044571.

Wagener, T., T. Gleeson, Gemma Coxon, A. Hartmann, N. J. K. Howden, F. Pianosi, R. Rosolem, L. Stein, and R. A. Woods. 2021. “On Doing Hydrology with Dragons: Realizing the Value of

Perceptual Models and Knowledge Accumulation." *WIREs WATER* (e1550). doi: doi.org/10.1002/wat2.1550.

Wakindiki, I. I. C., and M. Ben-Hur. 2002. "Soil Mineralogy and Texture Effects on Crust Micromorphology, Infiltration, and Erosion." *Soil Science Society of America Journal* 66(3):897–905. doi: 10.2136/sssaj2002.8970.

Walker, David, Magdalena Smigaj, and Nebo Jovanovic. 2019. "Ephemeral Sand River Flow Detection Using Satellite Optical Remote Sensing." *Journal of Arid Environments* 168:17–25. doi: 10.1016/j.jaridenv.2019.05.006.

Walraevens, Kristine, Ine Vandecasteele, Kristine Martens, Jan Nyssen, Jan Moeyersons, Tesfamichael Gebreyohannes, Florimond de Smedt, Jean Poesen, Jozef Deckers, and Marc van Camp. 2009. "Groundwater Recharge and Flow in a Small Mountain Catchment in Northern Ethiopia." *Hydrological Sciences Journal* 54(4):739–53. doi: 10.1623/hysj.54.4.739.

Wang, Shengping, Tim R. McVicar, Zhiqiang Zhang, Thomas Brunner, and Peter Strauss. 2020. "Globally Partitioning the Simultaneous Impacts of Climate-Induced and Human-Induced Changes on Catchment Streamflow: A Review and Meta-Analysis." *Journal of Hydrology* 590. doi: 10.1016/j.jhydrol.2020.125387.

Wanke, Heike, Armin Dünkeloh, and Peter Udluft. 2008. "Groundwater Recharge Assessment for the Kalahari Catchment of North-Eastern Namibia and North-Western Botswana with a Regional-Scale Water Balance Model." *Water Resources Management* 22:1143–1158. doi: 10.1007/s11269-007-9217-5.

Williams, Paul W., and Derek C. Ford. 2006. "Global Distribution of Carbonate Rocks." *Zeitschrift Fur Geomorphologie, Supplementband* 147(1–2).

Winter, Thomas C. 2001. "The Concept of Hydrologic Landscapes." *Journal of the American Water Resources Association* 37(2):335–49. doi: 10.1111/j.1752-1688.2001.tb00973.x.

Wirmvem, Mengnjo Jude, Mumbfu Ernestine Mimba, Brice Tchakam Kamtchueng, Engome Regina Wotany, Tasin Godlove Bafon, Asobo Nkengmatia Elvis Asaah, Wilson Yetoh Fantong, Samuel Ndonwi Ayonghe, and Takeshi Ohba. 2015. "Shallow Groundwater Recharge Mechanism and Apparent Age in the Ndop Plain, Northwest Cameroon." *Applied Water Science* 7(1):489–502. doi: 10.1007/s13201-015-0268-0.

Wolock, David M., Thomas C. Winter, and Gerard McMahon. 2004. "Delineation and Evaluation of Hydrologic-Landscape Regions in the United States Using Geographic Information System Tools and Multivariate Statistical Analyses." *Environmental Management*. doi: 10.1007/s00267-003-5077-9.

Wolski, P., H. H. G. Savenije, M. Murray-Hudson, and T. Gumbricht. 2006. "Modelling of the Flooding in the Okavango Delta, Botswana, Using a Hybrid Reservoir-GIS Model." *Journal of Hydrology* 331(1–2):58–72. doi: 10.1016/j.jhydrol.2006.04.040.

Wösten, J. H. M., Ya A. Pachepsky, and W. J. Rawls. 2001. "Pedotransfer Functions: Bridging the Gap between Available Basic Soil Data and Missing Soil Hydraulic Characteristics." *Journal of Hydrology* 251(3–4):123–50. doi: 10.1016/S0022-1694(01)00464-4.

Xiong, Jun, Prasad S. Thenkabail, Murali K. Gumma, Pardhasaradhi Teluguntla, Justin Poehnelt, Russell G. Congalton, Kamini Yadav, and David Thau. 2017. "Automated Cropland Mapping of Continental Africa Using Google Earth Engine Cloud Computing." *ISPRS Journal of Photogrammetry and Remote Sensing* 126:225–44. doi: 10.1016/j.isprsjprs.2017.01.019.

Xu, Yongxin, and Hans E. Beekman. 2003. *Groundwater Recharge Estimation in Southern Africa*. Vol. 64.

Yidana, Sandow Mark, and Eric Koffie. 2014. "The Groundwater Recharge Regime of Some Slightly

Metamorphosed Neoproterozoic Sedimentary Rocks: An Application of Natural Environmental Tracers.” *Hydrological Processes* 28(7):3104–17. doi: 10.1002/hyp.9859.

Zarate, E., D. Hobley, A. M. MacDonald, R. T. Swift, J. Chambers, J. J. Kashaigili, E. Mutayoba, R. G. Taylor, and M. O. Cuthbert. 2021. “The Role of Superficial Geology in Controlling Groundwater Recharge in the Weathered Crystalline Basement of Semi-Arid Tanzania.” *Journal of Hydrology: Regional Studies* 36. doi: 10.1016/j.ejrh.2021.100833.

Zhang, Yongqiang, Jorge L. Peña-Arancibia, Tim R. McVicar, Francis H. S. Chiew, Jai Vaze, Changming Liu, Xingjie Lu, Hongxing Zheng, Yingping Wang, Yi Y. Liu, Diego G. Miralles, and Ming Pan. 2016. “Multi-Decadal Trends in Global Terrestrial Evapotranspiration and Its Components.” *Scientific Reports* 6(19124). doi: 10.1038/srep19124.

Zheng, Chaolei, Li Jia, Guangcheng Hu, Massimo Menenti, Jing Lu, Jie Zhou, Kun Wang, and Zhansheng Li. 2017. “Assessment of Water Use in Pan-Eurasian and African Continents by ETMonitor with Multi-Source Satellite Data.” in *IOP Conference Series: Earth and Environmental Science*. Vol. 57.

Zhou, Liming, Yuhong Tian, Ranga B. Myneni, Philippe Ciais, Sassan Saatchi, Yi Y. Liu, Shilong Piao, Haishan Chen, Eric F. Vermote, Conghe Song, and Taehee Hwang. 2014. “Widespread Decline of Congo Rainforest Greenness in the Past Decade.” *Nature* 508(7498):86–90. doi: 10.1038/nature13265.

Zhou, Yuyu, Steven J. Smith, Kaiguang Zhao, Marc Imhoff, Allison Thomson, Ben Bond-Lamberty, Ghassem R. Asrar, Xuesong Zhang, Chunyang He, and Christopher D. Elvidge. 2015. “A Global Map of Urban Extent from Nightlights.” *Environmental Research Letters* 10(054011). doi: 10.1088/1748-9326/10/5/054011.

Zouari, Kamel, Rim Trabelsi, and Najiba Chkir. 2011. “Using Geochemical Indicators to Investigate Groundwater Mixing and Residence Time in the Aquifer System of Djeffara of Medenine (Southeastern Tunisia).” *Hydrogeology Journal* 19(1):209–19. doi: 10.1007/s10040-010-0673-2.