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 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 and its development is fundamental for securing current and future water supply (MacDonald et al., 2012). With such volume, groundwater in Africa exceeds the estimated annual volumes of streamflow by a factor of 100 (MacDonald et al., 2012). High inter-annual variability of streamflow in dryland river basins s the challenges of securing water supply solely from surface water sources (Conway et al. 2009; Siam and Eltahir 2017; Sidibe et al. 2019). For example, in the Sahel and Southern Africa, standard deviations in annual river flows can be up to 100% of the long term mean flow (Dettinger and Diaz 2000), and Siam and Eltahir, (2017) have already shown that inter-annual streamflow variability has increased with climate change in the Nile basin. In agriculture-dependent economies such as those in rural Africa, economic growth is hampered by such uncertain water supply due to the strong inter-annual variability in rainfall; for example Ethiopia may have 38% less economic growth than it would have under average rainfall conditions (Hall et al. 2014). Poor investments in reservoir infrastructure in much of Africa mean that per capita storage is low and does not sufficiently alleviate the problem of variability (Hall et al. 2014). Furthermore, in regions where streamflow predominantly varies at decadal timescales, such as in the Sahel, persistent dry periods can lead to long-term shortages in surface water supply (Conway et al. 2009; Sidibe et al. 2019). Increased use of groundwater could therefore 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).

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). 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] 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, these models largely rely upon global datasets for their parameterisation with only very limited levels of evaluation against hydrologic fluxes – especially fluxes rarely estimated locally such as groundwater recharge (Bierkens, 2015; Telteu *et al.*, 2021; Wagener *et al.*, 2021). Global models thus far also include only a limited number of process representations and neglect regionally dominant controls, such as karst (Hartmann et al., 2015; Hartmann et al., 2014) or dryland-specific hydrological processes (Quichimbo et al. 2021). [3] Most 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.

Here, we want to improve our understanding of the hydrologic controls governing the spatial variability of groundwater recharge (MacDonald et al., 2021) across Africa, utilizing the wider knowledge on controlling processes gained throughout the literature. 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 and exclude recharge from large discrete features such as rivers or lakes. 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).

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 less than the actual recharge since some potential recharge is rejected if the aquifer is full. 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 (> 95th percentile) rainfall (Taylor 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

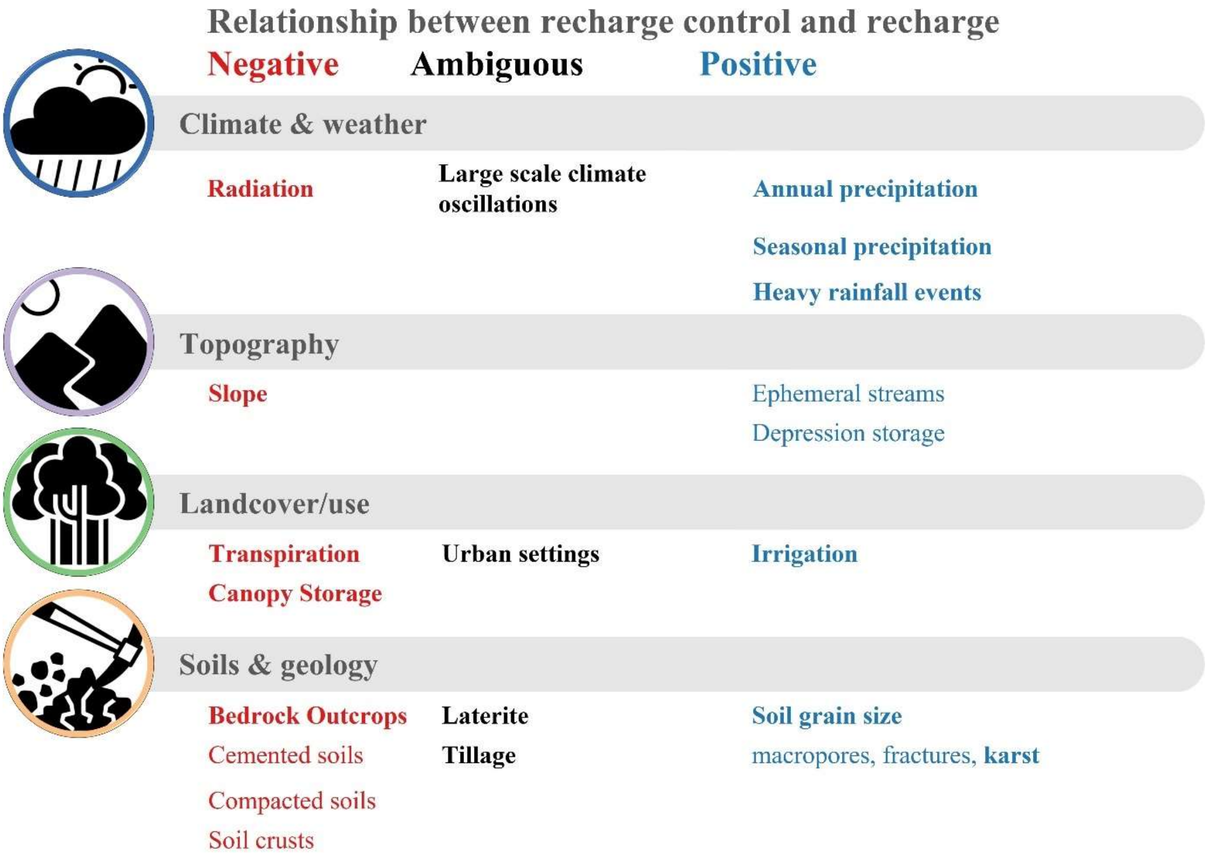

Figure 1. Summary of groundwater recharge controls for Africa identified in the literature. Controls are colour coded according to their relationship with recharge with red and blue representing negative and positive relationships, respectively. Bold font highlights controls which we can characterise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

3. Materials and methods

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)	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	Spatial res.: 0.5˚ Temporal res.: Monthly	
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 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.	-	-	SoilGrids250m Spatial res.: 250m	(Hengl et al. 2017)
Geology attributes					
Depth to bedrock	Average soil and sedimentary deposit thickness. Maximum of 50m.	m	-	Gridded Thickness of Soil, Regolith and	(Pelletier et al. 2016)

				Sedimentary Deposit Layers Spatial res.: 30 arc seconds	
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. 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).

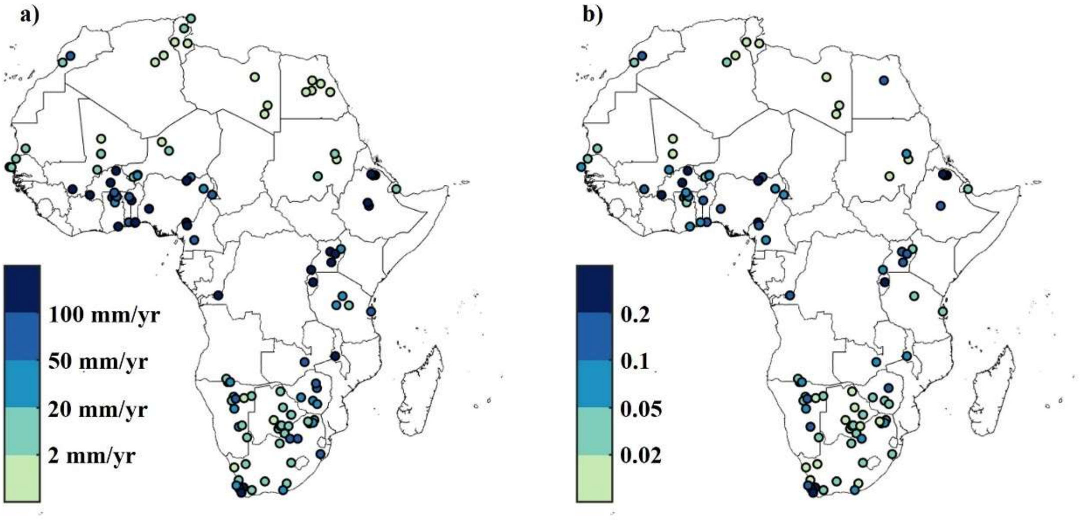

Figure 2. The remaining annual recharge and recharge ratio estimates collected from case studies in the literature by MacDonald et al. (2021), after initial screening of the data. The recharge ratio is defined as the fraction of precipitation being converted to recharge (recharge / precipitation).

3.3 Fuzzy 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).

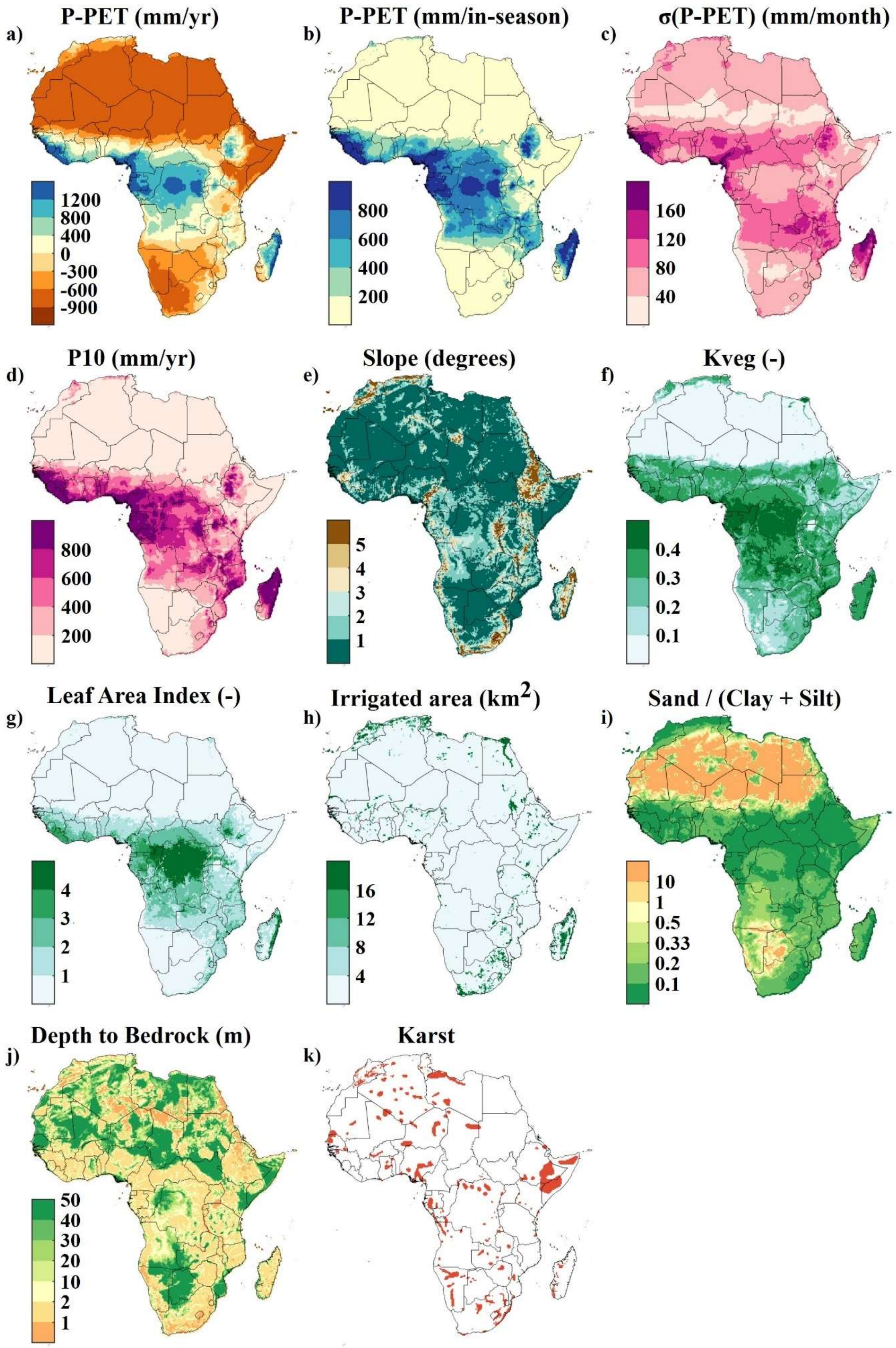
a)
P-PET (mm/yr)
1200
800
400
0
-300
-600
-900
b)
P-PET (mm/in-season)
800
600
400
200
c)
σ(P-PET) (mm/month)
160
120
80
40
d)
P10 (mm/yr)
800
600
400
200
e)
Slope (degrees)
5
4
3
2
1
f)
Kveg (-)
0.4
0.3
0.2
0.1
g)
Leaf Area Index (-)
4
3
2
1
h)
Irrigated area (km^2)
16
12
8
4
i)
Sand / (Clay + Silt)
10
1
0.5
0.33
0.2
0.1
j)
Depth to Bedrock (m)
50
40
30
20
10
2
1
k)
Karst

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.

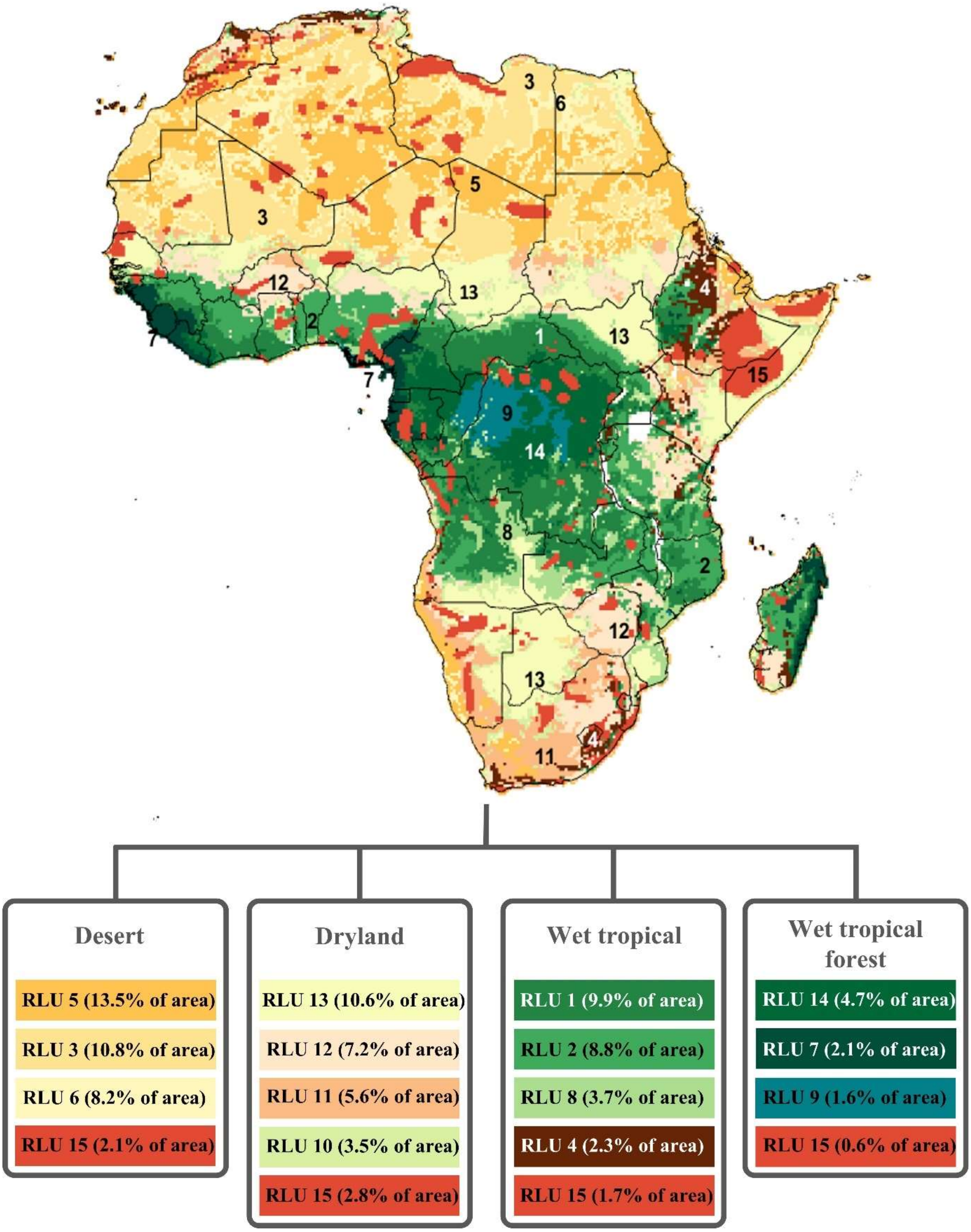

Figure 4. Map of the 15 Recharge Landscape Units of our classification for a priori understanding of recharge controls in Africa. We group the Recharge Landscape Units into broader groups of similar units which we call Recharge Landscapes.

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). 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 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.

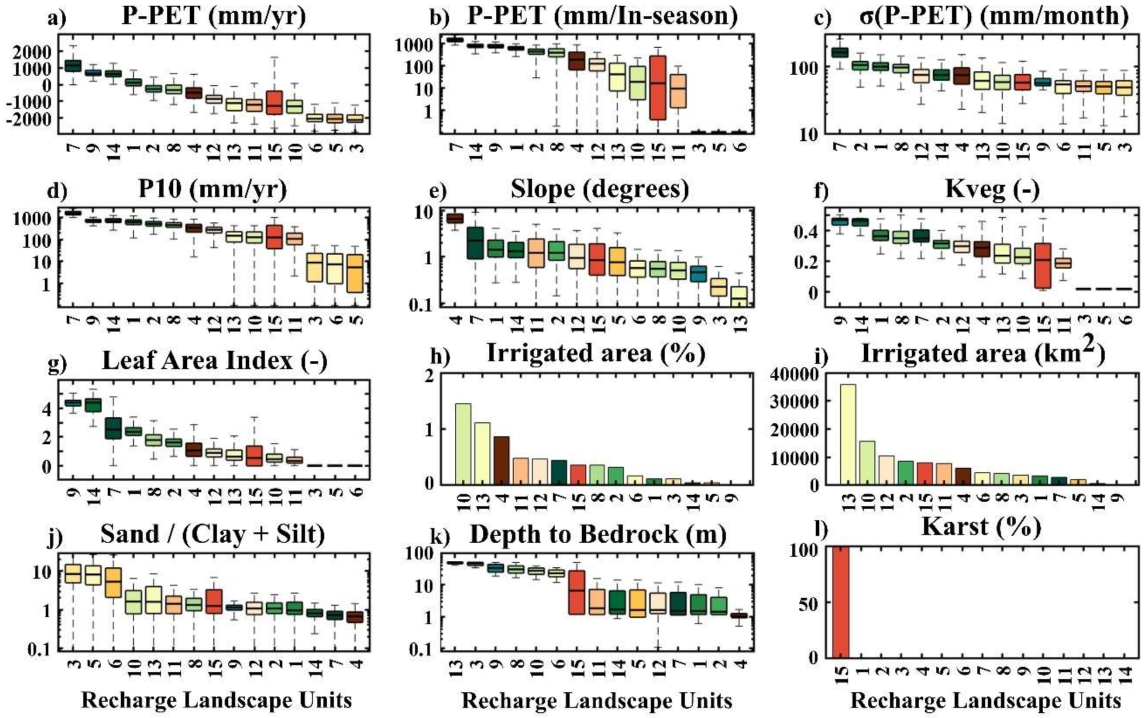

Figure 5. Boxplots showing the index values in each of the Recharge Landscape Units we identified. Boxplots are organised from left to right in descending order of the median values in each unit. We show irrigated area as both the total area irrigated within the Recharge Landscape Units (h) and as a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

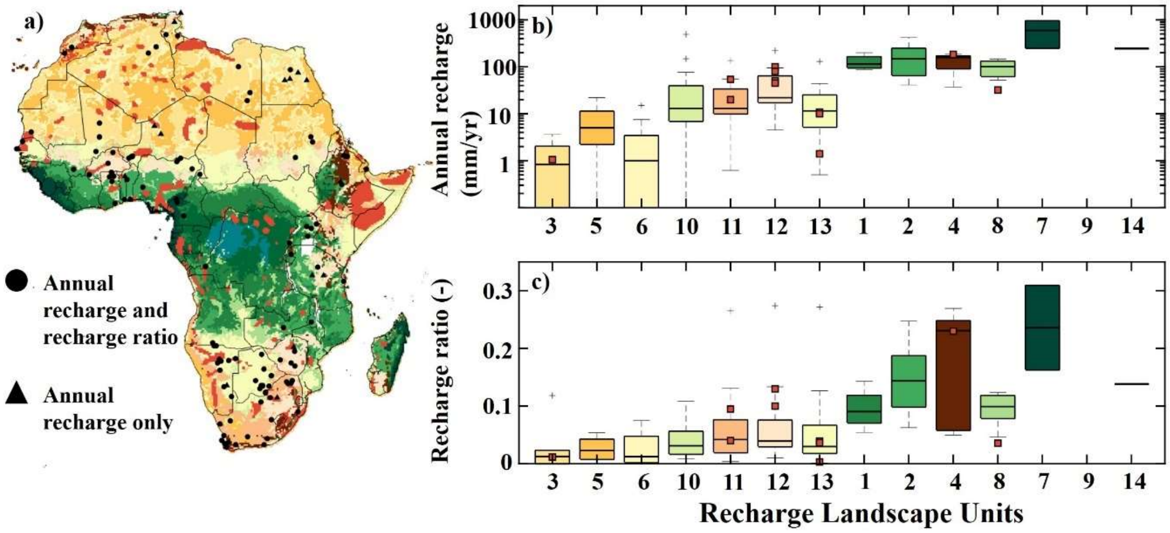

Figure 6. a) Map of ground-based estimate data points distributed across the Classification of recharge controls in Africa. Boxplots of the ground-based estimates of long-term mean annual recharge (b) and recharge ratio (c) found in each of the Recharge Landscape Units. No data points are located within 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.

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 in these units suggest that even when rain does fall, much of the water stored in the sandy soils is subsequently evaporated with very little deeper drainage occurring. 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).

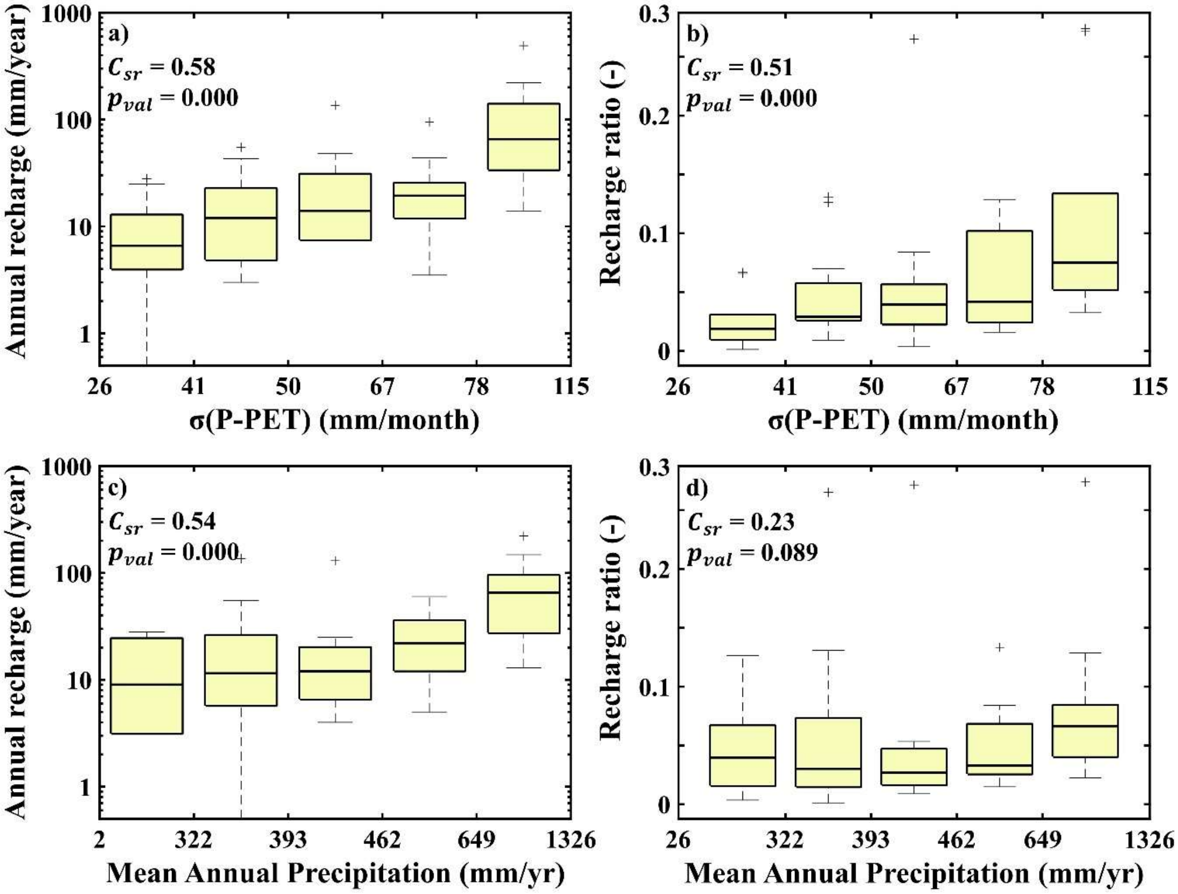

Figure 7. Boxplots showing how ground-based estimates of mean annual recharge (a, c) and recharge ratio (b, d) vary according to monthly variability of P-PET and Mean Annual Precipitation in Dryland Recharge Landscapes. Recharge signatures are binned according to percentiles (0-20; 20-40; 40-60; 60-80; 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 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 ration within this Recharge Landscape: 2 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, which according to our global dataset are located in karst geology, some studies did not report the presence of karst. Highlighting, the limitations of global datasets when investigating ground-based and regional recharge processes. 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. We have further aggregated our 14 (out of 15) Recharge Landscape Units into four Recharge Landscapes, largely according to climate. These Recharge Landscapes 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).

Our Recharge Landscapes broadly resembles 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 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. 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) 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.

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).

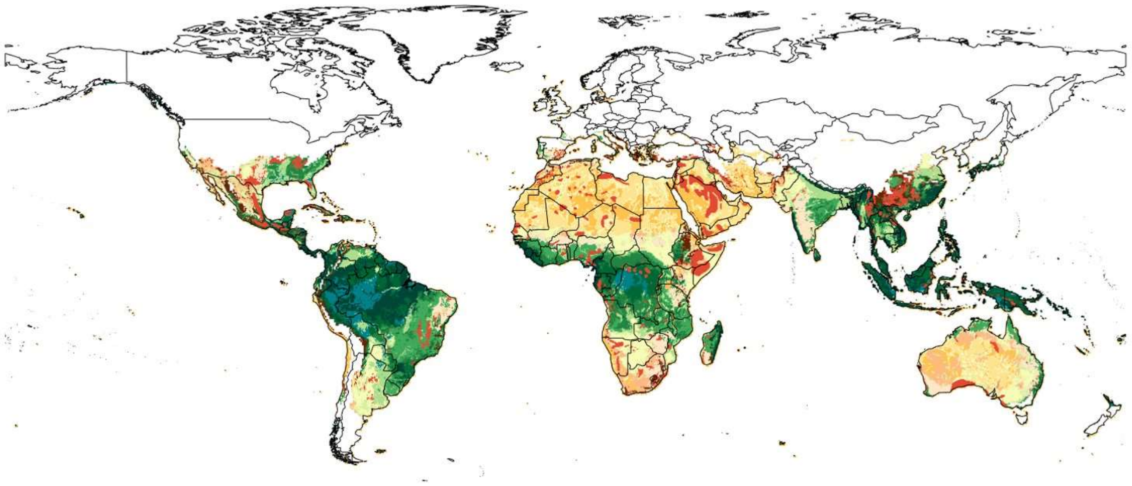

Figure 8. Application of the recharge landscape classification framework to domains outside of the study region. We used a random forest to transfer our Recharge Landscape Units across the rest of the world, with the previously discussed recharge control indices acting as predictor variables. The random 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 explain the variability of estimated recharge signatures within each of the Recharge Landscapes using global datasets alone.

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.

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Supplemental information

S1 Extended 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. We take an approach similar to that of Scanlon et al. (2006), where we record and describe the controls and mechanisms which the literature reports as controlling recharge processes. However, we look across the entire continent and not just dryland systems as is done by Scanlon et al. (2006).

A wide range of methods have been used 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). The most commonly used field methods depend on chemical and isotopic tracers to understand recharge rates, controls and mechanisms; observations of water table fluctuations, dissolved anthropogenic gases or more rarely baseflow separation of river flows are also used. Others also take modelling approaches including soil moisture balance approaches or water balance modelling. Details of the strengths and weaknesses of the different methods can be found in Scanlon et al. (2002) and Healy (2010). A small number of studies have begun to use findings from these approaches to investigate how and why groundwater recharge processes vary across continental or global scales or within certain eco-hydrological zones. Generally, these studies have approached this by compiling datasets of recharge estimates from across the world (Kim and Jackson 2012; Moeck et al. 2020) or by trying to understand recharge mechanisms in greater detail at a much small number of sites (Mark O. Cuthbert et al. 2019; Jasechko et al. 2014; Jasechko and Taylor 2015).

We organize the review of controls into four domains: climate/weather, topography, landcover/use, soils/geology. We initially try to understand the independent effects of each control to recharge and later discuss the interaction of each of the controls and how they define different landscapes in which recharge processes may differ.

S1.1 Climate and weather

The frequency with which groundwater recharge occurs generally varies in-line with the climate gradient (Cuthbert *et al.*, 2019). In humid and sub-humid regions, recharge reliably occurs seasonally or at least inter-annually. In contrast, groundwater stores in arid environments are much more dependent upon episodic rainfall events of great intensity and may largely contain water recharged in previous pluvial flood periods (Sturchio et al. 2004; Sultan et al. 1997). We therefore use the timescale at which groundwater recharge occurs as a means of organising our findings on the role of climate and weather in controlling groundwater recharge in Africa.

Annual scale components of the water-energy balance are considered a first order control on the spatial variability of groundwater recharge (Cuthbert *et al.*, 2019; Kim and Jackson, 2012; Mohan et al., 2018), as they control the quantity of water available to be partitioned into groundwater recharge, as well as the energy available to control atmospheric losses (Budyko, 1974). Globally, (Kim and Jackson 2012) found annual scale climate controls explained 41% of the spatial variability in recharge rates they compiled from the literature, more than any other type of control. In the desert regions of Northern and Southern Africa, where annual rainfall is typically less than 400 mm/year (Nicholson 2000), recharge estimates generally remain below 5mm/year (Dabous and Osmond 2001; Foster et al. 1982; Zouari, Trabelsi, and Chkir 2011). Whilst in the central Highlands of Ethiopia, where annual rainfall can be as high as 1300mm/year, recharge rates of 160 mm/year to 330 mm/year have been reported (Azagegn et al. 2015; Banks et al. 2021; Demlie 2015). Recharge rates of up to 940mm/year have been reported in a tropical upland catchment in Cameroon, where annual rainfall is in excess of 3000mm/year (Kamtchueng et al. 2015). Across a broad range of aridity conditions, Cuthbert et al. (2019) observe increasing annual recharge with annual precipitation in excess of some site specific threshold, though this relationships is not evident at the most humid or arid sites. In the Botswanan Kalahari, groundwater recharge is believed to depend upon annual rainfall exceeding 450mm/year, with water in excess to evaporative demand being stored in thick sands and used by vegetation in subsequent dry periods (Foster et al. 1982). Exceeding these annual rainfall thresholds can often depend upon intense seasonal rains in which much of the years precipitation is concentrated (Mechal, Wagner, and Birk 2015; Taylor et al. 2013; Wirmvem et al. 2015).

Across Africa, groundwater recharge volumes are biased towards rainy season as elevated rainfall is required to overcome high rates of evapotranspiration (Bromley et al. 1997; Demlie et al. 2007; Jasechko et al. 2014; Walraevens et al. 2009). Where precipitation follows a bimodal regime, such as in the equatorial regions (Knoben et al., 2019), the season with the longest duration often produces the most groundwater recharge (Kebede *et al.*, 2005; Owor *et al.*, 2009; Mechal et al., 2015). Throughout these seasons, elevated precipitation intensities lead to a more efficient conversion of rainfall to recharge (Jasechko et al. 2014; Jasechko and Taylor 2015). In Uganda, monsoon rains in excess of 10mm/day lead to seasonally enhanced recharge, contributing significantly to annual groundwater renewal (Owor et al. 2009; Taylor and Howard 1996). At sites in Ethiopia, Tanzania and Mali, recharge mainly occurs in months where rainfall is in excess of 240mm, 210mm and 140mm, respectively (Jasechko and Taylor 2015). Groundwater level observations in the Makutapora wellfield, Tanzania, suggest recharge is dependent upon months with the most extreme (>95th percentile) rainfall (Taylor et al. 2013).

Furthermore, Taylor et al. (2013) found that five of the seven largest recharge events coincided with seasonal rains enhanced by the El Nino Southern Oscillation and the Indian Ocean Dipole. The Pacific Decadal and North Atlantic Oscillations are also known to effect climate patterns in Africa, albeit in different regions (Brown, de Beurs, and Vrieling 2010). These large-scale climate oscillations, which are driven by variations in sea surface temperature, are also known to have opposite effects to climate in different parts of the continent. For example, in East Africa, El Nino (La Nina) events are associated to increased wetting (drying), in contrast to drying (wetting) in Southern Africa (Nicholson and Kim 1997). Cycles of wetting and drying are being reflected in observations of the groundwater hydrograph throughout Africa (Taylor *et al.*, 2013; Cuthbert *et al.*, 2019; 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; Wanke, Dünkeloh, and Udluft 2008). These more intense rainfall events can enable the rapid infiltration of water via preferential flow paths, thus limiting the influence of evapotranspiration during percolation (Mazor et al. 1977; Nkotagu 1996; Sibanda, Nonner, and Uhlenbrook 2009; Van Tonder and Kirchner 1990; De Vries, Selaolo, and Beekman 2000; Xu and Beekman 2003). 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 10mm/day to drylands, below which recharge could not occur. Having identified this threshold via an independent analysis of 25 chloride profile estimates of annual recharge distributed throughout the world and regional model estimates of recharge in Death Valley, California.

Throughout Africa's driest regions, its deserts, groundwater resources are not being actively recharged. Desert aquifers are typically dominated by deep 'fossil' groundwater resources; groundwater which was recharged over 12,000 years ago prior to the beginning of the Holocene (Sturchio et al., 2004; Guendouz et al., 2006; Abotalib et al., 2016; Jasechko et al., 2017). Across the Sahara, paleoclimate regimes have alternated between wet and dry cycles (Abotalib et al. 2016). In wet glacial periods, intensified paleo-winds brought moisture westerly across the desert from the Atlantic Ocean (Abouelmagd et al. 2012; Sultan et al. 1997), condensation of which subsequently led to the rising of groundwater levels and the development of paleo-surface waters such as lakes and swamps (Causse 1989). Between wet cycle glacial periods, the intensification of paleo-monsoons recharged aquifers (Pachur and Hoelzmann 2000; Yan and Petit-Maire 1994). Since the last glacial maximum, only an estimated 1% of groundwater volumes in these environments have been turned over, as rainfall renewal rates are extremely low (Befus et al. 2017).

S1.2 Topography

Landscape topography organizes the landscape into regions of predominantly diffuse, focused and mountain system recharge as discussed in the beginning of this section (Scanlon *et al.,* 2006). Diffuse groundwater recharge we generally perceive to occur in plainlands and places which may only gently undulate, as rainfall infiltration into the subsurface can occur throughout the landscape with limited effects from topographic gradients (Yenehun et al., 2017; Moeck *et al.*, 2020; Tilahun *et al.*, 2020). Though the dominance of each recharge mechanism within a region also depends upon the interaction of topographic features with other recharge controls such as climate, landcover and soil. For example, in arid regions, episodic storms can reactivate ephemeral rivers and water can infiltrate as focussed recharge, despite negligible diffuse recharge in interfluve regions due to high evaporation (Favreau *et al.*, 2009; Cuthbert *et al.*, 2019).

S1.2.1 Focussed Recharge

21% of precipitation in Africa is partitioned to runoff which then feeds the continent's surface water systems of rivers, wetlands and lakes (Schmied et al. 2016). When connected to the groundwater system this can lead to focussed recharge, though not all groundwater-surface interactions promote this recharge mechanism. In systems where the aquifer and surface water store are connected by a continuous saturated zone, both groundwater exfiltration (gaining) and surface water infiltration (losing) may occur (Brunner, Cook, and Simmons 2009; Ivkovic 2009; Winter et al. 1998). In some rivers, the state of losing or gaining stream can vary between the different reaches of the river, whilst in wetlands and lakes the direction of flow can even vary across different parts of the bed (Sophocleous 2002; Winter et al. 1998). These states are not stationary but can vary in time and depend on the net-direction of hydrostatic forces acting at the bed of the surface water body (Winter et al. 1998). Surface and groundwater systems are disconnected when water tables are sufficiently deep that alterations to its position do not influence the infiltration rate (Brunner et al. 2009; Winter et al. 1998). In disconnected systems, surface waters generally lose water to the groundwater system (Ivkovic 2009). The connectivity between groundwater and surface water systems is largely controlled by climate, as in humid environments water tables are typically shallower (M. O. Cuthbert et al. 2019).

Satellite observations now show how the occurrence of water bodies in Africa has changed over the last 30 years (Pekel et al. 2016). Water bodies, which were once perennial have since become seasonal or ephemeral and vice versa. Further still, the distribution of surface water across the continent has changed, with the new water bodies being formed and previous ones disappearing (Donchyts et al. 2016). The occurrence of water bodies thus provides a useful starting point for organising the relationship between surface waters and focused groundwater recharge.

Perennial

Perennial streams predominantly gain water from groundwater inflows, i.e. baseflow (Gordon, McMahon, and Finlayson 2004). This may be well founded, as Beck et al. (2013) show that streamflow in dry Southern African regions are less dependent upon groundwater inflows than streams in tropical regions of the continent. However, the river Nile which is a perennial stream sourced in the Ethiopian Highlands, losses water to the groundwater system in the arid downstream reaches of Sudan and Egypt (Abdalla 2009). Therefore, transmission losses from perennial rivers likely depends upon local climate conditions.

Lakes store 0.03 million km^3 of the Africa's water (Shiklomanov and Rodda 2004), a volume approximately 7.5 times the magnitude of annual freshwater renewability on the continent (FAO 2018; MacDonald et al. 2012; UNEP 2010) and almost entirely attributed to the Great Lakes of Eastern Africa. Owor et al., (2011) used piezometric data to investigate groundwater flows along the northern shores of Lake Victoria and Lake Kyoga in Uganda. They found that the along the stretches of shoreline they studied groundwater predominantly discharged into the lake. On the North Western Ethiopian Plateau, Kebede et al., (2005) suggest that groundwater was flowing towards Lake Tana due to the dipping of geology towards the lake. Other Lakes such as Lake Naivasha in Kenya and the Kosi Bay Lakes in South Africa exhibit though flow processes where regional groundwater discharges into the lake but then reinfiltrates into the groundwater system at a different part of the lake bed (Ojiambo et al., 2001; Ojiambo et al., 2003; Weitz and Demlie, 2014, 2015; Ndlovu and Demlie, 2016). 21%

of Lake Chad's inflows are estimated to recharge the surrounding unconfined shallow aquifer (Isiorho et al., 1996; Edmunds et al., 1999). However, climate forcing and abstractions have caused the surface area of the lake to shrink to less than 10% of its extent in the 1960s (Mahmood and Jia 2019), leading to declines in regional groundwater resources (Leblanc et al. 2007).

There are 726 reservoirs in Africa, with a storage approximately equal to 3% of the continent's lake storage (Lehner et al. 2011) and there are many more either planned or under construction (Zarfl et al. 2014). Existing reservoir storage is mostly concentrated in Southern Africa, although some of the largest reservoirs are along the Nile (High Aswan dam) and Volta (Akosombo dam) rivers as well as the Zambezi (Kariba dam). In dry countries such as Tunisia and Egypt, stable isotopes show reservoir storage is recharging local aquifers and mixing with groundwater recharged thousands of years ago (Aly et al., 1993; Dassi et al., 2005). Recently, (Abdelmohsen et al. 2019) used stable isotopes, borehole observations and observations from the GRACE satellite mission to find that the High Aswan Dam is influencing groundwater stores up to 280km away. They suggest the reservoir and the deep Nubian Sandstone Aquifer System are connected to one another through highly fractured and karstified bedrock, with the reservoir being a consistent source of groundwater recharge in both wet and dry periods. In contrast, groundwater recharge from the Bamendjin dam in tropical and mountainous north western Cameroon is restricted to within 100m (Wirmvem et al. 2015).

Seasonal

Seasonal wetlands often exist in climates and landscapes that prohibit rapid infiltration or lead to groundwater exfiltration (Winter et al. 1998). In a global review of flood plain and headwater wetlands, Bullock and Acreman, (2003) struggled to conclude whether seasonal wetlands enhanced groundwater recharge. Of their 69 references, only six discussed increases in recharge due to wetland conditions, whereas nine highlighted reductions in recharge. A further 32 simply stated that recharge takes places.

Seasonal inundation of some of Africa's large floodplains and inland deltas creates periodic opportunities for extensive groundwater recharge. During seasonal flooding of the Okavango delta in Botswana, the inundated surface area of the flood plain increases from 5,000 km^2 to up to 12,000 km^2. As the alluvial fan primarily consists of highly permeable sands, the groundwater table can rise from a depth 3-5m to the surface within a few days. Infiltration accounts for 90% of losses from the delta of which 80% drain laterally to the surrounding drylands (Ramberg et al., 2006; Wolski et al., 2006). On the other hand, recharge rates under the seasonally inundated Hadejia-Nguru floodplain in northern Nigeria, are less than 1mm/year, as extensive clay cover prevents infiltration (Carter and Alkali, 1996; Edmunds et al., 1999; Goes, 1999). Recharge to the regional aquifer is instead largely attributed to transmission losses directly from the Komadugu river running through the wetland, which equates to 160-260 million m^3 of aquifer recharge per year or 30% to 40% of the rivers total discharge (Genthon et al. 2015). Therefore, highlighting both streambed transmission losses and floodplain inundation as mechanisms through which seasonally high river flows can lead to groundwater recharge and that floodplain inundation further relies upon favourable soil conditions for recharge to occur.

Headwater wetland systems often occur in topographic depressions where most of the year's annual precipitation falls in a short wet season, leading to seasonal inundation. Names used to describe these wetland systems vary regionally and include, Dambos, Bolis, Bas-fonds, Mbuga or Vleis, though they are all frequently associated to crystalline basement geology (Faulkner and Lambert 1991; von der Heyden 2004; Séguis et al. 2011; Wright 1992). These wetlands are typically fed by groundwater recharged upslope as well as direct rainfall and saturation excess runoff and evapotranspiration are the dominant wetland outflows (Faulkner and Lambert 1991; Giertz and Diekkrüger 2003; McCartney 2000; Wright 1992). Infiltration below the wetland is frequently impeded by poorly draining clays which are responsible for the waterlogged conditions (McCartney et al., 1998; Séguis et al., 2011; von der Heyden, 2004). Groundwater fed wetlands can also occur along riparian channels as is the case in the Nyabisheki catchment of south western Uganda (Howard and Karundu 1992). These wetlands can extend up to several kilometres away from the stream channel and are characterized by phreatophyte plants which are capable of transpiring water at the full rate of potential evapotranspiration. Here evaporation and transpiration from the wetlands act as a direct loss to the aquifer system (Howard and Karundu 1992).

Ephemeral

In extremely dry landscapes such as the Sahara Desert, intense rainfall events are important drivers for focused recharge through flash flooding (Sultan et al. 2000) and the formation of ephemeral water bodies (Lehner and Döll 2004). In Northern Africa, the term Wadi refers to a dry riverbed which only receives flow sporadically or perhaps seasonally with similar dry river valleys also being characteristic of basins in southern Africa (Benito et al., 2010; Walker et al., 2019). These riverbeds are usually underlain by an alluvial aquifer system which gets recharged through riverbed transmission losses during heavy rainfall events (Tantawi et al., 1998; Sultan et al., 2000, 2007; Gheith and Sultan, 2002). In a wadi system of Egypt's Eastern Desert, Gheith and Sultan, (2002) estimate that transmission losses from a flooding event in the Red Sea Hills ranged from 21% to 31% of the precipitated volume. With similar rainfall events occurring once every 40 months. Annual flood waves through the Kuiseb River, Namibia, recharge the alluvial aquifer in the lower reaches of river as it crosses the Namib Desert (Benito et al. 2010; Morin et al. 2009). Stable isotope signatures of groundwater within alluvial aquifers of arid environments frequently show signs of fractionation as recharging water is affected by evaporation prior to infiltration (Tantawi et al., 1998; Abdalla, 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.

S1.2.2 Mountains System Recharge

The most well-known mountain ranges in Africa include the Atlas Mountains and Red Sea hills in Northern Africa, the Drakensberg Mountains and Table Mountain Group of South Africa, as well as the East Africa and Ethiopian rift systems. Other prominent mountain ranges can be found along the Nigeria-Cameroon border, Madagascar and across the Sahara (Smethurst 2000). These mountain blocks can be dominant sources of groundwater recharge to adjacent basin aquifers (Markovich et al., 2019; Meixner et al., 2016). We discuss the two components of groundwater recharge to basin aquifers proposed by Markovich et al. (2019), Surface Mountain Front Recharge and Mountain Block Recharge.

Surface Mountain Front Recharge is the infiltration from mountain-sourced perennial or ephemeral streams, through the basin fill at the mountain front, once streams have exited the mountain block (Markovich et al. 2019). Markovich et al. (2019) define the mountain front as the intersection between the land surface and the line of contact between mountain bedrock and basin fill. Though definitions can also encompass information about vegetation, soils, bedrock faulting and may refer to the mountain front as a transition zone instead of as a line or point (Wilson and Guan 2004). Bouimouass et al. (2020) used water table fluctuations and environmental tracers to investigate the effects of agricultural management on mountain front recharge in the High Atlas Mountains of central Morocco. They found that irrigation practices are altering the dominant recharge processes along the mountain front, though mountain front stream losses are still significant in snowmelt or flooding periods.

Mountain Block Recharge is the groundwater flow from the mountain block to the adjacent lowland aquifer, which can either occur diffusely across the entire mountain front, or in focused locations of high geologic permeability (Markovich et al. 2019). Researchers often use stable isotopes to determine the elevation at which precipitation recharged the groundwater system and hence identify groundwater recharged in the mountain block (Jasechko 2019). Combining this with groundwater age information can help understand the degree of mixing between younger and older groundwaters, but they don’t give explicit information about the location of infiltration or how groundwater travels to the basin aquifer (Bouchaou et al. 2008; Boukhari et al. 2015; Diamond and Harris 2000). Therefore many of these findings are highly speculative (Markovich et al. 2019). Kebede et al. (2008) used stable isotopes and groundwater ages from carbon dating to investigate groundwater flow along two transects in the Ethiopian Rift. They find that geological faults can acts as both barriers and conduits for Mountain Block Recharge to the basin aquifer, suggesting that older isotopically depleted groundwater in the basin indicates faults acting as conduits for recharge. Mechal et al. (2016) later explored Mountain Block Recharge in Ethiopian Rift by coupling a semi-distributed soil moisture balance model with a groundwater model. They found that groundwater models which explicitly represented faults as both barriers and conduits for Mountain Block Recharge had improved model performance when compared to hydraulic heads at 72 observations wells. Furthermore, they found that an estimated 25% of recharge in the Gidabo Basin infiltrates to deeper groundwater flows that contribute to Mountain Block Recharge, with the remainder draining to streams.

S1.3 Landcover/use

Tree cover, shrubland and bare soils are the three most dominant landcovers across Africa (Tsendbazar et al., 2017). Desert regions such as the Sahara, the Namib and the horn of Africa are unsurprisingly dominated by bare soils and sparse vegetation. In contrast dense rainforest can be found in central equatorial regions of the continent and tropical woodland spreading into West and South Eastern Africa (Hansen et al., 2013; Mayes et al., 2015; Tsendbazar et al., 2017) and shorter shrub, grass or crop cover is distributed across the Sahel and much of Eastern and Southern Africa (Tsendbazar et al., 2017). Urban settings account for less than 0.01% of the African landscape and are currently expanding at rates slower than the rest of the world (van Vliet 2019; Zhou et al. 2015).

Forests and woodland

Tall vegetation landcovers, such as dense rainforest, open forests and woodlands cover ~26% of Africa's land surface (Mayaux et al. 2004). Trees interact with the water cycle by increasing transpiration and interception and reducing evaporation (Gordon et al., 1992; Fan et al., 2013; Schlesinger and Jasechko, 2014; Goodet al., 2015; Zhang et al., 2016). Atmospheric losses due to transpiration dominate across the African continent. On average 49%, 21% and 7% of precipitation returns to the atmosphere via transpiration, bare soil evaporation and interception, respectively (Zhang et al. 2016). Once rainfall has entered the soil zone, vegetation roots can increase the permeability of soils and infiltration (Burgess et al. 2001). Deep rooting systems increase the capacity of root-zone moisture storage (Nijzink et al. 2016) and access to deeper groundwater (Barbeta and Peñuelas 2017), which leads to the bulk of continental transpiration being associated to tropical forests (Gordon et al., 1992; Good et al., 2015). However, increased canopy cover and shading lead to modest soil and surface water evaporation rates (Good et al., 2015) and moderately enhanced interception (Zhang et al. 2016). Hence, transpiration dominates the evapotranspiration flux in forested environments (Schlesinger and Jasechko 2014).

Globally, (Kim and Jackson 2012) show that woodlands have some of the lowest conversion rates of water input (precipitation + irrigation) to recharge, at just 6%. This is also confirmed in catchment scale studies, which frequently find lower recharge rates in forested parts of the catchment (Gebreyohannes et al. 2013; Houston 1982; Howard and Karundu 1992). Soil moisture balance modelling estimates the mean annual recharge rate for a Zambian catchment to be 281mm/year, though under open forest cover recharge estimations fell to 80mm/year (Houston 1982). In the Ethiopian Rift, Gebreyohannes et al. (2013) estimate mean groundwater recharge under forest cover to be 5mm/year whilst under agriculture and bare soils they find mean estimates of 86mm/year and 64mm/year respectively. Furthermore, the presence of woodland or forest can restrict groundwater recharge to years of particularly high rainfall, even when recharge in grassed, cropped or unvegetated parts of the catchment occurs annually and may exceed 200 mm/year (Houston 1982; Howard and Karundu 1992). Deforestation and the removal of tree cover can enhance groundwater recharge rates by reducing evapotranspiration (Taylor and Howard 1996; Været et al. 2009). In Uganda, (Taylor and Howard 1996) find that deforestation for agricultural expansion has led to an increase in recharge rates from 110mm/year to 240mm/year. While in South Africa, pine tree cover was removed to promote groundwater recharge and discharge to Lake St Lucia (Været et al. 2009).

Most of the continents' losses from interception evaporation occur in the densely forested regions of Central Africa (Miralles et al. 2010; Zhang et al. 2016; Zheng et al. 2017). In these densely forested regions, the evaporation flux of intercepted rainfall can approach rates of 300mm/year and exceed 10% of the precipitation input. Furthermore, canopy storage in these regions is largely continuous, unlike in areas with deciduous vegetation where it can vary (Kahiu and Hanan 2018). We could not find any studies directly discussing the relationship between rainfall interception and groundwater recharge in Africa or elsewhere. However, it seems reasonable to assume that by limiting the amount of rainfall that reaches the land surface, interception is consequently reducing the amount of groundwater recharge which can occur.

Grasslands/shrublands/agriculture

Shorter landcover types such as grasslands, shrublands and agriculture, are largely distributed throughout the Sahel and Southern and Eastern Africa (Tsendbazar et al. 2017), each accounting for an estimated 15.4%, 13.4% and 11.6% of the African land area respectively (Mayaux et al. 2004; Xiong et al. 2017). Managed agricultural land also extends into Northern Africa, along the banks of the river Nile and along the coastline (Xiong et al. 2017). Kim and Jackson (2012) show that globally, grasslands and croplands are more efficient in converting a water input (precipitation + irrigation) to recharge than woodlands, with rainfall-recharge rates of 8%, 11% and 6%, respectively. However, they also found shrublands heathlands and savannas only convert 5% of rainfall to recharge.

In semi-arid West Africa, Ilstedt et al., (2016) discuss the trade-off between the infiltration promotion properties of trees and their interception and transpiration functions. 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). Especially as trees in these drier landscapes can develop deep root systems allowing them to access the water table (Sibanda et al., 2009; Addai et al., 2016). This agrees with chloride profiles in Senegal, which suggest that as vegetation density increases, annual rates of groundwater recharge decline (Edmunds and Gaye 1994). However, Bargués Tobella et al., (2014) find that trees in dryland settings can increase soil infiltration and preferential flow.

Kim and Jackson (2012) show croplands throughout the world are more efficient in converting rainfall to recharge than grasslands, woodlands shrublands and savannas. Although, the impact of land clearing on recharge varies across climate zones and indigenous vegetation types. In an inter-mountain basin in tropical Cameroon, Wirmvem et al. (2015) believe that deforestation for agriculture has enhanced rapid infiltration mechanisms by increasing the number of openings in the soil. In contrast, extensive land clearing of natural savanna for agriculture in semi-arid South West Niger has led to soil crusting on slopes, which in turn has led to increases in seasonal runoff and drainage density (Leduc et al., 2001; Leblanc et al., 2008; Favreau et al., 2009). Increased seasonal ponding has since led to the continuous rising of the water table between 1963 and 2007, despite a monsoon rainfall deficit from 1970 to 1998, as pre and post clearing recharge rates for the area are 2mm/year and 25mm/year, respectively.

Adjacent to many of Africa's largest lakes and rivers, such as lake Chad and the rivers Nile, Senegal, Niger and Orange, agricultural land is being equipped for irrigation (Siebert et al. 2015). Excess irrigation water can infiltrate into the soil and percolate to the aquifer, increasing groundwater recharge rates. This type of recharge can be particularly important in semi-arid and arid environments which have very little natural water input from precipitation (Kim and Jackson 2012). However, groundwater fed irrigation often leads to a net decline in aquifer storage (Guendouz *et al.*, 2006; Bouchaou *et al.*, 2008; Tarki et al., 2012; Wada et al., 2012), unlike surface water fed irrigation which enhances natural recharge with water transferred from streams (Awad et al. 1995; Bouimouass et al. 2020; Scanlon et al. 2007). As irrigation technologies become more efficient, recharge via irrigation excesses will decline (Scanlon et al. 2007), which could also help reduce the salinization of groundwater by excess irrigation water (Bouchaou et al. 2008; Foster et al. 2018).

Bare Soil

Approximately 33% of Africa’s land surface, mostly in North Africa’s Sahara Desert, is classified as bare soil (Mayaux et al. 2004), with additional unvegetated landscapes along the Ethiopian, Somalian and Namibian coastlines. These desert landscapes mostly consist of stony pavements and desert dunes (also known as Ergs), as there is insufficient water to support vegetation (Crouvi et al. 2010; Fujioka and Chappell 2011; Kocurek 1988). Diffuse groundwater recharge is not actively occurring in many desert landscapes as precipitation rates are extremely low (Guendouz et al. 2006; Sturchio et al. 2004), but in less water stressed environments, bare soils can promote groundwater recharge as the transpiration fluxes are negligible (Gebreyohannes et al. 2013; Stone and Edmunds 2012).

Urban settings

40% of the Sub-Saharan population is living in urban areas (World Bank 2019) and many cities depend on groundwater for domestic water supply (Adelana et al. 2008). Understanding groundwater recharge to urban aquifers is therefore important when assessing groundwater availability for a large proportion of the African population.

The typical perception of urbanisation is that it reduces the permeable surface area and therefore reduces groundwater recharge, yet recharge rates in urban areas can be as high as or even higher than nearby rural areas (Lerner 2002; Sharp 2010). Large landscape alterations through urbanization can dampen and modify existing recharge mechanisms as well as introduce new recharge mechanisms. Localised recharge along the edges of roads, pavements and buildings can occur in municipal areas with very little drainage infrastructure (Lerner 2002; Sharp 2010). Leaking wastewater from on-site sanitation can be a source of groundwater recharge and pollution, degrading urban groundwater quality (Diouf 2012; Foster, Morris, and Chilton 1999; Guendouz et al. 2006; Lapworth et al. 2017). And if piped water supply is available, leakage from pressurized distribution networks can recharge the urban aquifer.

S1.4 Soils/geology

Soil texture (grain size)

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). In soils with high clay content, not only is the vertical percolation of water through the soil profile restricted (Attandoh et al. 2013; Edmunds et al. 1992), but soil moisture is more exposed to evapotranspiration fluxes (Mensah et al, 2014; Yidana and Koffie, 2014; Kotchoni et al., 2018). Often basic soil information such as soil texture is used to characterize the permeability of soils (Saxton et al., 1986; Wösten et al., 2001), though Gutmann and Small (2007) question the ability of soil textures alone for determining soil permeability.

Preferential flow

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 water to infiltrate preferentially through the subsurface, bypassing vegetation rooting zones and reducing the influence of evapotranspiration. In most soils, the primary influence to soil structure is biological activity through the formation of biopores and soil aggregation (Bargués Tobella et al. 2014; Beven and Germann 1982; Flury et al. 1994), though several abiotic processes are also influential (Oades 1993). The contribution of preferential flow to groundwater recharge can be estimated by comparing from saturated and unsaturated zone analysis (Cuthbert and Tindimugaya 2010; Demlie 2015; de Vries and Gieske 1990). Preferential flow path recharge mechanisms are important in contrasting environmental settings. In the Botswanan Kalahari Desert, semi-arid Tanzania and the tropical highlands of Ethiopia, preferential flow can account for as much as 24%, 60% and 36% of total recharge estimates, respectively (Demlie et al. 2007; Nkotagu 1996; de Vries and Gieske 1990).

Preferential flow paths may partly explain why Mazor (1982) identified more active recharge in the Kalahari when dating groundwaters using tritium and carbon dating, despite the previous perception that it was negligible. In South Africa’s Karoo basin, Van Tonder and Kirchner (1990) found that groundwater levels rose following a flood event, despite neutron probe measurements showing very little soil matrix flow very little soil matrix flow. Hence implying most of the recharge occurs via preferential flow paths. In Ethiopia, Demlie et al. (2007) suggest that as soils become deeper, the importance of preferential flow paths for enabling recharge increases.

Rock fracturing can also create pathways through which water can rapidly pass through the subsurface and recharge aquifers (Nkotagu, 1996; Xu and Beekman, 2003; Adams et al., 2004; Kebede et al., 2005; Azagegn et al., 2015). Extensive faulting and fracturing in the catchment of Lake Nyos, in the highland tropical north west of Cameroon, allows for approximately 30% of rainfall to be converted into recharge, with an estimated annual recharge rate of 941mm/year (Kamtchueng et al. 2015). In hard rock terrains of Southern Africa, van Wyk et al., (2012) suggest that a network of vertical and sub-vertical joints and fractures reaching depths of 45m, transports infiltrating rainfall to the water table within hours.

Another relevant geological unit related to preferential flows is karst, which can create significant subsurface heterogeneity of flowpaths. Vertical conduits in the karstified rock enable rapid recharge mechanisms whereby water does not occupy the soil zone for long times (Chemseddine et al., 2015), exposure to evapotranspiration is minimised and very little runoff is generated (Ayadi et al. 2018; Farid et al. 2014; Holland and Witthüser 2009; Leketa et al. 2019). Karst refers to a distinctive geological landform in which water is drained through subsurface channel and cavity features formed through the dissolution of soluble rocks such as carbonates and evaporites (Bakalowicz 2005; Ford and Williams 2007). This karstification leads to a highly heterogenous subsurface with extreme variations in hydraulic conductivity and storage due to the previously mentioned weathering processes (Ford and Williams 2007). Regional scale hydrological modelling of carbonate regions in Northern

Africa and Europe shows that by not characterizing the sub-surface heterogeneity of karst systems in global models, current estimates of annual recharge from global models could be grossly underestimating recharge in these landscapes (Hartmann et al. 2017).

Bedrock outcrops

In dry landscapes, bedrock outcrops are important for enhancing groundwater recharge because of rock fractures. In the Kalahari Desert, recharge under the bedrock outcrops can be up to six times larger than neighbouring areas with greater soil depths, with estimated rates reaching 75mm/year (Brunner et al. 2004; Mazor 1982; Wanke et al. 2008). Soils can become thinner with increasing elevation, which in turn can lead to more effective conversion of rainfall to recharge and higher annual rates, as Van Tonder and Kirchner (1990) found in two Karoo aquifers in South Africa. Isolated rock formations called inselbergs are widely distributed across crystalline continental shields and have been formed by erosion of the surrounding landscape (Burke 2003). Groundwater responses under inselbergs are generally much faster than in the broader surroundings, as infiltration through the fractured rock is easier and less exposed to evaporation (Brunner et al. 2004; Butterworth et al. 1999).

Soil perturbation

Crusting, cementation, weathering, tillage and compaction are soil perturbations at the surface that can have significant impact on recharge rates.

(i) In arid and semi-arid regions soil crusting can prevent precipitation from infiltrating into the soil where it has fallen (Wakindiki and Ben-Hur 2002), but often leads to runoff run-on process which cause surface water accumulation and focussed recharge (Favreau et al. 2009; Jacks and Traoré 2014). Surface crusting occurs because of the disaggregation of soil particles at the surface via the impact of raindrops (Agassi et al., 1981; Thierfelder et al., 2013; Jacks and Traoré, 2014) or immersion in water (Nciizah and Wakindiki 2015).

(ii) The cementation of soil layers by secondary minerals (minerals that occur due to the weathering of primary minerals) such as silica and calcium is common in dry landscapes with large evaporation fluxes (Francis et al. 2007). Collectively referred to as duricrusts (Nash et al., 1994; Nash and Shaw, 1998), these cemented layers reduce the permeability of the soil and promote water logging (Francis et al. 2007). However, preferential flow paths can bypass these layers to permit groundwater recharge (De Vries et al., 2000; Mazor, 1982; Van Tonder & Kirchner, 1990; Xu & Beekman, 2003).

(iii) Deeply weathered soils known as laterite are found extensively across tropical regions of Africa (Bonsor et al., 2014) and the world (FAO, 2001; McFarlane, 1970). The weathering process creates distinct soil horizons which are responsible for extremely non-linear variations in soil permeability with depth (Bonsor et al. 2014). Clays at the base of the laterite can inhibit recharge to the underlying bedrock aquifer (Bonsor et al. 2014), while tubular voids in the upper horizons can allow fast recharge to the overlying regolith aquifer (Bromley et al. 1997; Cuthbert and Tindimugaya 2010) as wells as rapid shallow sub-surface flows to the stream (Bonsor et al. 2014). When the upper soil horizon does not contain large voids, low soil permeability can cause a runoff run-on process leading to focussed recharge (Rueedi et al., 2005).

(iv) Tillage is the practice of mechanically loosening soil within the crop rooting zone in preparation for agricultural activities. The current understanding of how tilling effects soil infiltration rates is still rather unclear as findings from studies can be inconsistent (Strudley, Green, and Ascough 2008), with evidence for both increases (Mrabet, 2002; Spaan et al., 2005) and decreases (Lal, 1976; Osunbitan et al., 2005) in infiltration, depending upon the soil type (Thierfelder and Wall 2009), the equipment being used (Abu-Hamdeh 2004) and tilling depth (Hussein et al., 2019).

(iv) Soil degradation caused by soil compaction affects approximately 0.6% of Africa's land area (Oldeman et al., 2007) due to livestock and wildlife (du Toit et al., 2009; Howison et al., 2017) or human activity (Randrup, 1997; Hamza and Anderson, 2005; Umer et al., 2019). It reduces the infiltration capacity of the soil (Hamza and Anderson 2005; du Toit et al. 2009), thus reducing groundwater recharge and increasing runoff, especially in regions where infiltration excess is the dominant runoff mechanism (Alaoui et al. 2018).

S1.5 Managed Aquifer Recharge

Managed Aquifer Recharge refers to a range of methods used to intentionally increase groundwater recharge, which include, modifying the channel streambed, bank filtration, recharge wells, spreading water or reservoir releases (Dillon et al. 2019; Stefan and Ansems 2018). These methods can help maximise natural water storage, support groundwater dependent ecological systems and help manage groundwater quality and the aquifer (Stefan and Ansems 2018). Current capacity for Managed Aquifer Recharge is lower in Africa than in all other regions of the world and accounts for just 0.2% of groundwater use in Southern Africa (Dillon et al. 2019). Highlighting one possible opportunity for advancing groundwater security in Africa (Grönwall and Oduro-Kwarteng 2018). In a rural Ethiopian catchment, (Walraevens et al. 2015) find that hill slope runoff captured by trenches and infiltration ponds can contribute between 30% and 50% of recharge to the local aquifer, which supports community scale irrigation practices. Sand storage dams, which store stream flows in sediments accumulated behind the small dams, can capture water from flash flooding events and minimise storage losses by evaporation (Hut et al. 2008). Abiye et al., (2009) even suggest that Managed Aquifer Recharge could be a preferred discharge option for treated urban wastewater effluents in Addis Ababa, instead of returning flows to more polluted surface waters.

S1.6 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).

S1.7 Summary

Summarizing our review, we believe that 15 of the 22 recharge controls identified have a clear positive (blue) or negative (red) relationship with recharge (Figure 1). Before integrating any of the recharge controls into our classification shown in the results section, they were screened against three criteria. Firstly, there needed to be a clear, well-founded and direct relationship between the recharge control and recharge. We do not include elevation as a control on groundwater recharge, although others have (Moeck et al. 2020), as we argue it only indirectly influences recharge through its relationship with climate, slope, landcover, soils and geological characteristics. Secondly, only controls which could be identified by global datasets were included. Finally, as our focus is on diffuse groundwater recharge, we exclude controls which were not found to directly effect this recharge mechanism.

S2. Fuzzy clustering

To delineate regions with similar recharge control indices we use the fuzzy c-means clustering algorithm (Bezdek 1981) implemented in Matlab as the function fcm. At first the membership of pixels to each of the units is randomly initialized. The algorithm starts by randomly assigning the membership of pixels to each of the units. It then continues to iteratively calculate the centroid of each unit, the membership of each pixel to each of the units and an objective function which we are trying to minimise. This continues until the difference between consecutive objective function scores falls below a user-specified threshold or until a maximum number of iterations (also specified by the user) has been reached. To prevent biasing the clustering process to the recharge control index with the largest range, we first standardized all indices between 0 and 1.

$$c_j = \frac{\sum_{i=1}^{D} \mu_{i,j}^{m} x_i}{\sum_{i=1}^{D} \mu_{i,j}^{m}}$$

$$\mu_{i,j} = \frac{1}{\sum_{k=1}^{N} \left(\frac{\lVert x_i - c_j \rVert}{\lVert x_i - c_k \rVert} \right)^{\frac{2}{m-1}}}$$

$$OF_m = \sum_{i=1}^{D} \sum_{j=1}^{N} \mu_{i,j}^{m} \lVert x_i - c_j \rVert^2$$

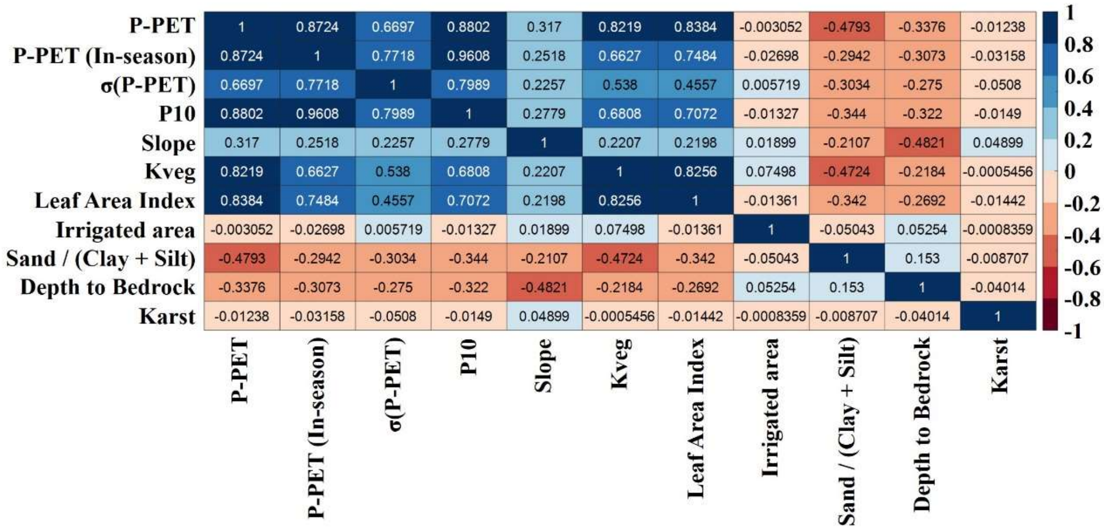
where,

- OF is the clustering objective function.
- m is a fuzzy exponent parameter.
- N is the number of units specified.
- D is the number of data points.
- x_i is the i^{th} data point.
- c_j is the centroid of the j^{th} unit.
- $\mu_{i,j}$ is the membership of x_i to the j^{th}cluster. For a given data point, the sum of the membership values to each of the units is equal to one.

Algorithm parameters include the number units (N) used to delineate similar regions as well as a fuzzy exponent parameter (m), which determines the fuzziness of boundaries between units (Schwämmle and Jensen 2010). We tested different combinations of the number of units (1 to 40) and the fuzzy exponent (1.05 to 3) to observe how this effected the objective function of the clustering algorithm as well as the median membership of pixels to their primary unit of the realized classification. We specified 14 units and a fuzzy exponent of 1.25, as this minimised the objective function to a level similar to classifications with much higher units, whilst still finding pixels with a high degree of membership to their primary unit.

As the initial centroids of each unit are randomly assigned before being iteratively manipulated towards their final positions, their final positions and hence the classification can vary with each initiation of the clustering algorithm. We therefore used a multistart framework (20 initialisations) to test the robustness of our results, using the Adjusted Rand Index (Hubert and Arabie 1985) to assess the similarity between each of the realized classifications. Scores of 0 indicate no similarity between two classification schemes, whereas a score of 1 implies that the two classification schemes are identical.

S3. Supporting results



	P-PET	P-PET (In-season)	σ(P-PET)	P10	Slope	Kveg	Leaf Area Index	Irrigated area	Sand / (Clay + Silt)	Depth to Bedrock	Karst
P-PET	1	0.8724	0.6697	0.8802	0.317	0.8219	0.8384	-0.003052	-0.4793	-0.3376	-0.01238
P-PET (In-season)	0.8724	1	0.7718	0.9608	0.2518	0.6627	0.7484	-0.02698	-0.2942	-0.3073	-0.03158
σ(P-PET)	0.6697	0.7718	1	0.7989	0.2257	0.538	0.4557	0.005719	-0.3034	-0.275	-0.0508
P10	0.8802	0.9608	0.7989	1	0.2779	0.6808	0.7072	-0.01327	-0.344	-0.322	-0.0149
Slope	0.317	0.2518	0.2257	0.2779	1	0.2207	0.2198	0.01899	-0.2107	-0.4821	0.04899
Kveg	0.8219	0.6627	0.538	0.6808	0.2207	1	0.8256	0.07498	-0.4724	-0.2184	-0.0005456
Leaf Area Index	0.8384	0.7484	0.4557	0.7072	0.2198	0.8256	1	-0.01361	-0.342	-0.2692	-0.01442
Irrigated area	-0.003052	-0.02698	0.005719	-0.01327	0.01899	0.07498	-0.01361	1	-0.05043	0.05254	-0.0008359
Sand / (Clay + Silt)	-0.4793	-0.2942	-0.3034	-0.344	-0.2107	-0.4724	-0.342	-0.05043	1	0.153	-0.008707
Depth to Bedrock	-0.3376	-0.3073	-0.275	-0.322	-0.4821	-0.2184	-0.2692	0.05254	0.153	1	-0.04014
Karst	-0.01238	-0.03158	-0.0508	-0.0149	0.04899	-0.0005456	-0.01442	-0.0008359	-0.008707	-0.04014	1

Figure 9. Pearson correlation coefficients between the different recharge control indices we used to develop our classification of recharge controls across Africa. Coefficients relate to the linear relationships between indices across Africa only.

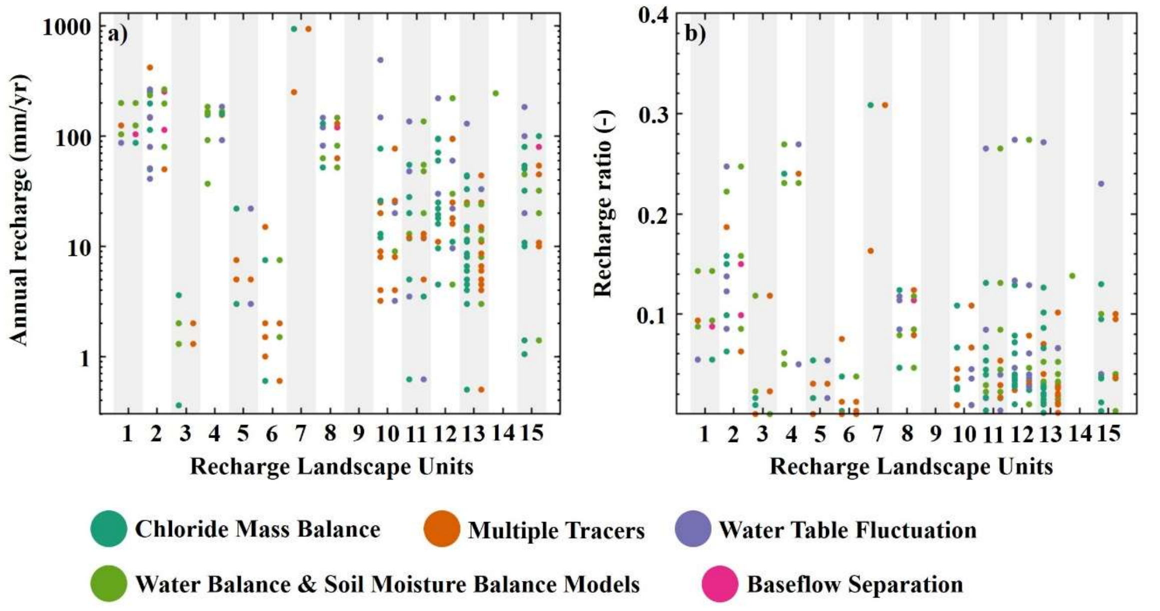


Figure 10. a) Local estimates of annual recharge and b) local estimates of recharge ratio. Estimates are organised according to the Recharge Landscape Unit they are located in, and colour coded according to estimation approach. Most data points are represented by two side-by-side markers reflecting the primary (left) and secondary (right) estimation method. Estimates which are found using one approach only are represented by a single marker.

From figure 2 we cannot see any clear separation of annual recharge or recharge ratio estimates according to the different estimation methods used. Therefore, we assume that the estimation method is not the primary reason for variability in annual recharge and recharge ratio estimates in within Recharge Landscape Units.

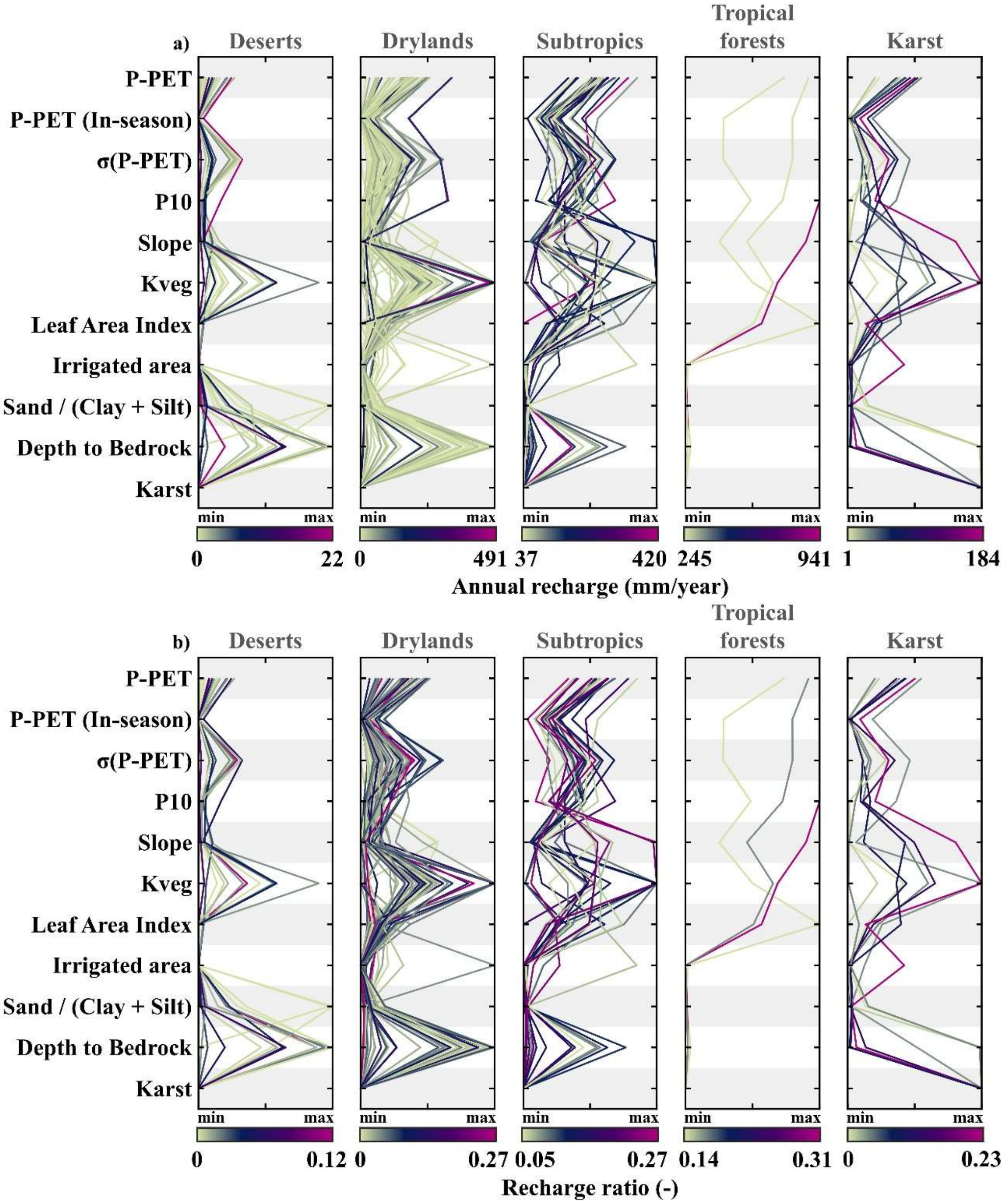


Figure 11. Parallel co-ordinate plot showing the scaled recharge control indices at each individual site organised into its corresponding Recharge Landscape. Indices at each site are scaled between 0 (minimum) and 1 (maximum) using the index values corresponding to our local estimate sites. Each line represents an individual site and colour coding reflects a) annual recharge and b) recharge ratio. The colour axis for each subplot is specific to the range of local annual recharge or recharge ratio estimates in that landscape. We separate out sites in karst settings to explore what causes recharge variation within these environments.

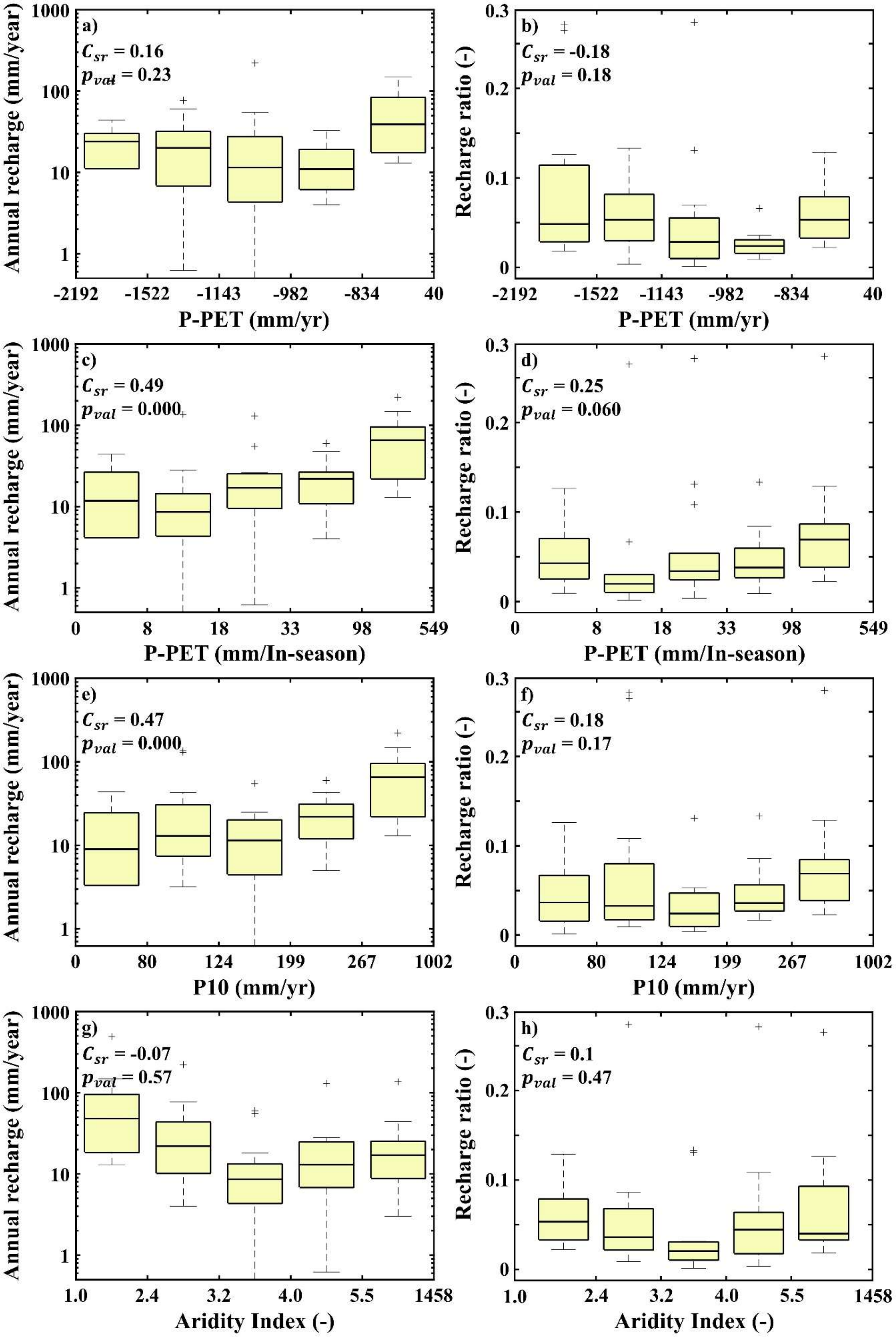


Figure 12. Boxplots showing how ground-based estimates of mean annual recharge vary according to (a) P-PET; (c) P-PET in-season; (e) P10; (g) Aridity Index (i.e., PET/P) *in Dryland Recharge Landscapes*. Boxplots showing how ground-based

estimates of mean annual recharge ratios vary according to (b) P-PET; (d) P-PET in-season; (f) P10; (h) Aridity Index (i.e., PET/P) *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.

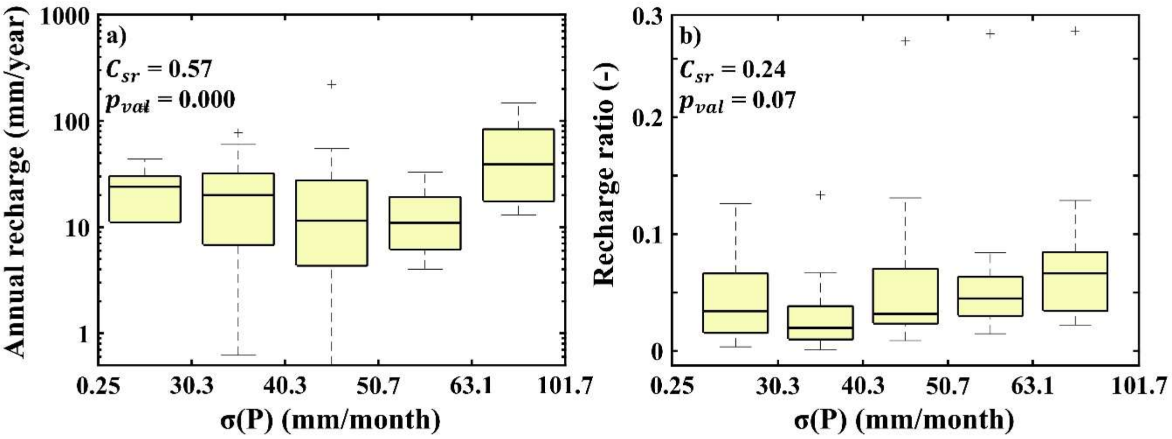


Figure 13. Boxplots showing how ground-based estimates of mean annual recharge (a) and recharge ratio (b) vary according to monthly variability of precipitation in Dryland Recharge Landscapes. Recharge signatures are binned according to percentiles (0-20; 20-40; 40-60; 60-80; 80-100) of the controlling 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.

S4. Expanding our classification for diffuse groundwater recharge controls in Africa to the rest of the world

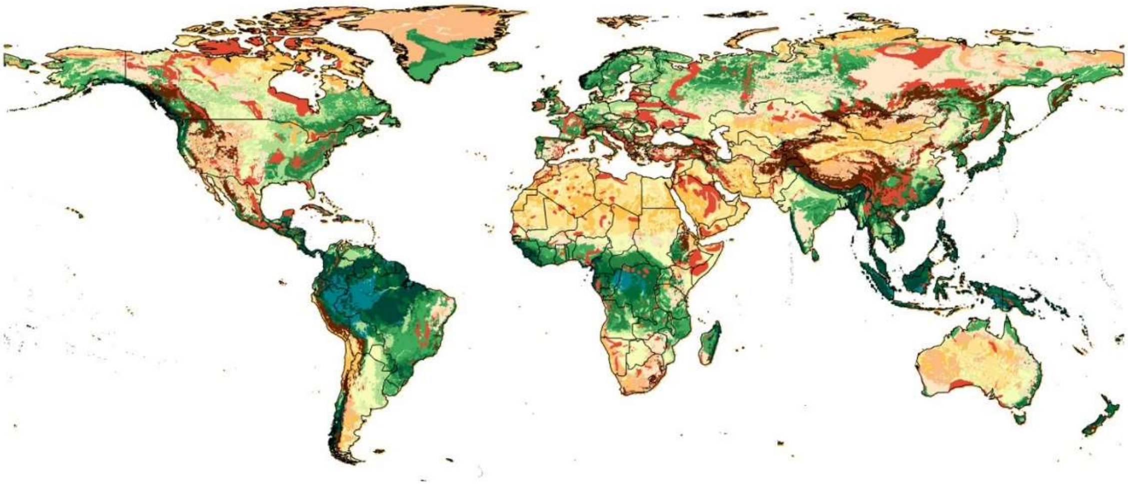


Figure 14. Transferal of Recharge Landscape Units to domains outside Africa using the random forest model and still including areas which we defined as significantly dissimilar to Africa according to temperatures and snow fractions.

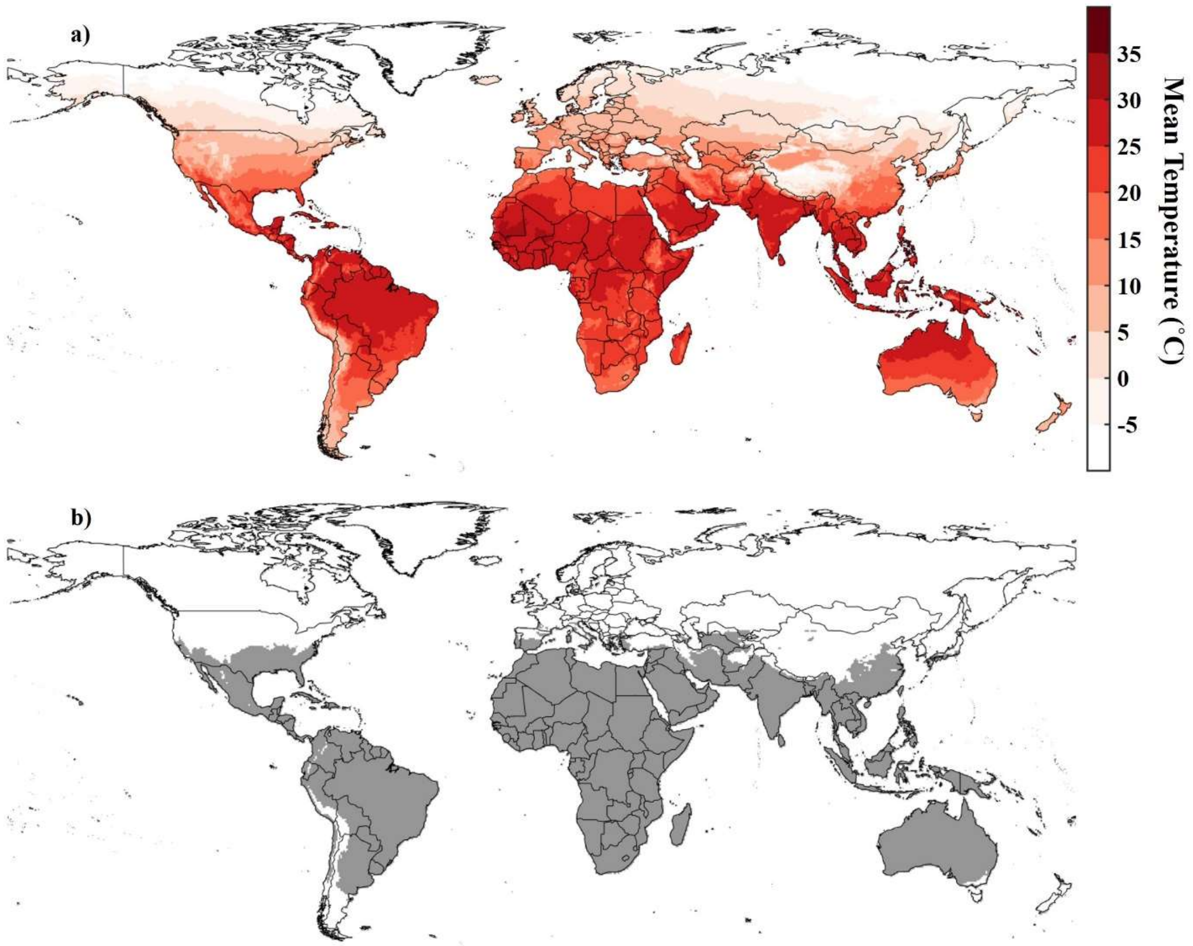


Figure 15. a) Mean temperature in degrees Celsius; b) Regions included in global classification of Recharge Landscape Units according to mean temperatures. Areas outside of Africa are excluded if the mean temperature is regarded as an outlier, whilst all pixels within Africa are included. We defined outliers as pixels where the temperature is below $Q_1 - (1.5 \times IQR)$ or above below $Q_3 + (1.5 \times IQR)$. Where Q_1 is the 25th percentile of mean temperatures within Africa, Q_3 is the 75th percentile of mean temperatures within Africa and IQR is the inter-quartile range mean temperatures within Africa. We use a global gridded dataset of daily temperature provided by the Climate Prediction Center, NOAA (NOAA/OAR/ESRL PSD).

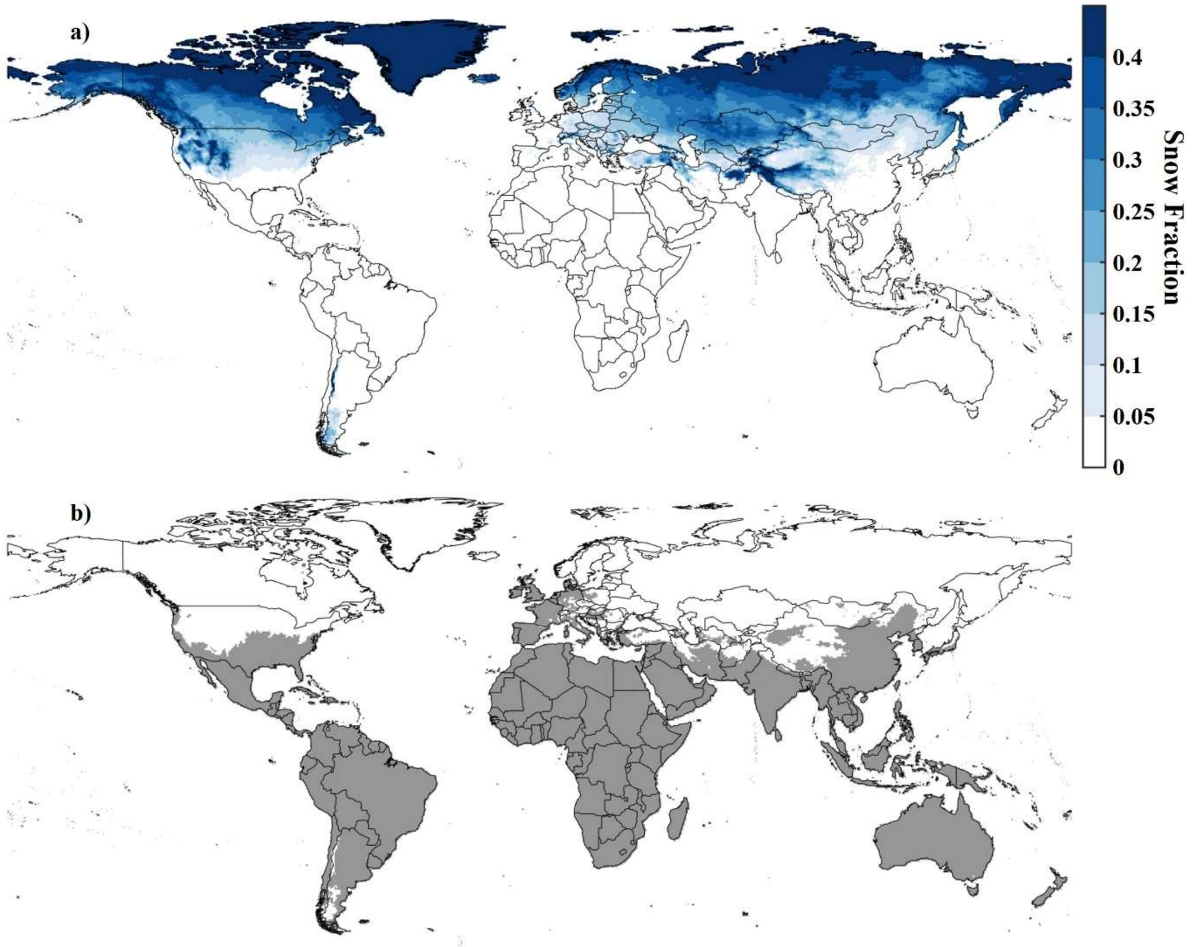


Figure 16. a) Snow fraction (Mean annual snowfall/Mean annual precipitation); b) Regions included in global classification of Recharge Landscape Units according to Snow fractions. Areas outside of Africa are excluded if the snow fraction is above 0.1. The maximum snow fraction we find in Africa is 0.087. 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; Stein et al., 2020). We use a global gridded dataset of daily temperature provided by the Climate Prediction Center, NOAA (NOAA/OAR/ESRL PSD).

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