A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships

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Abstract

Groundwater recharge indicates the existence of renewable groundwater resources and is therefore an important component in sustainability studies. However, recharge is also one of the least understood, largely because it varies in space and time and is difficult to measure directly. For most studies, only a relatively small number of measurements is available, which hampers a comprehensive understanding of processes driving recharge and the validation of hydrogeological model formulations for small- and large-scale applications.

We present a new global recharge dataset encompassing more than 5000 locations. In order to gain insights into recharge processes, we provide a systematic analysis between the dataset and other global-scale datasets, such as climatic or soil-related parameters. Precipitation rates and seasonality in temperature and precipitation were identified as the most important variables in predicting recharge. The high dependency of recharge on climate indicates its sensitivity to climate change. We also show that vegetation and soil structure have an explanatory power for recharge. Since these conditions can be highly variable, recharge estimates based only on climatic parameters may be misleading.

The freely available dataset offers diverse possibilities to study recharge processes from a variety of perspectives. By noting the existing gaps in understanding, we hope to encourage the community to initiate new research into recharge processes and subsequently make recharge data available to improve recharge predictions.

1. Introduction

Understanding the balance between recharge input and discharge output of aquifers forms a basis of groundwater resource management. Groundwater recharge feeds aquifers, which supply fresh water to large parts of the global population and irrigated agriculture and feeds rivers and lakes, thereby maintaining aquatic ecosystems during dry periods (Aeschbach-Hertig and Gleeson, 2012, Döll and Fiedler, 2008, Ferguson and Gleeson, 2012, Gleeson, et al., 2016, Gleeson, et al., 2010, Gurdak, 2017, Jasechko, et al., 2014, Jasechko, et al., 2017, Wada, et al., 2016, Wada, et al., 2010). As the global population continues to grow, more people will rely on groundwater resources, especially in semi-arid and arid regions (Scanlon, et al., 2006).

Recharge occurs through diffuse and focused mechanisms (Bakker, et al., 2013, Germann and Beven, 1981, Ghasemizade, et al., 2015, Scanlon, et al., 2002, Weiler and Naef, 2003). Diffuse recharge in natural settings is distributed in response to precipitation infiltrating the soil surface and percolating through the unsaturated (vadose) zone to the water table due to matrix flow. Focused, or localized, recharge occurs through pooling at the soil surface and fast infiltration via predominantly vertical joints and cracks in the unsaturated zone (macropore flow). Also, biological effects (e.g. earthworm and root channels) can enhance the infiltration capacity in the topsoil (Cheng, et al., 2017). Typically, diffuse recharge dominates in humid settings, whereas focused recharge occurs in semi-arid/arid environments with relatively few but intense rain events(Saez et al., 2016, Herrera et al., 2018). The spatial variability of rainfall can have a significant impact on recharge rates and other hydrological responses (Sapriza-Azuri et al., 2015). As the degree of aridity is expected to increase under climate change, the importance of focused recharge is expected to increase (Alley, 2009).

A special case is mountain recharge, which provides freshwater for a large part of the global population, especially in semi-arid regions ((Manning and Solomon, 2003, Viviroli, et al., 2007). The mountain system recharge can be separated into i) mountain front recharge, which is the contribution of mountain regions to the recharge of aquifers in adjacent basins and includes infiltration of mountain stream runoff into the alluvial fan streambeds and in ii) mountain block recharge where precipitation infiltrates through the bedrock (Ajami, et al., 2011, Wilson and Guan, 2004). A mountain block includes all the mass composing the mountains, including vegetation, soil, bedrock (exposed and unexposed), and groundwater. The mountain front is positioned somewhere between the mountain block and the basin floor. Thus, mountain block water can be transported through local and

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regional flow paths to the mountain front and through regional flow to the deep basin. The combination of hydrochemical and isotope techniques allow defining the processes controlling the aquifer recharge besides delineating conceptual models that explain aquifer behavior (Barberá et al., 2019, Lambán et al., 2014, Urrutia et al., 2019). Although mountain recharge is important for providing freshwater and a conceptual models can be derived, key recharge processes in these systems are difficult to assess and absolute recharge rates are rarely reported (Bresciani, et al., 2018). Irrigation can locally be the dominant process for aquifer replenishment, because of the predominance of irrigated agriculture in many regions (Baillieux et al., 2015, Lauffenburger et al. 2018; Meixner et al. 2016). To a lesser extent, managed aquifer recharge may also play a role in some regions, especially considering the increasing demand for groundwater for residential and industrial use supplied by these systems (Bekele et al., 2014, Dillon, P., 2005, Dillon et al., 2019, Moeck et al., 2017). Although irrigation and managed aquifer recharge can be important, they are neglected in this study due to sparse global information available about practices and amounts.

Recharge rates may also vary and change due to land use changes even though climatic conditions remain the same (DeFries and Eshleman, 2004, Harbor, 1994, Huang and Pang, 2011, Minnig, et al., 2018, Scanlon, et al., 2005). For instance, Scanlon et al. (2005) demonstrated that changes in recharge occur when grassland is converted to agricultural ecosystems and Minnig, et al. (2018) as well as Wakode, et al. (2018) show that recharge rates can be considerably higher in an urban environment compared to regions without urban influences, an important finding considering that half of the world's population lives in urban areas (McDonald et al., 2014; Schirmer et al., 2013, Vazquez-Sune et al., 2010). Urbanization-related processes affecting groundwater recharge are the increase of impervious surfaces, leading to evapotranspiration reduction and runoff increase (Lerner, 2002, Minnig et al., 2018) and water supply and sewer networks, which increase groundwater recharge rates due to leakages (del Campo et al., 2014, Minnig et al., 2018).

Although recharge is one of the most important components in groundwater sustainability studies, it is also one of the least understood, largely because recharge rates vary greatly in space and time and are difficult to measure directly (Healy and Cook, 2002, Moeck, et al., 2018, Scanlon, et al., 2002, von Freyberg, et al., 2015). Indeed, at the catchment scale, recharge cannot be readily measured experimentally (Scanlon et al., 2002); direct measurements of recharge can only be obtained at the plot scale, for example from lysimeters (von Freyberg et al., 2015). Lysimeters typically imitate the surrounding environment, which allows for direct measurements of evapotranspiration, soil

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moisture and seepage through the unsaturated zone (Goss et al., 2010, Muller and Bolte, 2009, Stumpp et al., 2009). Measured seepage can be a good indicator for groundwater recharge and groundwater fluctuation on different temporal scales (Lehmann et al., 2019, Moeck et al., 2018, Scanlon et al., 2002, von Freyberg et al., 2015). However, even though, lysimeter measurements are available at various sites around the world, long-term continuous measurement time series are very scarce (Seneviratne et al., 2012, Lanthaler and Fank, 2005). An interesting concept is the German soil-climate crossed factorial experiment (TERENO-SOILCan; Pütz et al., 2016). The lysimeter network has been initiated to assess effects of climatic changes on soil ecosystems and use a "space-for-time" concept where intact soil monoliths were moved to sites with contrasting climatic conditions (Groh et al., 2018). However, lysimeters are expensive and high maintenance is required and the size of the lysimeters, both in terms of diameter and depth as well as the chosen bottom boundary can be critical for the measured fluxes (Groh et al., 2016, Healy 2010, Scanlon et al., 2002, von Freyberg et al., 2015). Moreover, only vertical fluxes are assessed, and uncertainties might be introduced by a distorted soil-moisture and pressure-head profile due to the open drainage collection system (Scanlon et al., 2002) and preferential flow along the inner lysimeter wall (Stumpp et al., 2012). Thus, to minimize inherent uncertainty from field methods such as lysimeters measurements, water-balance calculations and hydrogeological models are additionally applied to understand relationships between climate, land-use changes and recharge in order to generate recharge predictions, (Gleeson, et al., 2012, Meixner, et al., 2016, Scanlon, et al., 2007).

For most recharge studies, only a relatively small number of measurements is available (Ghasemizade, et al., 2015, Gurdak, et al., 2007, Scanlon, et al., 2002). To upscale these results, large-scale models may be employed to compensate for the lack of observations and fill spatial gaps (de Graaf, et al., 2017, Döll and Fiedler, 2008, Döll, et al., 2014, Döll, et al., 2003, Döll and Zhang, 2010, Wada, et al., 2016, Wada, et al., 2011, Wada, et al., 2010). This approach is commonly used, especially to estimate spatial soil moisture conditions and evapotranspiration (ET) as well as groundwater recharge rates (Döll and Fiedler, 2008, Orth and Seneviratne, 2015, Wada, et al., 2016). Alternatively, large-scale evapotranspiration rates can also be narrowed down with stable water isotope methods as highlighted by Barth et al. (2007) and Schulte et al. (2011). Incorporating isotopes in regional or global studies and models will certainly be a tool for monitoring large-scale changes in continental water budgets and for model validation, but this work will require more comprehensive monitoring efforts for both surface water, subsurface and meteoric precipitation isotopic composition (Gibson et al., 2010, Jasechko et al., 2013). In any case

large-scale models typically oversimplify processes by generalizing relationships between climate and hydrological fluxes (Hartmann, et al., 2017). The validation of simulated recharge rates is often also lacking. For example, in a global modelling study of Döll and Fiedler (2008), runoff was divided into fast surface runoff, slow subsurface runoff and recharge using a heuristic approach, despite very scarce recharge measurements for validation. Also, due to the typically unknown recharge rates, it can be speculated that in many hydrological models the groundwater recharge term is used to close the hydrological water balance and thus includes all the errors of the other terms (Filimonau and Barth, 2016). Moreover, current large-scale hydrological models do not adequately consider subsurface heterogeneity, which can lead to erroneous current and future recharge estimates (Hartmann, et al., 2017). Notwithstanding their limitations (de Graaf, et al., 2017), these models are often the only means to simulate large-scale processes due to long model running times (Wada, et al., 2016) and lack of parameters and data (Bierkens et al., 2015, Condon and Maxwell, 2019, Maxwell et al., 2016), although the extent to which these models might bias water-balance simulations is unknown. As shown in a recent synopsis of climate change effects on recharge (Smerdon, 2017), together with current studies (Crosbie et al., 2011, ,Moeck, et al., 2016, Moeck, et al., 2018), the need to systematically evaluate the choice of model structure and degree of simplification for recharge impact studies was identified. However, without a sufficient dataset this knowledge gap remains unresolved. While modelling tools with increasing complexity are becoming widely available along with an increasing number of model parameters (Brunner and Simmons 2012, de Graaf, et al., 2017, Kolditz et al., 2012, Kollet and Maxwell 2008, Moeck et al., 2015, Partington et al., 2017), more detailed observations must be collected in order to train and validate these models and reduce predictive uncertainty.

Here we present a newly compiled groundwater global recharge dataset of more than 5000 published plot-scale locations (see section 2 for more details about the dataset). This freely available dataset can provide insights into recharge processes and be used to validate conceptual and mathematical models for many different model types in the future. Model validation with our new dataset is particularly important because the commonly applied datasets (e.g. FAO AQUASTAT database with recharge values for 157 countries (FAO, 2005)) cannot be considered reliable, as the data are not based on measurements or well-founded computations (Döll, et al., 2009, Mohan, et al., 2018). Moreover, existing recharge datasets only cover a limited range of climatic conditions, such as only semi-arid and arid regions (Scanlon, et al., 2006). For example, Nasta, et al. (2016) simulate recharge for all of Africa but validated the results with only 13 published recharge field measurements. Lacking rigorous validation, it is difficult to draw firm

conclusions from such recharge models, which can only be considered for potential recharge rates. Therefore, we anticipate that our compiled dataset will be widely used in the future as a benchmark for various recharge studies.

This paper also provides a systematic analysis and comparison between the aforementioned global recharge dataset and many global-scale climatic and soil-related parameters. The idea for the provided analysis is based on previous detailed recharge reviews which provides also an excellent overview about the history of the recharge subject and estimation methods (Crosbie et al., 2010a, Crosbie et al., 2010b; Doble and Crosbie 2017, Healy 2010, Kim and Jackson, 2012; Scanlon et al., 2006). Thus, our review will less delve into the history of recharge and estimation approaches, rather the provided relationships between global-scale parameters and recharge measurements will be discussed which will help to identify the most influential variables and processes driving large-scale groundwater recharge.

2. Groundwater recharge dataset

The presented groundwater recharge dataset is a compilation of published values. We combined and expanded previously known smaller datasets (Crosbie, et al., 2010, Döll and Flörke, 2005, Kim and Jackson, 2012, McMahon, et al., 2011, Mohan, et al., 2018, Scanlon, et al., 2006, Tögl, 2010, Wang, et al., 2010) with additional recharge rates from various locations around the globe. The literature search was carried out on Web of Science and Google Scholar with relevant keywords such as "groundwater recharge", "diffuse and focused recharge", "groundwater percolation", "deep drainage" and "vertical groundwater flux". In order to ensure a robust dataset without unrealistic values or biased recharge rates, the following validation steps were carried out: i) Recharge rate estimates for less than one year were omitted to avoid bias due to seasonal effects (incomplete annual recharge). ii) Only naturally occurring recharge was considered and recharge rates presumed to be affected by irrigation or managed aquifer recharge were omitted and iii) Study sites where rivers and streams dominate the estimated recharge rates were excluded as the focus of this study was to collect naturally occurring and direct recharge.

Although we provide a unique global recharge dataset, which offers the possibility to study recharge processes from a variety of perspectives, the dataset is certainly not complete. There are many more studies about groundwater recharge. However, in many cases the access to the data is not provided or not straightforward and reported partly in grey literature (Xu and Beekman 2019). Based on our review, we recognized that often the exact location within many publications cannot be directly derived because results are shown within figures and recharge rates are

sometimes presented in interpolated maps, rather than directly providing the rates from the measurement location. With our work we therefore also hope to encourage the community to make recharge data (more readily) available in order to improve recharge predictions and to increase our process understanding.

The compiled recharge rates are based on several different estimation methods, where chemical tracer methods cover ~80%, followed by the water table fluctuation method (~5%). The remaining studies used modelling and water balance methods, lysimeter, Darcy methods, heat tracer and geophysical methods to estimate recharge. The large variety of methods can lead to different rates for an individual site (Crosbie et al., 2010b, Doble and Crosbie, 2017, von Freyberg, et al., 2015, Scanlon, et al., 2002). Different methods give estimates of different components of the water balance and also operate on varying time scales which becomes very important when land use change has occurred (Doble and Crosbie, 2017). Certainly, an important consideration is the temporal and spatial scale of different estimation techniques (Scanlon et al., 2002, Doble and Crosbie 2017, von Freyberg, et al., 2015) which may limit the reliability of the estimates. The recharge estimation studies collated for our dataset originate from the period 1968 to 2018. We assume that the date of the publication is approximately the year when recharge was estimated. However, this will not always be the case, especially for semi-arid and arid zones, and those in high mountain regions with large unsaturated zones (Herms et al., 2019) and large transient times for the infiltrated water to reach the water table (McMahon, et al., 2006, Jódar et al. 2016, Burri et al., 2019). This timing can introduce bias and might locally inhibit comparison between different locations. Furthermore, the effects of climate change over that period are likely to be visible. As already discussed, time series of recharge measurements are rare, limiting our ability to assess whether or not climate change impacts recharge rates at the different locations. However, based on the available knowledge in the literature (Crosbie et al. 2013, Holman et al., 2012, Ng et al., 2010, Moeck et al., 2016, Vaccaro 1992, among others), it is very likely that already over the investigated time period climate change has affected recharge in some locations. As we will demonstrate within this study, the influence of climatic forcing functions on groundwater recharge can be highly site specific, such that simple estimates of recharge based only on precipitation are often misleading as they do not include other factors controlling recharge such as vegetation, soil factors or land use changes. Moreover, climate change projection can lead to significant differences in precipitation rates and temperature among the different GCM-RCM combinations (Moeck et al., 2016, Niraula et al., 2017) and the different downscaling approaches will further increase uncertainty in the predicted climatic forcing functions and consequently in recharge rates (Crosbie et al., 2011, Stoll et al., 2011). Based on our dataset, it is, however, not

possible to identify if an increasing or decreasing trend in recharge rates has occurred. Land use changes over that period can also lead to changes in recharge even though climatic conditions remain the same (DeFries and Eshleman, 2004, Doble and Crosbie, 2017, Minnig, et al., 2018, Scanlon, et al., 2005). These and other issues and uncertainties regarding the compiled dataset are discussed in section 5.

Fig. 1 shows the locations of the global recharge data. Most of the data points are located within the US, Australia and Europe. Fewer data exist for South America, Asia, the Arabian Peninsula and Africa, with the exception of Southern Africa. In Australia, the majority of recharge data is close to coastal areas, whereas far inland regions where recharge rates are typically small (Barron, et al., 2012, Crosbie, et al., 2010, Crosbie, et al., 2010) are underrepresented. Moreover, most recharge data are located in relatively low altitudes. Recently, it was recognized that our knowledge about recharge processes and rates in high altitude locations often dominated by snow and permafrost is relatively limited compared to the flat and snow free valleys (Hood and Hayashi, 2015, Hood, et al., 2006, Viviroli, et al., 2011, Viviroli, et al., 2007).

The location and respective climatic conditions greatly influence the annual recharge amounts. Dry inland continental areas often exhibit very low recharge rates, (e.g. < 20 mm/a in the High Plains in the USA, the South American Altiplano, western China, the Sahel, central Australia). Much higher values (> 100 mm) are observed in humid coastal regions, such as the eastern US, eastern Australia and large parts of western Europe. Regions with a tropical monsoon climate such as the Amazon Basin have some of the highest recharge rates.
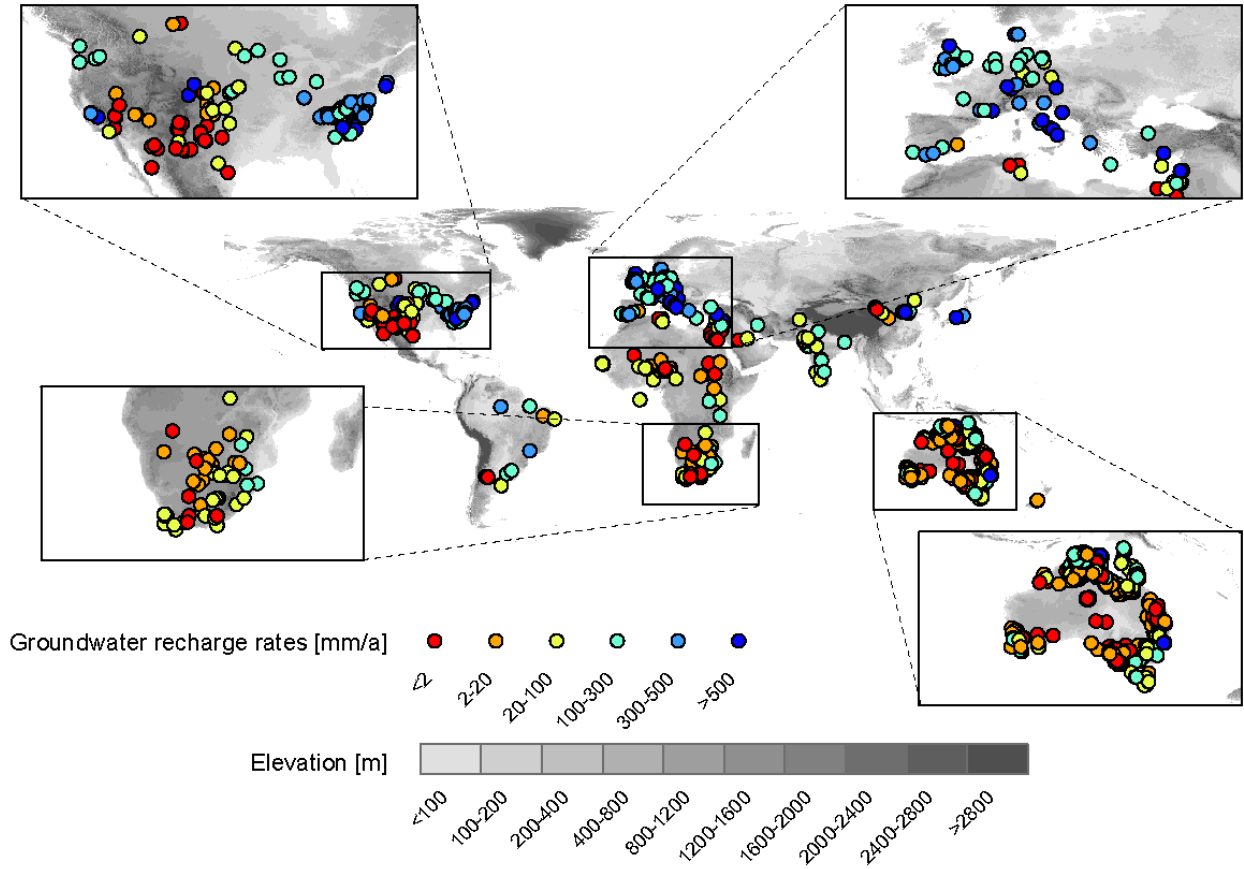
Fig. 1 Locations of global annual estimated recharge rates (n =5207), where red colors show low annual recharge rates (< 2mm/a) and blue colors show high annual recharge rates (> 500 mm/a). The background map is a global digital elevation model (Danielson and Gesch (2011).

Figure 2 displays the summary statistics of the global recharge dataset. The mean value is 234 mm/a and the median 50 mm/a, with lower and upper quartiles of 9 mm/a and 238 mm/a, respectively. A large majority of data points have rates between 0 and 25 mm/a, whereas relatively few are greater than 500 mm/a. The distribution in this dataset is therefore dominated by low recharge rates.
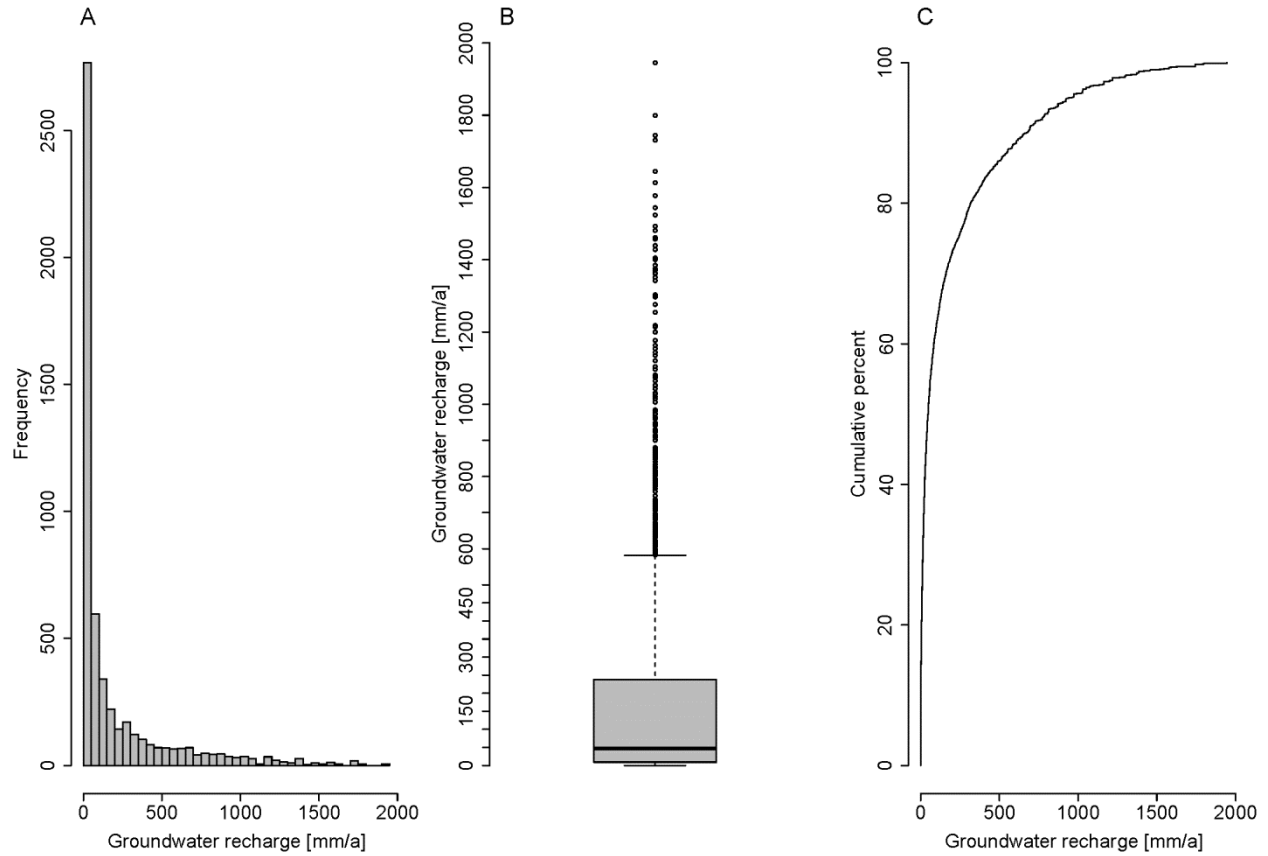
Fig. 2 Summary statistics of the global recharge data shown as a a) histogram with 50 classes (50 mm/a breaks), b) boxplot with the rectangle spanning the first to third quartiles (*interquartile range (IQR)*) and the black segment inside the rectangle indicating the median. The whiskers above and below the box indicate the locations of 1.5* IQR. Data outside this range are plotted as outliers, c) cumulative probability plot.

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3. Relationships between groundwater recharge and global variables

In the following sections, we present relationships between the compiled recharge dataset and 17 independent potential predictor variables (Table 1 and Fig. 3). The values of all independent variables were extracted from the associated GIS datasets (Table 1) at each recharge measurement point and compiled in a table.

The selection of the aforementioned variables was based on established or hypothesized relationships with groundwater recharge rates. For example, precipitation is certainly one of the most influential factors on recharge rates, whereas vegetation has been reported to be an important determinant of recharge (Gerten, et al., 2004, Keese, et al., 2005, Kim and Jackson, 2012, among others). Knowing that recharge is dependent upon climate, vegetation and soil type is not something that was discovered this century, e.g. the effect of vegetation has been known for nearly 100 years (Wood, 1924). However, some of these drivers controlling recharge are still not well understood on a global scale and are difficult to characterize given the generally sparse availability of groundwater recharge observations.

The independent potential predictor variables include 30-year mean climatic forcing functions of annual precipitation (P), annual potential evapotranspiration (ETp), precipitation seasonality (expressed as a coefficient of variation), temperature seasonality (standard deviation) and aridity index (ET/P). Temperature seasonality is a measure of temperature variation over the course of the year. The larger the standard deviation, the greater the variability of temperature. Precipitation seasonality is a measure of variation in monthly precipitation totals over the course of the year. It is expressed as the ratio of the standard deviation of the monthly total precipitation to the mean monthly total precipitation. Larger values represent greater variability in precipitation.

Other independent variables evaluated are the fraction of sand, silt and clay in soil (soil texture), digital elevation model (DEM), depth to water table, depth to bedrock and the topographic wetness index (TWI). The fraction of absorbed photosynthetic active radiation (FAPAR) is used as an indicator for vegetation occurrence and productivity. FAPAR is generally well correlated with the Leaf Area Index (Trigo, et al., 2011). All of these variables are continuous (i.e. the numbers can take any values within the given interval), whereas slope, land use, landform and lithology are discontinuous (categorical variables, e.g. "mountains", "hills" and "plains" as in the landform dataset).
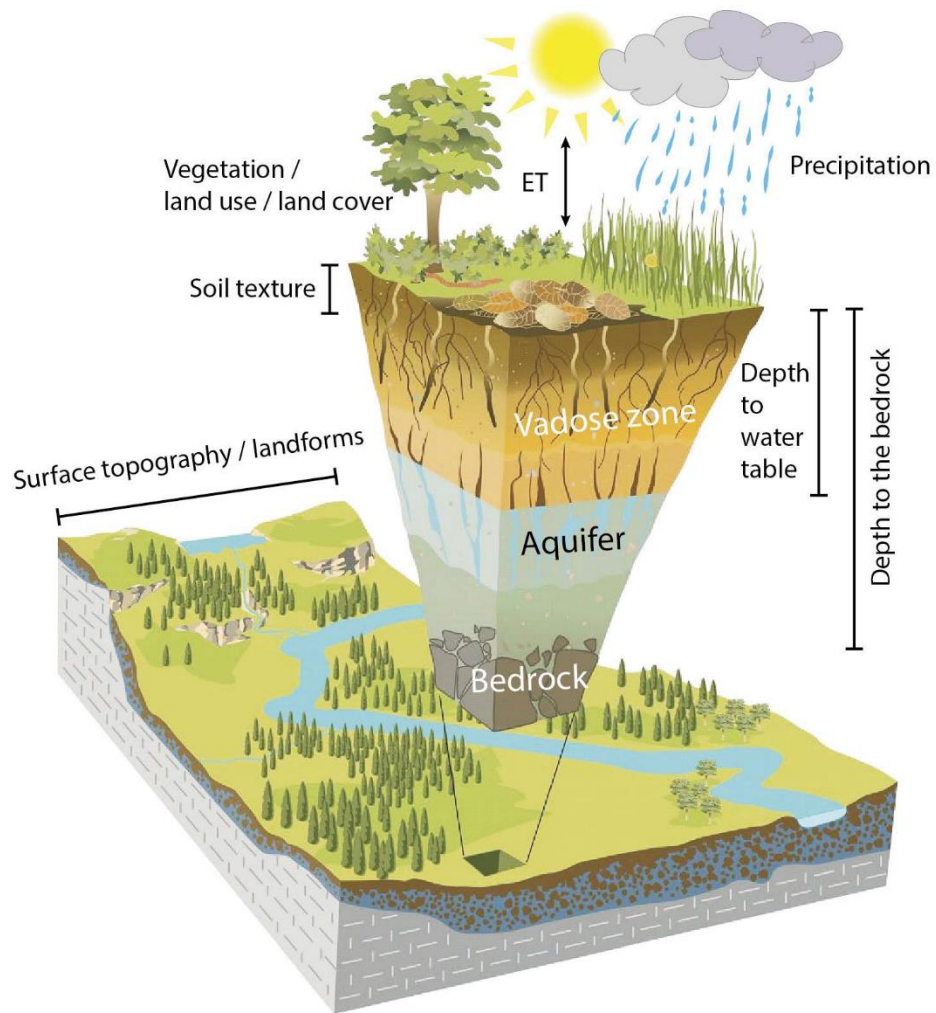
Fig. 3 Schematic diagram of a watershed showing water balance components and variables potentially related to groundwater recharge (modified from Chorover, et al. (2007)).

Table 1 Global-scale independent variables with units, spatial resolution and source. These variables where used to determine established or hypothesized relationships with groundwater recharge rates. FAPAR is the Fraction of Absorbed Photosynthetic Active Radiation and is used as an indicator of the presence and productivity of vegetation.

Variable	Units	Resolution	Source
Annual precipitation (P)	mm/a	~1km	Fick and Hijmans (2017)
evapotranspiration (ET_p)	mm/a	~1km	Trabucco and Zomer (2019)
Aridity index (ET/P)	-	~1km	Trabucco and Zomer (2019)
Temperature seasonality (standard deviation)	°C	~1km	Fick and Hijmans (2017)
Precipitation seasonality (coefficient of variation)	%	~1km	Fick and Hijmans (2017)
Digital Elevation Model (DEM)	m	~1km	Danielson and Gesch (2011)
Depth to water table	m	~1km	Fan, et al. (2013)
Depth to bedrock	m	~1km	Wei, et al. (2017)
Slope	radians	~1km	Yamazaki, et al. (2017)
Topographic Wetness Index (TWI)	-	~1km	Hengl (2018b)
Sand fraction	%	~250m	Hengl, et al. (2017)
Silt fraction	%	~250m	Hengl, et al. (2017)
Clay fraction	%	~250m	Hengl, et al. (2017)
Lithology	-	~250m	Hengl (2018c)
Landform	-	~250m	Hengl (2018c)
Land use	-	~1km	Friedl, et al. (2010)
Vegetation (FAPAR)	%	~250m	Hengl (2018a)

3.1 Climatic variables and aridity index

Figure 4 shows different climatic variables plotted against recharge rates. Increasing annual precipitation leads to higher recharge, especially for the precipitation range of 1300-1600 mm/a (Fig. 4(a)). This trend is not observed for precipitation rates greater than 1600 mm/a. However, this may be related to observation bias due to few available field observations with high recharge rates, as previously mentioned. For precipitation seasonality, values between 100-115, high recharge rates stand out (Fig. 4(b)). The field data associated with these values are mainly located in the tropical monsoonal zones of northern Australia and in Africa. In these regions, heavy and extreme precipitation events lead to high recharge rates as demonstrated in Taylor, et al. (2013) and Taylor and Howard (1996), amongst others.

Higher ET_p leads to smaller recharge values (Fig. 4(c)) until a tipping point of approximately 1500 mm/a is reached, beyond which ET is limited by water availability, soil type and the presence of vegetation. Even with ET_p greater than 1500 mm/a, recharge rates can still be considerable. Again, this largely occurs in tropical latitudes where precipitation amounts, and variability can be very high and annual recharge rates are less affected by high ET_p (Fig. S1-5). ET values are typically strongly affected by temperature (Zhao et al., 2013) and thus temperature seasonality can be important. Temperature seasonality also indicates a distinct trend where recharge rates are high (values of 15-22) (Fig. 4(d)). The corresponding field data are again in the tropical monsoon zones of Australia and Africa as well as eastern Brazil and southern India. Moreover, where recharge rates are higher (100-500 mm/a) in Europe and the east coast of the US, a strong temperature seasonality exists (Fig. S4), which is associated with higher precipitation rates (Fig. S5).

The combined effect of ET and precipitation is represented by the aridity index (defined as ET_p/P). A higher aridity index is associated with lower recharge (Brutsaert and Stricker, 1979), an effect that is also observed in our dataset (Fig. 4(e)). Not surprisingly, groundwater recharge is higher in humid regions (lower aridity index) than in arid regions (larger aridity index). Although the aridity index provides some trends and is a robust and commonly used metric to describe climatic conditions (Zomer et al., 2008), it has to be used carefully. The classification can lead to i) spatial lumping of areas which are actually very different, e.g. the temperate plains of southern England being lumped together with parts of the tropical savannah of Northern Australia and ii) the neglecting of climatic seasonality effects which can influence recharge (Taylor et al., 2013). The aridity index is certainly very useful in water limited environments (typically $P<ET_p$) but loses its predictive power in energy limited environments

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(typically P>ET_p) (Kingston et al., 2009, Newman et al., 2006). An alternative for energy limited environments could be the Budyko curve, a tool to estimate mean annual water availability as a function of aridity, among other things (Zhang et al., 2001), but a comparison is not within the scope of this paper and is therefore not further investigated here.

One limitation of only considering annual precipitation and ET_p is that seasonal recharge patterns are overlooked. In some regions, ET_p is larger than precipitation on a yearly average, but periods where precipitation surpasses ET_p may still occur during the course of the year, as is the case in a monsoonal climate with dry spells followed by heavy precipitation events. For instance, ET_p increases with increasing proximity to the equator (Fig. S1) whereas temperature seasonality shows a lack of large difference (Fig. S4). Precipitation amount (Fig. S5) and seasonality (Fig. S2) increase with increasing proximity to the equator and thus, total annual recharge rates are also linked to strong variation in seasonality. Annual climate variability is considered via precipitation and temperature seasonality within our study, however, recharge rates are only represented by annual values. As already mentioned, long time series of recharge are rare and as a result seasonality in recharge cannot be incorporated.

The ratio between groundwater recharge and precipitation is less than 1 for 98% of the compiled data, although 2% of recharge values exceed their coinciding precipitation amount (Fig. S15). Various reasons may be responsible for this paradox. It is possible, for example, that the used long-term average precipitation rates do not correctly reflect the climatic conditions when recharge was estimated in the field. Moreover, where thick unsaturated zones exist and transient times are long until the infiltrated water reaches the water table, recharge rate estimates can be less related to current climatic conditions, but rather represent the paleoclimate (Gurdak, et al., 2007, McMahon et al., 2006, Urbano, et al., 2004, Walvoord, et al., 2002). Additionally, uncertainties in the recharge estimation method or artificial impacts on recharge rates, such as non-reported irrigation, leakage from water supply, wastewater pipelines or managed aquifer recharge, can strongly affect the ratio and lead to recharge/precipitation ratios greater than 1. The mean ratio of the 98% of data with a recharge/precipitation ratio <1 is 0.17, with lower and upper quartiles of 0.01 and 0.27 (Fig. S15). The 0.17 ratio indicates that on average on the global scale, only 17% of annual precipitation becomes recharge.
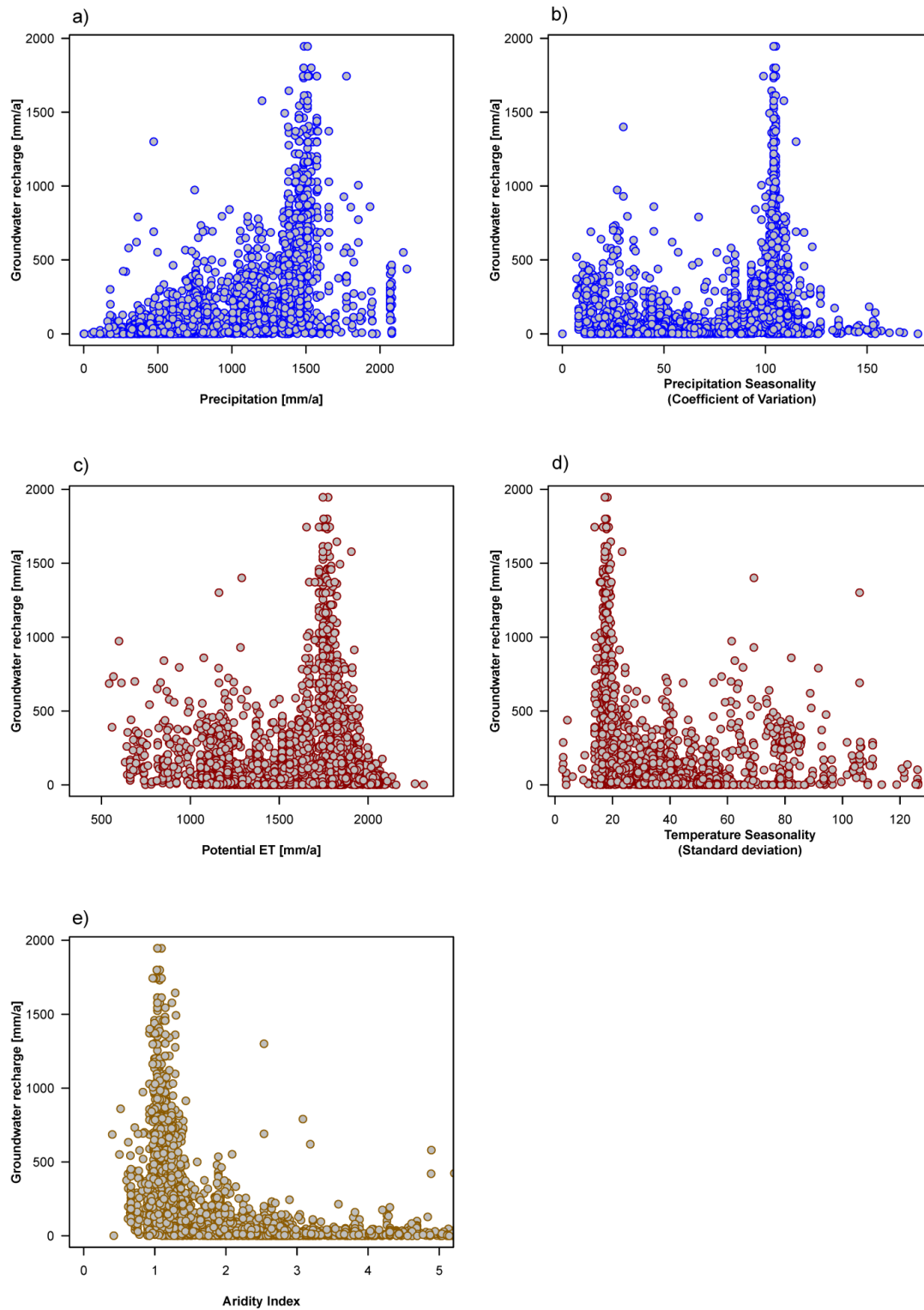
Fig. 4 Relationships between groundwater recharge rates [mm/a] and a) precipitation [mm/a], b) precipitation

seasonality, c) potential evapotranspiration [mm/a], d) temperature seasonality and e) aridity index.

3.2 Recharge versus elevation, depth to water table, depth to bedrock, slope and topographic wetness index

The relationship between elevation (DEM) and groundwater recharge (Fig. 5(a)) shows that recharge decreases with increasing altitude. The greatest recharge values occur for an elevation smaller than 400 m and where the terrain is predominantly flat, as seen in Fig. 5(b). Flat topography at low altitudes often forms groundwater discharge zones that harbor rivers, closed lakes, oases, forests and riparian wetlands (Berthold, et al., 2004, Fan, Li and Miguez-Macho, 2013, Fan, et al., 2007, Manning and Solomon, 2003, Scanlon, et al., 2002). On the contrary, steeper slopes typically present at higher altitudes have limited storage capacity and generally favor runoff and interflow over recharge. This is especially the case when large water volumes are available at the surface, for instance, during snow melt processes and intense summer rainfall (Hood and Hayashi et al., 2015, Muir et al., 2011). Moreover, mountain systems are often characterized by fractured bedrock that enables deep flow paths, leading to higher recharge in lower elevations at the mountain front or as spring discharge (Ajami et al., 2011, Smerden et al., 2009). If the bedrock is relatively impermeable, local flow paths are developed typically above the bedrock (Manning and Solomon, 2005). If those bedrock materials are weathered, it can behave like an local aquifer and, recharge might increases with rock weathering (Martos-Rosillo et al., 2019). Nevertheless, a positive correlation between recharge and elevation could also be expected, as precipitation increases with altitude and temperature, evapotranspiration and soil water stress are usually lower in mountains than in the lowlands. The relationship shown in Fig. 5a between recharge and elevation might be biased by the low number of aquifer recharge studies conducted in high altitudes. Overall, the volume of mountain recharge to groundwater and how recharge patterns respond to climate variability are poorly known in most mountain ranges (Bales et al., 2006).

As seen in Fig. 5(c), groundwater recharge decreases with depth to the water table. In regions with a deep water table, precipitation rates are often low and arid to semi-arid conditions prevail (Gurdak, et al., 2007, Gurdak and Qi, 2012, Wada, et al., 2016). Thick unsaturated zones can result in a substantial reduction in recharge, as a significant portion of infiltration may remain in the unsaturated zone (Cao, et al., 2016). However, Crosbie (2003) and Carrera-Hernández, et al. (2011) found that the depth to the water table also impacts recharge in humid and subtropical regions, where shallow water tables are typically present. For example, the depth to the water table controls evaporation from groundwater and the extinction depth (Shah, et al., 2007). Shallow water tables will typically have larger evaporation. On the other hand, where shallow water tables exist, large rainfall amounts are available, leading

to larger recharge rates. Smerdon et al. (2008) show for a study site with a sub-humid climate that for water table depths less than 6 m below ground surface, the occurrence of recharge depends on climatic conditions of the current and previous year. However, for water table depths of 6 m or more, recharge will depend on climate conditions from the most recent decade, thus having less annual variability (Schwarz et al., 2009). Winter (1986) indicate that on coarse-textured landforms (e.g., glacial outwash), the timing of groundwater recharge is controlled by the depth of the water table and Cook et al. (1989) found for a semiarid study site that most rainfall was captured by actual ET in the uppermost 2 m of the soil column. However, as the depth to water table increased, the annual variability of groundwater recharge decreased, illustrating that a thicker unsaturated zone provides a greater opportunity for infiltration below an extinction depth for evaporation. The magnitude of groundwater recharge at monthly or annual timescales was shown to depend on the thickness of the unsaturated zone (i.e., the depth to the water table) (Kuss and Gurdak 2014). Thicker unsaturated zones are associated with lag times that have the potential to record many years of changes in soil moisture (Scanlon et al., 2007). Thus, the influence of annual climate fluctuations will have varying results on groundwater recharge, depending on the thickness of the unsaturated zone. The differences in lag time, however, can be attributed to the characteristics of soil texture that govern infiltration processes (Burri et al., 2019, Gurdak, et al., 2007, Scanlon et al., 2007, amongst others).

Most of the data points in the compiled dataset correspond to a bedrock depth of less than 100 m (Fig. 5(d)). Comparing recharge rates to bedrock depth does not reveal any clear relationship; only larger recharge rates show some correlation that will be discussed in more detail in section 5. In general, a shallow depth to impermeable bedrock can limit the capacity of the unsaturated zone to accept infiltrating water, preferentially leading to surface runoff or overflow instead of recharge, whereas larger depth to bedrock might increase the groundwater storage capacity. If the bedrock is permeable or fractured, rapid and localized recharge can occur (Gleeson et al., 2009, Jiménez-Martínez et al., 2013, Levison et al., 2012). Overall, bedrock groundwater dynamics and their influence on hydrologic flow behavior are poorly understood (Gabrielli et al., 2012, Welch et al., 2012).

The topographic wetness index (TWI) is derived from a digital elevation model and gives an indication of soil moisture distribution. Specifically, TWI is calculated from slope values and the upstream contributing area per unit width orthogonal to the flow direction (Rodhe and Seibert, 1999, Sörensen, et al., 2006). As already discussed, both elevation and slope show relationships with groundwater recharge rates that can also be seen between recharge and TWI (Fig. 5(f)). Greater TWI is associated with higher recharge. TWI is typically highly correlated with soil

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moisture, the latter often being correlated with groundwater levels and consequently recharge rates (Rodhe and Seibert, 1999, Sörensen, et al., 2006). Locations with a high TWI, such as flat valleys are fed by the surrounding mountains and hills and usually have a thick accumulation of sediments and high groundwater recharge (Fan, et al., 2013, Gleeson, et al., 2011).
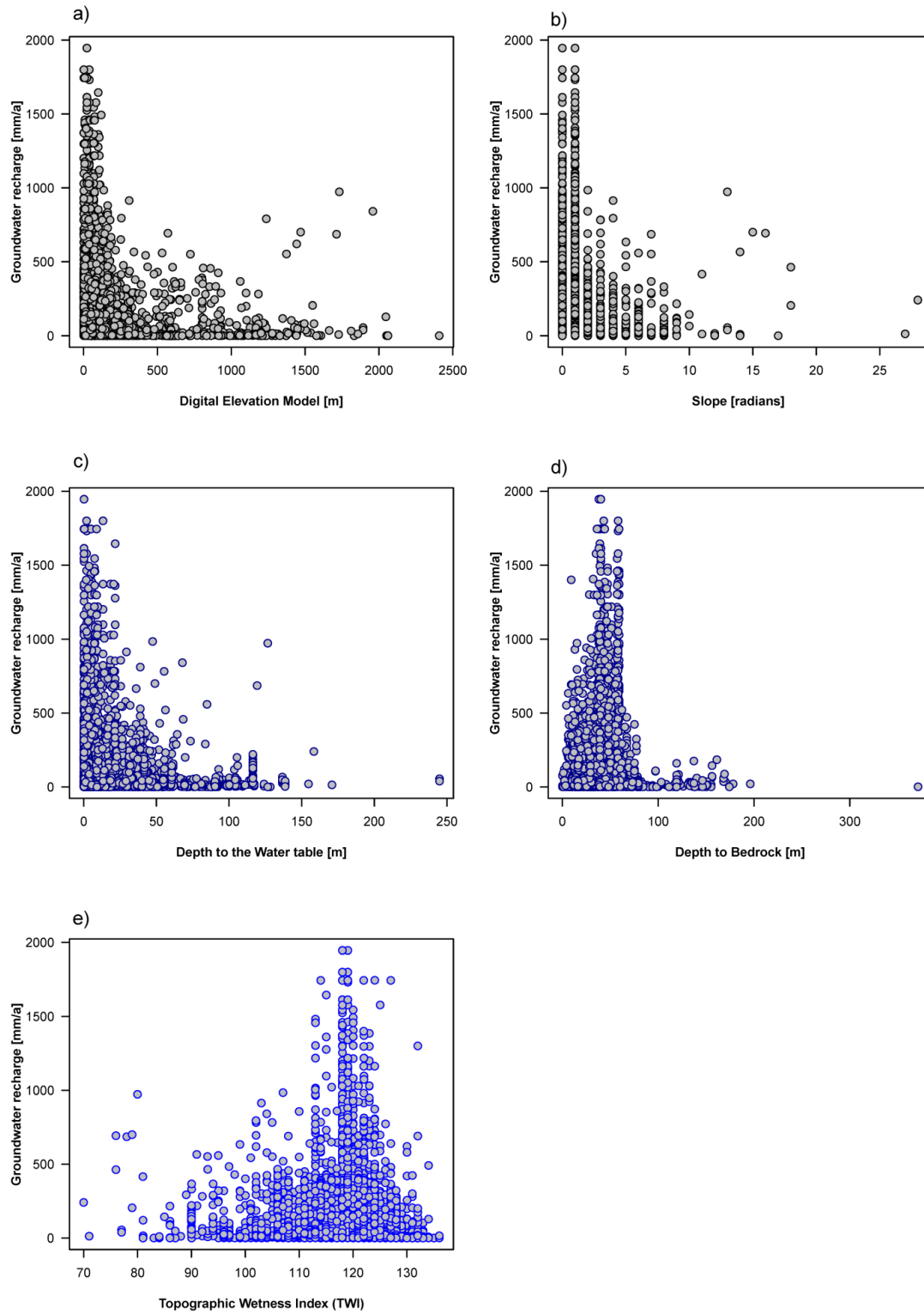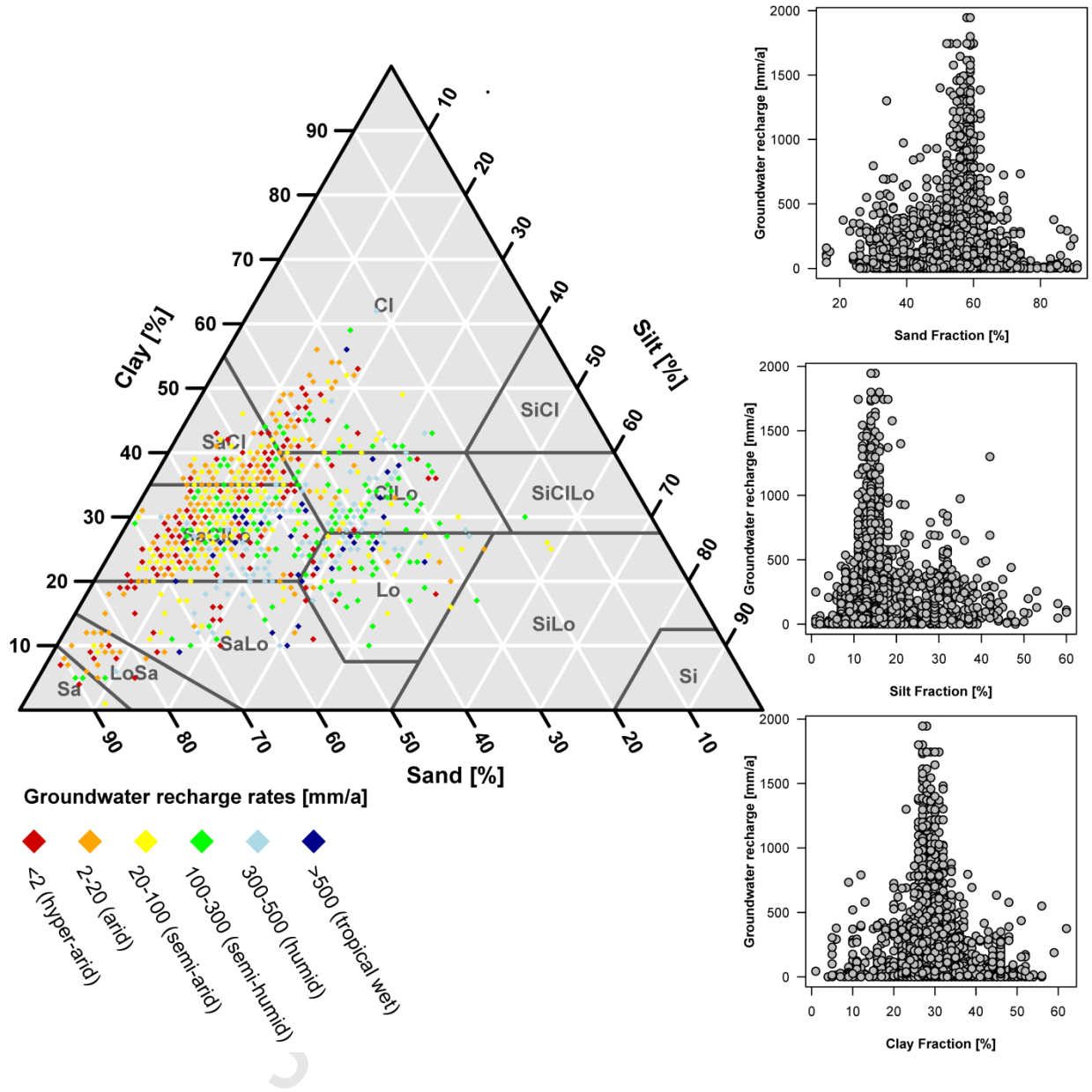
Fig. 5 Relationship between groundwater recharge rates [mm/a] and a) elevation [m] b) slope [radians], c) depth to water table [m], d) depth to bedrock [m] and e) topographic wetness index.

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3.3 Soil Fraction and Texture

Since soil texture can impact the water balance and groundwater storage at various scales of inter-annual variability (Keese, et al., 2005, Nolan, et al., 2003, Wang, et al., 2009), understanding the relationship between soil texture and recharge is important for water resource management. A common approach is texture-based classification of soils which has been used for grouping the soil material (Schaap et al., 2001, Van Looy et al., 2017). This classification of soils becomes especially important for large-scale studies where the spatial and temporal variability in the hydraulic properties of soils exceeds the field sampling capabilities (Twarakavi et al., 2010). If available, bulk density and organic matter values may also be incorporated to further improve the classification (Wösten et al., 1999), however, information on a global scale are difficult to obtain. An excellent review about pedotransfer functions in earth system science is provided by Van Looy et al. (2017).

Figure 6 shows the relationship between the fraction of sand, silt and clay in soil and annual groundwater recharge as well as recharge rates plotted on the texture ternary plot based on the USDA soil classification. The highest recharge occurs when soils have a sand fraction of 50 -65%, a clay fraction of 25-35% and a silt fraction of 10-20%. Most of the recharge data points fall in the sandy clay loam and sandy clay soil texture classes. Very few of the recharge data points are associated with soils predominantly composed of clay and silt, which is due to the very small pore sizes and restricted infiltration capacity of such soil types. Interestingly, low recharge rates plot within a relatively small area of the soil texture diagram. Although the sand fraction is relatively high, which is typical for desert areas, recharge is low due to associated low precipitation rates. Although it has been shown that recharge is typically greater in coarser versus finer textured soils (Cook and Kilty, 1992), the climatic conditions control recharge rates more strongly. Therefore, high sand content alone is not enough to ensure high recharge fluxes.

Fig. 6 Relationship between groundwater recharge rates [mm/a] and soil texture as fraction of sand [%], silt [%], and clay [%]. The soil classification for the texture ternary plot is based on the USDA classification system. Recharge rates are shown with a color range from red to blue, where red colors show low recharge rates (< 2mm/a) and blue colors show high recharge rates (> 500 mm/a).

3.4 Geology, Land forms, Land use and Vegetation

The relationships between groundwater recharge rates and geology, land forms (such as flat plains, hills, and mountains) land use and vegetation are shown in Figure 7. The highest recharge rates occur in unconsolidated sediments (Fig. 7(a)). As discussed in section 3.2, flat valleys with thick accumulations of unconsolidated sediments can experience high groundwater recharge rates because they often form discharge zones draining the surrounding mountains (Fan, et al., 2013, Gleeson, et al., 2011). Higher recharge rates also occur in mixed and siliciclastic sedimentary rocks, metamorphic rocks and carbonate sedimentary rocks. Especially in karstic areas (carbonate rocks) where fast infiltration in epikarst and conduits occurs, recharge rates can be high (Allocca, et al., 2014, Hartmann, et al., 2015, Hartmann, et al., 2017, Meeks, et al., 2017, Sauter, 1992). This fast infiltration can lead to lower evapotranspiration, surface runoff and storage in the unsaturated zone. Regarding the impact of land forms (Fig. 7(b)), higher recharge rates occur in flat and smooth plains and low hills. As already mentioned, the highest recharge occurs where the terrain is predominantly flat (see also section 3.2)

Land use influences recharge rates and timing (DeFries and Eshleman, 2004, Harbor, 1994, Huang and Pang, 2011, Minnig, et al., 2018, Scanlon, et al., 2005). The highest recharge rates are observed in mixed forest close to open water and in (woody) savannas (Fig. 7(c)) and, to a lesser extent, where forests exist. In mixed, temperate forests precipitation inputs are typically larger than the water lost due to evapotranspiration and runoff. In contrast are the woody savannas where annual precipitation rates are low, but seasonal extreme precipitation events can still lead to considerable recharge (Taylor et al., 2013). It may also be that the available recharge studies from savannas are in locations where recharge is expected, creating bias.

We have used the Fraction of absorbed Photosynthetic Active Radiation (FAPAR) as an indicator for vegetation occurrence and productivity (Fig. 7(d)). Low FAPAR values less than 70 correspond to dry and/or cold regions with little vegetation productivity, whereas higher FAPAR values are typical of more humid and warmer regions with abundant vegetation (see also Fig. S14). This climatic dependence of FAPAR values is also partly reflected in the groundwater recharge rates, with the lowest rates corresponding to low FAPAR values, i.e. dry settings with low vegetation occurrence and productivity.
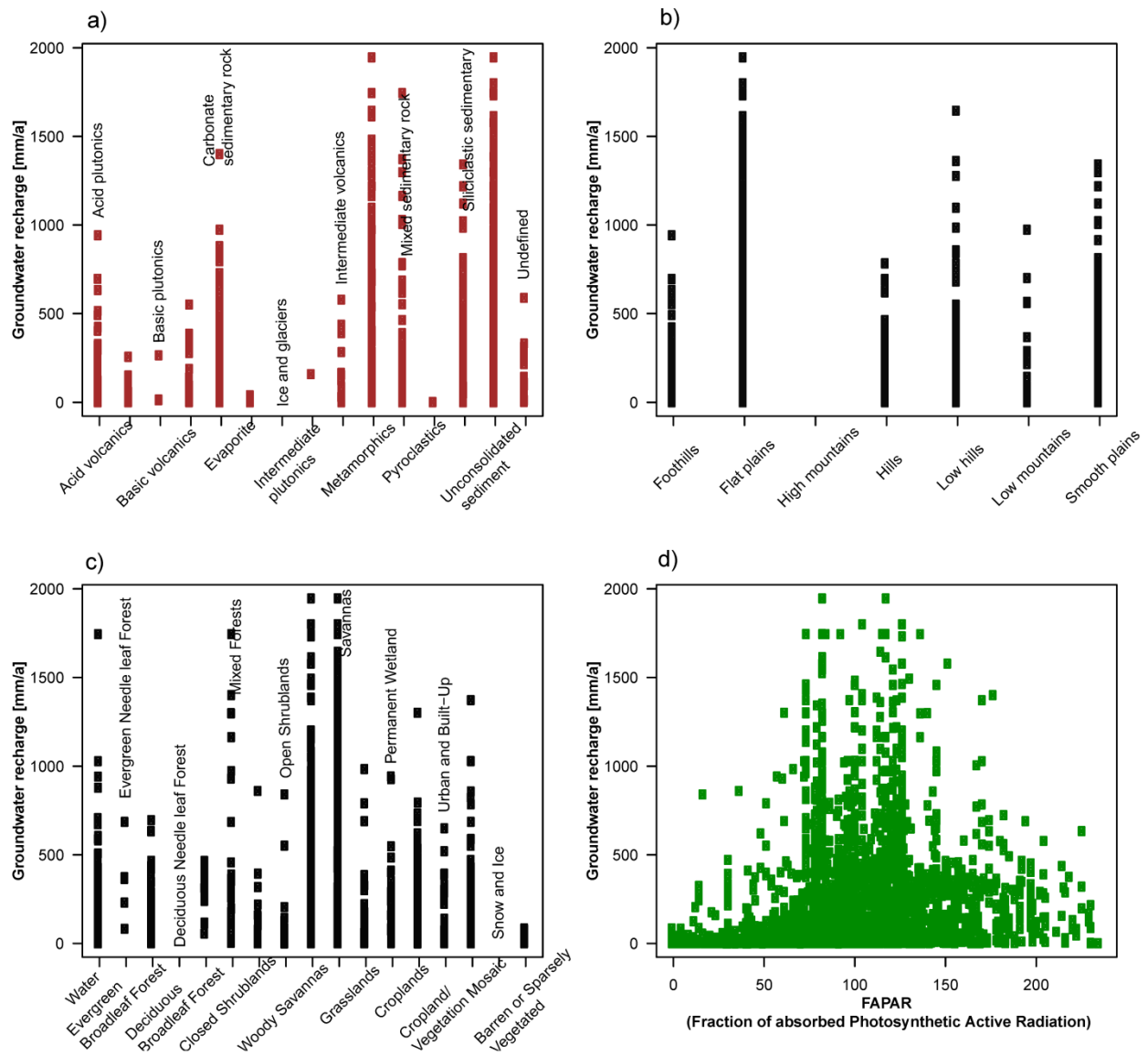
Fig. 7 Relationship between groundwater recharge rates [mm/a] and a) lithology, b) land forms, c) land use and d) FAPAR.

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4. Correlation analysis

To help identify important influencing factors on groundwater recharge, we calculated Spearman's Rho correlations between the continuous global variables and recharge rates. These correlations were made using the percentage of recharge rates greater than a chosen threshold for 14 bins across the range of each independent variable. The number of bins was determined using Sturges' formula (Sturges, 1926), and the bin width was varied to have each bin contain the same number of observations. Thresholds for recharge rates were chosen to represent different conditions ranging from dry to wet. These thresholds were associated with climatic conditions which mostly reflect the corresponding recharge rates (groundwater recharge < 2 mm/a = hyper-arid , <20 mm/a = arid, <100 = semi-arid ,<300 mm/a = sub-humid, <500 m/a humid, > 500 mm/a = tropical wet). Although this classification is more a function of climate than recharge, it provides some hints also for expected recharge rates, even though there are examples where recharge rates are greater than 2 mm/a for semi-arid regions. The significance of the correlation coefficient was assessed through its P-value (Table 2). P-values at the 90% confidence level (alpha (a) level = 0.1) indicate that recharge rates exceeding a given threshold are significantly correlated with the independent variable in question. This analysis is not applicable to categorical variables, e.g. landform, land use, lithology or slope. We found moderate ($|0.4 - 0.59|$) to strong ($|> 0.6|$) correlations between groundwater recharge and ten variables, listed here from highest to smallest correlation for a recharge threshold of 20 mm/a: 1) aridity index, 2) precipitation, 3) elevation (DEM), 4) temperature seasonality, 5) silt fraction, 6) precipitation seasonality, 7) depth to water table, 8) Topographic Wetness Index (TWI), 9) vegetation (FAPAR) and, 10) clay fraction (Table 2).

Table 2 Sperman's Rho coefficients between the percentage of recharge measurements exceeding different thresholds (2, 20,100 ,300 and 500 mm/a) and 14 bins of equal member-size across the range of each independent variable. The statistically significant correlations are indicated with p-values < α-level = 0.10, which are shown in bold.

| Dataset	Spearman's Rho and P-value				
Recharge measurements exceeding threshold [mm/a]	2	20	100	300	500
Aridity Index	-0.93	-0.97	-0.98	-0.91	-0.84
	<0.001	**<0.001**	**0.016**	**0.058**	**0.088**
Annual Precipitation (P)	0.89	0.92	0.94	0.91	0.9
	<0.001	**<0.001**	**<0.001**	**<0.001**	**0.002**
Elevation (DEM)	-0.59	-0.85	-0.84	-0.86	-0.87
	<0.001	**0.003**	**0.026**	**0.049**	**0.068**
Temperature Seasonality (Standard deviation)	-0.87	-0.8	-0.71	-0.65	-0.67
	0.013	**0.024**	**0.07**	**0.056**	**0.021**
Silt fraction	0.63	0.77	0.74	0.72	0.59
	0.093	**0.035**	**0.05**	0.29	0.78
Precipitation Seasonality (Coefficient of Variation)	0.66	0.6	0.32	0.3	0.57
	0.007	**0.003**	**0.079**	0.12	**0.096**
Depth to water table	-0.15	-0.6	-0.63	-0.71	-0.71
	0.53	**0.038**	**0.023**	**0.049**	**0.07**
Topographic Wetness Index (TWI)	-0.64	-0.57	-0.47	-0.35	-0.31
	0.083	0.22	0.54	0.88	0.97
Vegetation (FAPAR)	0.53	0.54	0.71	0.64	0.45
	0.008	**0.005**	**0.003**	**0.1**	0.35
Clay fraction	-0.27	-0.46	-0.49	-0.53	-0.48
	0.24	**0.071**	**0.1**	0.13	0.25
Depth to bedrock	0.21	0.28	0.41	0.4	0.41
	0.57	0.96	0.55	0.29	0.2
Potential Evapotranspiration (ET$_p$)	0.26	0.22	0.11	-0.026	0.024
	0.38	0.39	0.7	0.42	0.33
Sand fraction	0.079	0.051	-0.11	-0.095	-0.015
	0.88	0.87	0.76	0.83	0.62

The aridity index shows a significant negative correlation with recharge rates (Table 2 and Fig. 8), whereby ET_p shows only weak correlation with recharge (Table 2). This may not seem intuitive at first, but is due to the fact that some regions with high ET_p also have considerable precipitation and therefore high recharge (see also Fig. S1-S5).
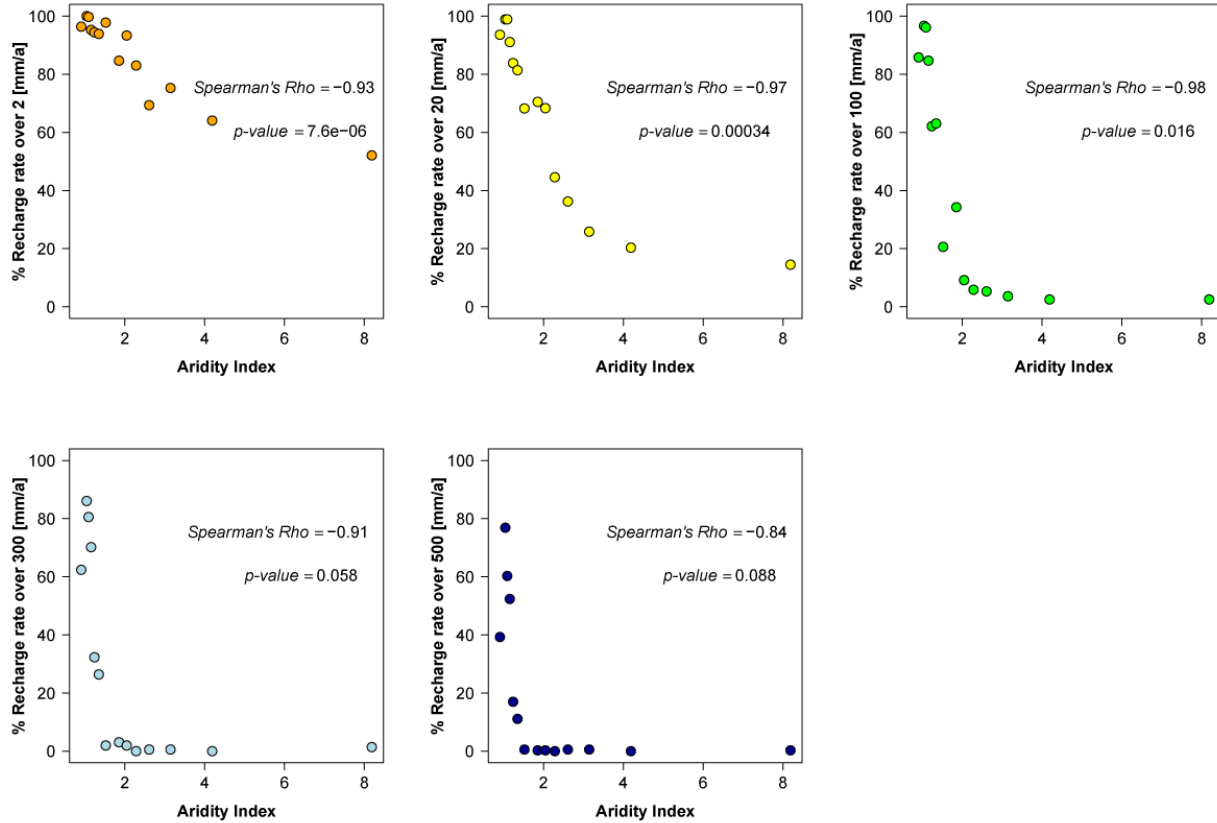
Fig. 8: Correlation of groundwater recharge rates [mm/a] exceeding 5 different thresholds (groundwater recharge < 2mm/a = hyper-arid, <20 mm/a = arid, <100 = semi-arid ,<300 mm/a = sub-humid, <500 m/a humid, > 500 mm/a = tropical wet) against aridity index.

Since there is much less variability in ET_p than in precipitation, correlation between the aridity index and recharge is similar (but inverse) to that between precipitation and recharge (Fig. 9). A strong positive correlation exists between annual precipitation amounts and recharge rates. The magnitude of the correlation decreases with higher recharge rates for both the aridity index and precipitation, though the latter only very slightly. It appears that in drier regions (recharge < 300 mm/a) changes in precipitation and to a smaller amount ET significantly alter recharge rates, resulting in a strong correlation. We speculate that the relationship is less pronounced in very humid regions (recharge > 500 mm/a) due to a presumed abundance of perennial surface water bodies (i.e. lakes, rivers, wetlands)

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that buffer changes in precipitation. Moreover, soils are typically wet and groundwater levels shallow in such regions. Therefore, surface runoff will frequently occur and may reduce the direct correlation between precipitation and recharge at a given location. Moreover, this may be related to observation bias due to few available field observations with high recharge rates, as previously mentioned. However, even though a small decreasing trend is observed, the Spearman's Rho values are still around 0.8-0.9. Moreover, seasonality in temperature and precipitation are also showing a correlation with recharge rates (Table 2). As demonstrated, in some regions ET_p is larger than precipitation on a yearly basis but precipitation larger than ET_p is also possible during the course of the year (e.g. a monsoonal climate with dry spells followed by heavy precipitation events). Therefore, estimates of recharge based on only one variable (e.g. annual precipitation) are often misleading because they do not reflect other factors involved, such as seasonality effect on recharge rates.
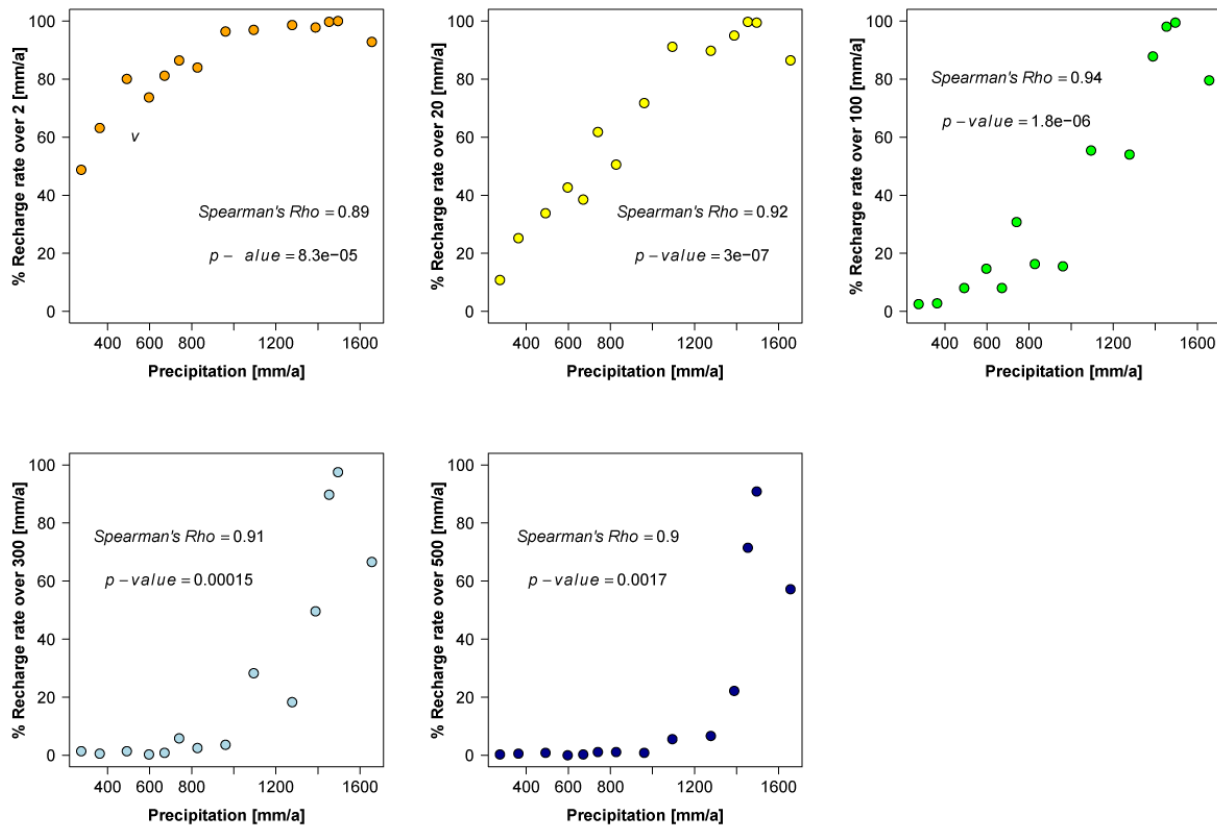
Fig. 9: Correlation of groundwater recharge rates [mm/a] exceeding 5 different thresholds (groundwater recharge < 2mm/a = hyper-arid, <20 mm/a = arid, <100 = semi-arid ,<300 mm/a = sub-humid, <500 m/a humid, > 500 mm/a = tropical wet) against precipitation [mm/a].

The fraction of absorbed photosynthetic active radiation (FAPAR) correlates reasonably well with recharge values (Fig. 10). Infiltration processes and vegetation mass are strongly influenced by precipitation and temperature seasonality (Fig. S17, S18), which are often highly variable in mid-latitudinal continental areas. Greater groundwater recharge can occur during winter in arid and temperate climates due to intra-annual fluctuations in the evapotranspiration potential and precipitation (Jasechko et al., 2014). Seasonal differences in surface temperature can affect plant growth and consequently evapotranspiration. Thus, lower summer recharge rates can result from higher evapotranspiration induced by higher temperatures and greater vegetation density.

The results for FAPAR shows again that one variable is not enough to explain recharge fluxes. For instance, higher FAPAR indicates the occurrence of vegetation and productivity and thus higher ET, which can lead to lower recharge values, whereas we observe that recharge is greater for larger than for smaller FAPAR values. This is due to the fact that increasing FAPAR are also associated with increasing precipitation (Ceccherini et al., 2014, Van den Hoof et al., 2018) and thus this water surplus more than compensates the increase in ET.
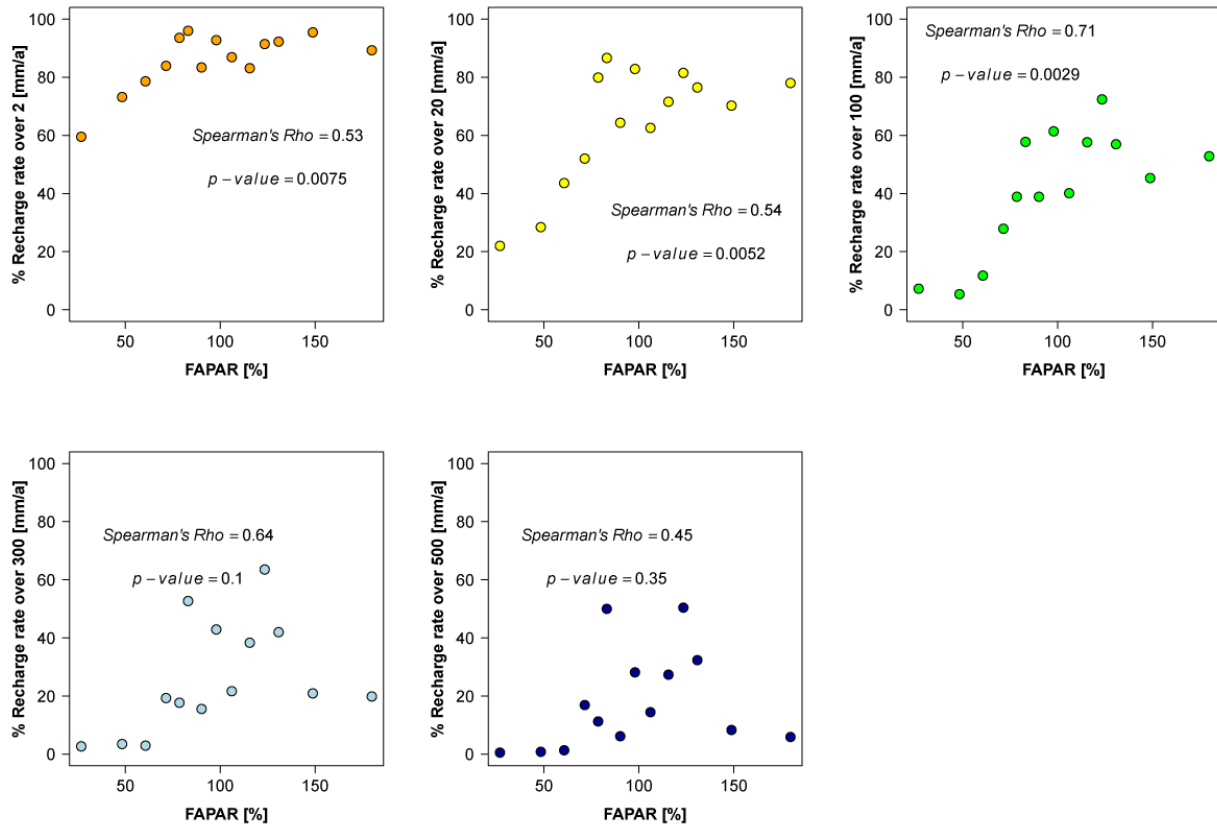
Fig. 10: Correlation of groundwater recharge rates [mm/a] exceeding 5 different thresholds (recharge < 2mm/a = hyper-arid, <20 mm/a = arid, <100 = semi-arid ,<300 mm/a = sub-humid, <500 m/a humid, > 500 mm/a = tropical wet) against FAPAR.

Out of the remaining global variables, some correlation is found at least for certain recharge rates with elevation, depth to water table, topographic wetness index and silt and clay fraction, (Fig. S19, S20, S22, S24-S25) and will be discussed in section 5.2.

5. Discussion

5.1 Limitations and Uncertainties

To our knowledge, this is a unique global recharge dataset, which offers the possibility to study recharge processes from a variety of perspectives. By combining the results of many small-scale studies spanning a wide range of climate zones, this dataset will help attain a deeper understanding of groundwater recharge processes that would not be possible from the individual studies alone. Nevertheless, some limitations and uncertainties exist and are discussed below.

The recharge rates in the global dataset are based on various physical and chemical methods, which introduce some bias at each location. The large variety of such methods can lead to different rates for an individual site due to varying spatio-temporal scales and the complexities that the applied methods represent (Crosbie et al., 2010a, Crosbie et al., 2010b, Gee and Hillel, 1988, Healy, 2010, Simmers, 2013, Scanlon, et al., 2002, von Freyberg, et al., 2015). For example, the water table fluctuation method provides absolute recharge rates and is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. In contrast, the chloride mass balance method provides potential recharge which may percolate down to the water table, or it may be evapotranspired to the atmosphere depending on the capillary fringe and decoupling, root and extinction depth.

Irrigation is neglected in our dataset but can be the dominant recharge process locally (Lauffenburger, et al., 2018, Meixner, et al., 2016). Irrigation-affected recharge rates and those substantially dominated by rivers and streams were excluded. However, based on the sparse information available about irrigation practices and amounts, it cannot be completely ruled out that some of the recharge measurements in the global dataset are still affected.

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We have taken the date of the publication to be the same as the year when recharge was estimated. This may not always be the case, and there is the issue that infiltration through a thick unsaturated zone, particularly in semi-arid and arid zones, will result in long transient times until the water table is reached (McMahon, et al., 2006, Burri et al., 2019). This difference between the year when the study was conducted and resulting recharge can locally hamper a comparison between these two variables and may lead to misleading relationships.

Even though temporal dynamics are neglected in the dataset, groundwater levels and recharge rates are affected by inter-annual to multi-decadal climate variability (Kuss and Gurdak 2014). For example, the El Niño–Southern Oscillation (ENSO) can lead to greatly reduced recharge rates in eastern and southern Africa (Kolusu, et al., 2019) but may have the opposite effect in other parts of the world (Holman, et al., 2009, Kuss and Gurdak, 2014). From a global perspective, the effect of lower precipitation in some areas may be offset by higher precipitation in other areas, resulting in relatively small inter-annual variation in recharge rates on the global scale but greater fluctuations locally.

The recharge estimates in the global dataset do not distinguish between slow, diffuse recharge through a matrix and faster preferential fluxes through cracks, root holes and highly heterogeneous soils which can be an important process increasing recharge rates (Beven and Germann, 2013, Lin, et al., 2006, Moeck, et al., 2016). Moreover, the resolution of the global variables used for comparison does not permit the differentiation of these small-scale environmental processes, even though the maximum resolution used is 1 km (min. 250 m).

Depending on the availability of published recharge data, the compiled dataset does not evenly represent all climate zones or altitudes. That is, most of the studies were carried out in arid, semi-arid or temperate zones at low altitudes with the majority of recharge rates being less than 47 mm/a (median) and only a small percentage greater than 500 mm/a. Apart from limitations and uncertainties in the recharge data, uncertainties that are difficult to quantify may also stem from the global datasets.

Although we have only looked at single factors (individual global variables, i.e. precipitation) in the analysis undertaken, studies exist where the interactions of factors were analyzed through modelling (Barron et al., 2012, Batelaan et al., 2003, Doble et al., 2006, Keese et al., 2005, Moeck et al., 2018) or statistical analysis (Fu et al., 2019, Mohan et al., 2018), but only few have used field recharge estimates directly (Crosbie et al., 2010a, Crosbie et al., 2018, Kim and Jackson, 2012 Wohling et al., 2012, among others). In line with our findings, Barron et al. (2012) conclude that due to a lack of data, most studies have not been able to draw strong conclusions on a larger scale

beyond establishing rainfall as the major determinant of recharge. Thus, we expect that the provided dataset will help to overcome this limitation as already demonstrated in our analysis and that follow-on studies will increase our knowledge of recharge processes.

It is not possible to provide generally applicable guidelines on how to use our recharge dataset as a benchmark, as the study setup, approach and purpose (including calibration of hydrological models) depends on the study target and is highly individual. Most of the compiled recharge estimates do not include an uncertainty term, but lessons can be learnt from recent studies that do estimate the uncertainty in recharge. Overall, saturated-zone methods generally provide recharge estimates that are more reliable because they estimate actual recharge, whereas unsaturated-zone techniques estimate potential recharge (Healy 2010). In addition, surface-applied and historical tracers in the unsaturated zone require a minimum recharge rate to transport the tracers through the root zone (Scanlon et al., 2002) and can have considerable uncertainties. For example, Crosbie et al. (2018) showed that magnitude of uncertainty when using the chloride mass balance method combined with regression kriging to upscale the point information to regional scale is often close to the magnitude of the median recharge estimate. This outcome is quite important because the chloride mass balance method is the most widely used approach globally (Crosbie et al., 2010a, Pavlovskii et al., 2019, Scanlon et al., 2006). Typically, water-budget approaches and models are less accurate in semiarid and arid zones compared to humid regions because recharge constitutes a smaller fraction of the water budget in dry areas and the recharge term accumulates the errors in all the other terms of the water-budget equation (Gee and Hillel 1988). Shallow water tables, typically located in more humid regions, are often observed to respond in a highly disproportionate manner to precipitation events (Gillham 1984). Gillham (1984) indicate that if the capillary fringe extends to the ground surface, the addition of a very small amount of precipitation can result in a large rise in the water table. It is further shown that calculations of groundwater recharge based on the water-table response (e.g., the water fluctuation method) and an assumed specific yield can lead to substantial errors. Water balance approaches and models that also include, for example, coupled water and energy balance models usually have a large number of parameters, the uncertainty of which may result in a large uncertainty in groundwater recharge estimates (Xie et al., 2018, Healy 2010, von Freyberg, et al., 2015). Xie et al. (2018) demonstrate that the ratio between groundwater recharge and precipitation is between 2% and 36% due to the uncertainty in vegetation parameters. The upper bound increases to almost 60% when different sets of pedotransfer functions are used in addition. Numerical modelling approaches can generally be used to estimate any range in recharge rates on every

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scale; however, the reliability of these recharge estimates should be evaluated in terms of the uncertainties in the conceptual model formulation, parameters and calibration approach (Brunner et al., 2012, Friedel et al., 2005, Hartmann et al., 2017, Ines and Droogers, 2002, Scanlon et al., 2002, Moeck et al., 2016, Moeck et al., 2018). For example, Moeck et al. (2018) compared four different recharge models with varying model complexity (simplified to complex physically-based models) and conclude that calibrated models will not ensure reliable predictions under dissimilar conditions, especially the simplified models.

5.2 Recharge processes

Recharge processes are largely controlled by climate, soils, geology, topography, hydrology as well as vegetation and land use. These factors need to be considered in formulating every conceptual model for all scales.

The analysis presented in this study confirms that climatic parameters, especially precipitation rates and seasonality in temperature and precipitation, are the most important factors influencing recharge rates, followed by soil and vegeation factors. In general, higher precipitation rates and stronger precipitation seasonality increase the potential for recharge by increasing the availability of water at the surface. In comparison, global variability in ET has less of an effect on groundwater recharge.

The high correlation and dependency of recharge rates on the climatic forcing functions indicate the sensitivity and vulnerability of recharge to future climate change, as indicated also in other studies (Cuthbert and Tindimugaya, 2010, Doble and Crosbie, 2017, Green, et al., 2011, Holman, 2006, Smerdon, 2017, among others). For instance, Cavé, et al. (2003) show that a 20% decrease in annual rainfall over the central parts of Southern Africa could translate to an 80% decline in recharge rates. An increase in precipitation variability may also increase recharge rates, even if the annual amount decreases (Pulido-Velazquez, et al., 2015, Taylor, et al., 2013, Thomas, et al., 2016). In any case, changes in the climatic forcing functions including seasonality and the occurrence of extreme events will influence future recharge rates.

As demonstrated, the influence of the climatic forcing functions on groundwater recharge can be highly site specific, such that simple estimates of recharge based only on annual precipitation and/or temperature can be misleading, also because they do not include other factors controlling recharge such as vegetation or soil parameters (Allison, et al., 1994, Kim and Jackson, 2012, Minnig, et al., 2018, Petheram, et al., 2002, Zhang, et al., 2001). Our analysis confirms that vegetation has considerable explanatory power for recharge rates. This is important because the

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treatment of vegetation parameters in global models is often cursory and not commonly interpreted with regard to recharge (Gerten, et al., 2004, Kim and Jackson, 2012). Vegetation has a high correlation with recharge and interacts with other physical variables such as climatic forcing functions, soil moisture, runoff capacity and porosity to add to its recharge-explanatory power (Kim and Jackson, 2012; Scanlon et al., 2005).

Finer soils with high clay and silt content have a thicker capillary fringe and greater decoupling depth (where all ET is provided by groundwater) and extinction depth (Doble and Crosbie, 2017), with the consequence that infiltration can be evaporated or transpired from the unsaturated zone reducing the volume that recharges groundwater at the water table (Wohling, et al., 2012). Coarser soils such as sands and loams allow faster rates of infiltration, although dry, hydrophobic sands can limit infiltration. Petheram, et al. (2002) point out that soil structure becomes more important for higher clay content soils compared to sandy soils, which is line with our study, where increasing clay content shows a correlation with recharge rates. Moreover, Petheram, et al. (2002) shows that preferential pathways such as cracks, root holes and karstic soils will allow groundwater to recharge more quickly through the soil matrix. This means that a greater proportion of infiltration will reach the water table as recharge without being delayed or stored in the unsaturated zone (Beven and Germann, 2013, Ghasemizade, et al., 2015, Lin, et al., 2006). We found that even though the sand fraction can be relatively high at some locations (e.g. typical for desert areas), recharge is low due to associated low precipitation rates. Although it has been shown that recharge is typically greater in coarser versus finer textured soils, the climatic conditions control recharge rates more strongly. Therefore, high sand content alone is not enough to ensure high recharge fluxes.

Recharge was shown to generally be higher at low altitudes and when the terrain is flat. Flat, low-lying topography fosters the formation of closed lakes, oases, gallery forests and riparian wetlands, characterized by shallow water tables (Berthold, et al., 2004, Fan, et al., 2013, Fan, et al., 2007, Manning and Solomon, 2003, Scanlon,et al., 2002). The relationship between depth to water table and groundwater recharge rates shows that high recharge rates occur with shallow water tables, pointing also to a climate control (Fan et al., 2013, Gleeson, et al., 2011). Shallow water tables normally exist where a significant amount of precipitation and water at the surface is available. In regions with deep water tables, long transient times for the percolating water to reach the water table and infiltration being converted to unsaturated zone storage result in low recharge rates (Cao, et al., 2016, Gurdak, et al., 2007, Gurdak and Qi, 2012, Wada, et al., 2016).

We also found that the impact of temperature seasonality and TWI decrease with higher recharge rates. In line with Jasechko et al. (2014),we presume that groundwater recharge in arid and temperate climates is higher during winter than in the summer because less evapotranspiration occurs in winter and snow melt might also contribute to recharge, if applicable. Subsequently, soil moisture conditions strongly control recharge rates, thus explaining the correlation of recharge rates to TWI, as the latter is an indicator for soil moisture conditions (Sörensen, et al., 2006). For higher recharge rates, seasonality and TWI seem to be less important, likely due to the surplus of water available at the surface. In tropical regions, groundwater recharge is highest during the wet season due to higher and more intense rainfall (Jasechko et al., 2014, Mileham et al., 2009, Taylor, et al., 2013). While the drivers behind these observations are not clear and the seasonality of groundwater recharge is intuitive, no data exist to quantify these patterns systematically on a global scale (Jasechko et al., 2014).

5.3 Benefits and Perspectives

Better understanding of recharge processes and readily available recharge measurements are valuable inputs to studies employing hydrological modelling. An analysis of existing data for the chosen study site, as well as recharge measurements of similar areas can shape and influence the initial conceptual model. The resulting better knowledge of the spatial distribution of recharge can lead to an improved validation of the hydrological water balance, especially for larger scale models. A proper validation of all components of the water balance is particularly important to avoid that the groundwater recharge term is only used to close the hydrological water balance and thus includes all the errors of the other water balance terms. In addition, by validating all components of the water balance, model bias induced by model calibration is easier to detect (Xie et al., 2018). However, the conceptual model and water balance calculation should typically evolve and be revised over time, as new data is collected and incorporated. We foresee the presented recharge dataset being used to help formulate, as well as validate conceptual and mathematical hydro(geo)logical models at all scales and that it will help to overcome limitations in various studies due to non-existing data. Due to the availability of the dataset (see section "Data and material availability") we anticipate that it will initiate new research into recharge processes, leading to increased data availability and improved recharge predictions.

6. Summary and Conclusion

Recharge processes are largely controlled by climate, soils, geology, topography, hydrology, vegetation and land use. These factors need to be considered in formulating every conceptual model. Our correlation analysis shows that climatic forcing functions, particularly annual precipitation and seasonality in temperature and precipitation, are the most important predictor variables of groundwater recharge rates. Heavy precipitation events or strong seasonality in the climatic forcing functions can lead to high recharge rates, although the annual water balance does not point to an increase in recharge. Moreover, temperature seasonality affects vegetation patterns and evapotranspiration and thus recharge rates and timing. Overall, the high correlation and dependency of recharge rates on the climatic forcing functions indicate the potential vulnerability of recharge to predicted climate change.

We also show that vegetation and soil structure can help predict recharge rates. Therefore, the influence of climatic forcing functions on groundwater recharge can be highly site specific and recharge estimates based solely on fixed fractions of precipitation are often misleading. Although variable vegetation has a high correlation with recharge and interacts with other physical variables, the treatment of vegetation parameters in global models is often cursory and not commonly interpreted with regard to recharge. Our analysis thus helps identify the most influential predictor variables of groundwater recharge rates for different climatic conditions. Furthermore, the compiled freely available global recharge dataset (see section "Data and material availability") can be used as a benchmark to systematically validate conceptual and mathematical model formulation for small- to large-scale recharge applications.

By highlighting where the availability of groundwater recharge data and process understanding are lacking, we hope to encourage the hydro(geo)logical community to help fill these gaps by conducting research projects to further our process understanding and make new recharge data publicly available.

Data and material availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

The groundwater global recharge data compiled and used in this study is available from [we will provide a link to the

open-access repository Zenodo with a doi number after acceptance] or from the corresponding author

(Christian.moeck@eawag.ch) on request.

We hope to encourage the community to make own published recharge data available in order to improve recharge

predictions. We welcome any contribution with sufficient information provided to expand the database. Please

contact Christian Moeck (link above) if you would like to add a resource.

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Graphical abstract

Global-scale dataset of groundwater recharge
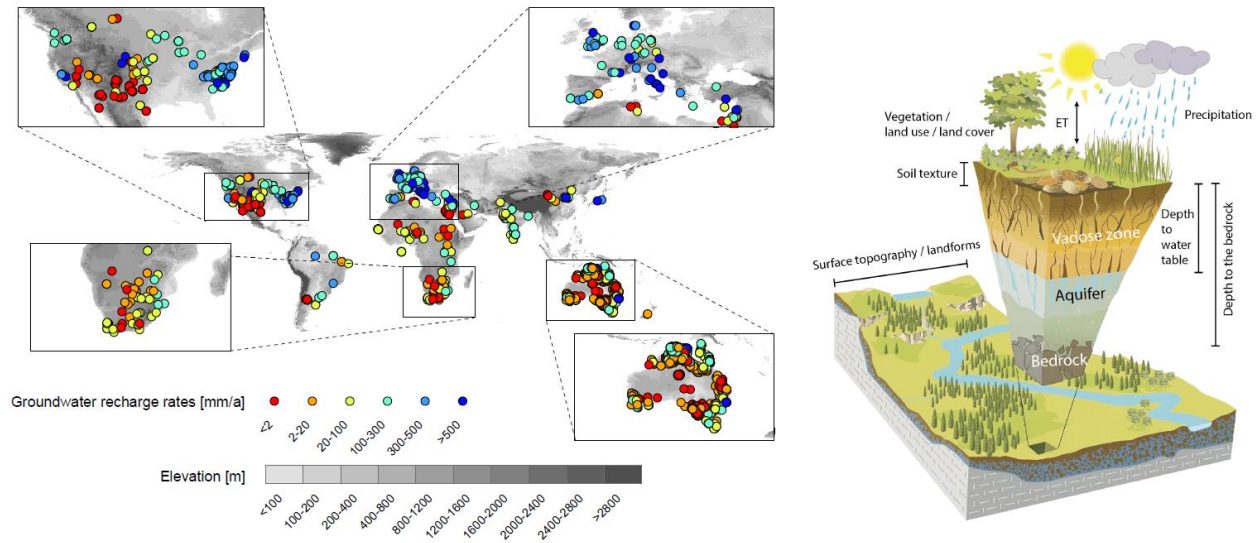
Highlights

We present a new freely available global recharge dataset of more than 5000 locations

Climatic forcing functions, including seasonality are the most important variables

Vegetation and soil structure can also help to predict recharge rates

High dependency of recharge on climate indicate the sensitivity to climate change

Dataset offers diverse possibilities to study recharge from a variety of perspectives