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Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099010

Global Recharge Data Set Indicates Strengthened Groundwater Connection to Surface Fluxes

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Key Points:

- A global recharge data set indicates that climate strongly shapes the fraction of precipitation that will recharge groundwaters
- This recharge data set indicates more recharge globally than existing global hydrological models suggest
- Thus, more groundwater must contribute to evaporation and streamflow than represented by current global models and water cycle diagrams

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Berghuijs, W. R., Luijendijk, E., Moeck, C., van der Velde, Y., & Allen, S. T. (2022). Global recharge data set indicates strengthened groundwater connection to surface fluxes. *Geophysical Research Letters*, *49*, e2022GL099010. https://doi.org/10.1029/2022GL099010

Received 6 APR 2022
Accepted 18 NOV 2022

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Abstract

Groundwater is an invaluable global resource, but its long-term viability as a resource for consumption, agriculture, and ecosystems depends on precipitation recharging aquifers. How much precipitation recharges groundwaters varies enormously across Earth's surface, yet recharge rates often remain uncertain. Here we use a global synthesis of field-estimated recharge across six continents to show that globally recharge first-order follows a simple function of climatic aridity. We use this relationship to estimate long-term recharge in energy-limited systems outside of permafrost regions. Our aridity-based recharge estimates are consistent with the global field data but, on average, double previous estimates of global models. Our higher recharge estimates are likely caused by preferential groundwater recharge and discharge occurring at grid scales finer than global models. The higher recharge estimates suggest that more groundwater contributes to evapotranspiration and streamflow than previously represented by global hydrological models and global water cycle diagrams.

Plain Language Summary

Groundwater is an essential resource for societies and ecosystems. The rate at which rainfall and snow replenish groundwater storage is important as it dictates the upper limit of sustainable groundwater use. Here we use measurements of groundwater recharge to show how climate determines groundwater recharge rates. Measured recharge rates, on average, strongly exceed those of models. This suggests there is more recharge globally than currently acknowledged. Consequently, also more groundwater recharge must get back to Earth's surface via river flow or water use of vegetation.

1. Introduction

Groundwater constitutes almost all of Earth's liquid fresh water (Abbott et al., 2019; Gleeson et al., 2016) and is extensively extracted, with global withdrawals of hundreds of cubic kilometers per year (Döll et al., 2014; Margat & Van der Gun, 2013; Sutanudjaja et al., 2018). Groundwater provides approximately 2 billion people with drinking water (Morris et al., 2003) and supplies almost 40% of irrigated lands worldwide (Siebert et al., 2010). Groundwater also shapes ecosystems and landscapes as rivers and vegetation can source their waters from aquifers (Berghuijs & Kirchner, 2017; Evaristo & McDonnell, 2017; Fan et al., 2017; Jasechko et al., 2016).

The dynamic roles of groundwater are not always apparent, but aquifers must be sufficiently recharged for groundwater to sustain ecosystems and water resources into the future (Alley et al., 2002; Gleeson et al., 2012). Earth's diversity of landscapes and climates results in groundwater recharge rates that vary by orders of magnitudes globally (MacDonald et al., 2021; Moeck et al., 2020; Scanlon et al., 2006). Yet, for most of Earth's surface, groundwater recharge rates remain uncertain because measurements are sparse (Moeck et al., 2020; Scanlon et al., 2006), and large-scale modeled recharge remains mostly unvalidated (de Graaf et al., 2015, 2019; Döll & Fiedler, 2008; Li et al., 2021; Müller Schmied et al., 2021; Reinecke et al., 2021). In addition, upscaling recharge estimates derived from extensively studied sites to other locations is challenging because many landscape, vegetation, and surface properties can affect recharge (Crosbie et al., 2018; De Vries & Simmers, 2002; Moeck et al., 2020). These issues are problematic because accurate recharge estimates are needed to assess the sustainability of groundwater use and the role of groundwater in supporting ecosystems and surface waters (Gleeson et al., 2020).

Writing – review & editing: Wouter R. Berghuijs, Elco Luijendijk, Christian Moeck, Ype van der Velde, Scott T. Allen

Regional analysis across carbonate rock landscapes indicates that many widely used hydrological models seem to underestimate recharge (Hartmann et al., 2017). However, it remains unclear how widespread this model bias is, as the enhanced recharge rates were attributed to the strong preferential flows in karst landscapes (Hartmann et al., 2017). Yet, other evidence also suggests that global models overestimate the sensitivity of recharge to climate change across arid regions in Africa because recharge induced by intense rainfall can lead to focused recharge through losses from ephemeral overland flows, which are often not captured by large-scale models (Cuthbert et al., 2019). Such discrepancies between models and observations are based on recharge and groundwater observations across specific landscapes and climate conditions. Thus, it remains unclear how widespread such issues are across other parts of Earth.

A recent global synthesis of recharge measurements from 5237 sites globally (Moeck et al., 2020) may alleviate this issue. This synthesis data set provides a basis to investigate how observation-based recharge values vary globally and to what extent there may be a widespread recharge bias in existing models. However, such investigations are hampered by the large unquantified uncertainty associated with observation-based recharge estimates (Crosbie et al., 2010, 2018; Moeck et al., 2020). In addition, the exact spatial scale and period these measurements represent remain uncertain and will never exactly overlap with those of models. However, the large number of sites in the data set still allows to investigate the primary controls on global patterns of recharge and quantify to what extent there could be a systematic recharge bias in existing models.

Here we show that climate aridity (Trabucco & Zomer, 2009)—*the ratio of potential evapotranspiration to precipitation*—strongly controls the fraction of precipitation that becomes groundwater. We parameterize a function that captures this relationship using the synthesis of groundwater recharge estimates (Moeck et al., 2020). We show that the synthesis of groundwater recharge estimates (Moeck et al., 2020) indicates that existing hydrological models, that have been previously used to predict recharge across the globe, underestimate recharge.

2. Methods and Data

2.1. Recharge Data

We obtain recharge rates from a recent global synthesis of groundwater recharge rates of 5237 sites located across all continents but Antarctica (Moeck et al., 2020). The compiled data primarily originate from tracer methods (~80%) but are also derived from water table fluctuations, water balance methods, lysimeters, heat tracers, and geophysical methods. This large variety of methods can affect estimated recharge rates at individual sites. The recharge estimation studies cover the period from 1968 to 2018. The mean recharge rate is 234 mm yr^{-1}, but over 40% of data points have rates between 0 and 25 mm yr^{-1} (median 51.3 mm yr^{-1}). The data set contains recharge rate estimates based on datasets that exceed at least 1 year to avoid bias in the rates due to seasonal effects and incomplete annual recharge values. The 5237 sites are assumed to represent naturally occurring recharge, as recharge rates presumed to be affected by irrigation or managed aquifer recharge were already omitted by Moeck et al. (2020). Study sites where rivers and streams dominate the estimated recharge were also omitted by Moeck et al. (2020). Almost all these measurements will fall on recharge zones of the landscape, which in surface area strongly dominate over the discharge zones near rivers (e.g., O'loughlin, 1981). The global data has no quality flags or uncertainties on recharge estimates because these estimates are also typically absent in many of the past reports. For more information on the data, see Moeck et al. (2020) and the references therein. Most of the observations (n = 4,386) originate from Australia (Crosbie et al., 2010) but these data have a similar relationship of recharge fractions with aridity as the other data in the data set (Figure S1 in Supporting Information S1).

2.2. Climate Data

We use temperature, aridity, precipitation, and FAO Penman-Monteith potential evapotranspiration data from WorldClim (Fick & Hijmans, 2017) and the global aridity and potential evapotranspiration database (Trabucco & Zomer, 2009). We define the aridity index as the ratio of mean potential evapotranspiration to mean precipitation. Accordingly, high aridity index values reflect drier climates, whereas low values reflect humid climates. Regions are classified as likely to have permafrost conditions when the mean annual temperature is below −2°C.

2.3. Relationship Between Climate and Recharge

We use a mathematical expression that describes the global relationship between climate aridity and groundwater recharge fractions:

$$\frac{R}{P} = \alpha\left(1 - \frac{\ln\left(\phi^{\beta}+1\right)}{1+\ln\left(\phi^{\beta}+1\right)}\right) \tag{1}$$

where R is groundwater recharge (mm yr^{-1}), P is precipitation (mm yr^{-1}), ϕ is aridity (dimensionless), defined as the ratio of potential evapotranspiration to precipitation (E_p/P), and α (dimensionless) is a constant equating to the fraction of precipitation that becomes recharge for $\phi \to 0$ (i.e., humid conditions). β is the characteristic exponent (dimensionless) of the aridity index. We calibrate the α and β using a least absolute residuals fit. The sigmoidal equation was selected because it is among the simplest equations that enforce physically realistic upper and lower limits for recharge fractions. It closely follows the exponential decrease of recharge fraction with increasing aridity visible in global recharge data. We reorganize the equation to estimate total recharge (mm yr^{-1}) using global precipitation and aridity data:

$$R = P \cdot \alpha\left(1 - \frac{\ln\left(\phi^{\beta}+1\right)}{1+\ln\left(\phi^{\beta}+1\right)}\right) \tag{2}$$

2.4. Groundwater Recharge Estimates From Global Models

We obtained simulated diffuse recharge estimates from the PCR-GLOB hydrological model (de Graaf et al., 2015, 2019) and the WaterGAP Global Hydrology Model (versions v2.1f and v2.2d) (Döll & Fiedler, 2008; Müller Schmied et al., 2021), and machine learning (Mohan et al., 2018). Also considering recharge from surface water bodies did not change the overall results significantly. For the 5237 stations with recharge data, we compare the observed recharge with the simulated recharge (Figure 3). The simulated recharge values from the global hydrological models represent mean annual recharge over a period that ranges from the year 1960 to 2001 (Döll & Fiedler, 2008), 1957 to 2002 (De Graaf et al., 2015), 1960 to 2010 (de Graaf et al., 2019) and 1901 to 2016 (Müller Schmied et al., 2021), respectively.

3. Results and Discussion

3.1. The Relationship Between Aridity and Recharge

The observation-based recharge estimates from sites spanning most regions of the globe show that recharge fractions are strongly controlled by climate aridity (Figure 1), despite many other factors also affecting groundwater recharge globally (e.g., Moeck et al., 2020). In humid climates, typically, larger fractions of precipitation recharge groundwater. This recharge fraction shrinks with increasing aridity, often approaching almost zero in very arid sites. This relationship is nonlinear, and the empirical data show substantial variation for a given aridity, reflecting an influence of other environmental conditions. However, the pattern is sufficiently monotonic to yield a highly significant correlation between climate aridity and the fraction of precipitation that recharges groundwaters (Spearman $\rho = -0.674$; $p < 0.001$). This relationship is consistent with past work, which indicated that both precipitation and potential evapotranspiration can strongly affect groundwater recharge (e.g., Moeck et al., 2020; Scanlon et al., 2006), but goes beyond these past works by also showing how the partitioning of precipitation changes. This quantified partitioning pattern is important as it substantiates the relative importance of recharge across different climates.

The vast majority (i.e., 99%) of the observation-based recharge values are from regions with climate aridities exceeding 0.75. These aridities cover most of Earth's surface aside from several of Earth's wettest regions (e.g., Congo Basin, Amazonia, Southeastern Asia), which largely fall outside the observational range. The observation-based recharge values (Figure 1b) suggest recharge fractions can shrink again at very low aridities, but this remains uncertain because only few of the recharge-measurement sites fall in energy-limited systems with aridity below one. In addition, the observation-based recharge sites fall outside regions underlain by permafrost

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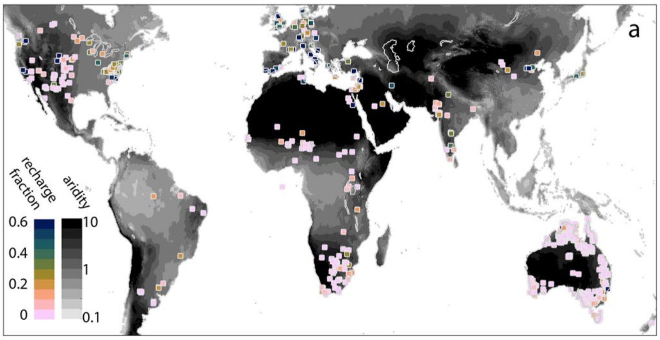

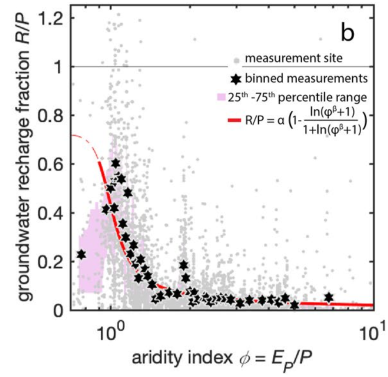

Figure 1. Groundwater recharge fractions vary with aridity. Recharge fractions (the ratio between long-term recharge and long-term precipitation) at the 5237 sites and the global pattern of climate aridity (a), whereby recharge negatively correlates with aridity (b). The gray markers indicate the recharge fractions of individual groundwater recharge sites, whereas dark markers average across 2% of the sites, removing most local site-to-site variability. The pink shading indicates a 25–75th percentile over 100 data points. The red line depicts the calibrated sigmoid function Equation 1. These data show how a distinct trend of groundwater recharge fractions decreasing with aridity. The relationship is least constrained at low aridities, where both high and low recharge rates can occur. There is substantial site-to-site recharge variability that is not explained by aridity which is caused by other conditions that affect the physical recharge rates, and the large uncertainties associated with recharge measurements.

(Obu, 2021), where recharge processes often differ from non-permafrost regions (Walvoord & Kurylyk, 2016). It is good to note that a large part of the observation-based global data set ($n = 4{,}386$) originates from the Australian continent, mostly synthesized by another study (Crosbie et al., 2010). These Australian data have higher recharge rates (mean = 244 mm yr^{-1}) compared to the remainder of the global data set (mean = 188 mm yr^{-1}) (Figure S1 in Supporting Information S1), but both parts of this global data set have a similar pattern of recharge fractions that shrink with aridity according to the worldwide trend (Figure 1; Figure S1 in Supporting Information S1). Therefore, the aridity-recharge relationship is likely representative for large parts of Earth's surface, but how recharge in very humid and permafrost regions evolves with aridity cannot be directly constrained by the existing data.

Much of the variations in recharge can be described by a sigmoidal function of climate aridity (Equation 1; Figure 1b). Calibrated on all data, this function describes how recharge exceeds 50% of precipitation ($\alpha = 0.72$, with 95% confidence bounds 0.71, 0.73) when aridity approaches one (i.e., precipitation equals potential evapotranspiration), and decreases with increasing aridity ($\beta = 15.11$, with 95% confidence bounds 14.91, 15.30). The relationship seems inaccurate at low aridities, where both high and low recharge rates can occur.

Large but unquantified uncertainties associated with recharge measurements can limit the correspondence between our model and the observations. However, although this parameterization is simple, it captures the observed global trend in the fraction of precipitation that becomes groundwater recharge more accurately than widely used global hydrological models (Figure 3), which underestimate recharge in both arid and humid regions (Extended Data Figure S2 in Supporting Information S1). The parsimony of our aridity-recharge relationship (Figure 1b) may limit its predictive power but using more predictor variables does not substantially improve its predictive capacity (Figure S3 in Supporting Information S1). A split-sample test using 80% of the data for calibration and the remaining 20% for validation still yields relatively narrow confidence bounds of the fitted parameters (95% confidence intervals $\alpha = 0.69$–0.75, $\beta = 14.0$–16.2, not displayed), thus also subsets of the empirical data effectively constrain the relationship (Figure S3 in Supporting Information S1). Thus, the seemingly overly simple predictions of groundwater recharge based on only climate aridity appear surprisingly effective compared to the status quo, despite excluding many other factors that may also affect groundwater recharge.

3.2. Global Recharge Pattern

The parameterized relationship between climate aridity and recharge fraction (Equation 1; Figure 1b) enables estimating the global distributions of groundwater recharge fractions (Figure 2a) and total groundwater recharge (Figure 2b) using global aridity and precipitation data (see Methods). The estimated global pattern of groundwater recharge fractions shows large regional differences in how much precipitation recharges groundwater, broadly

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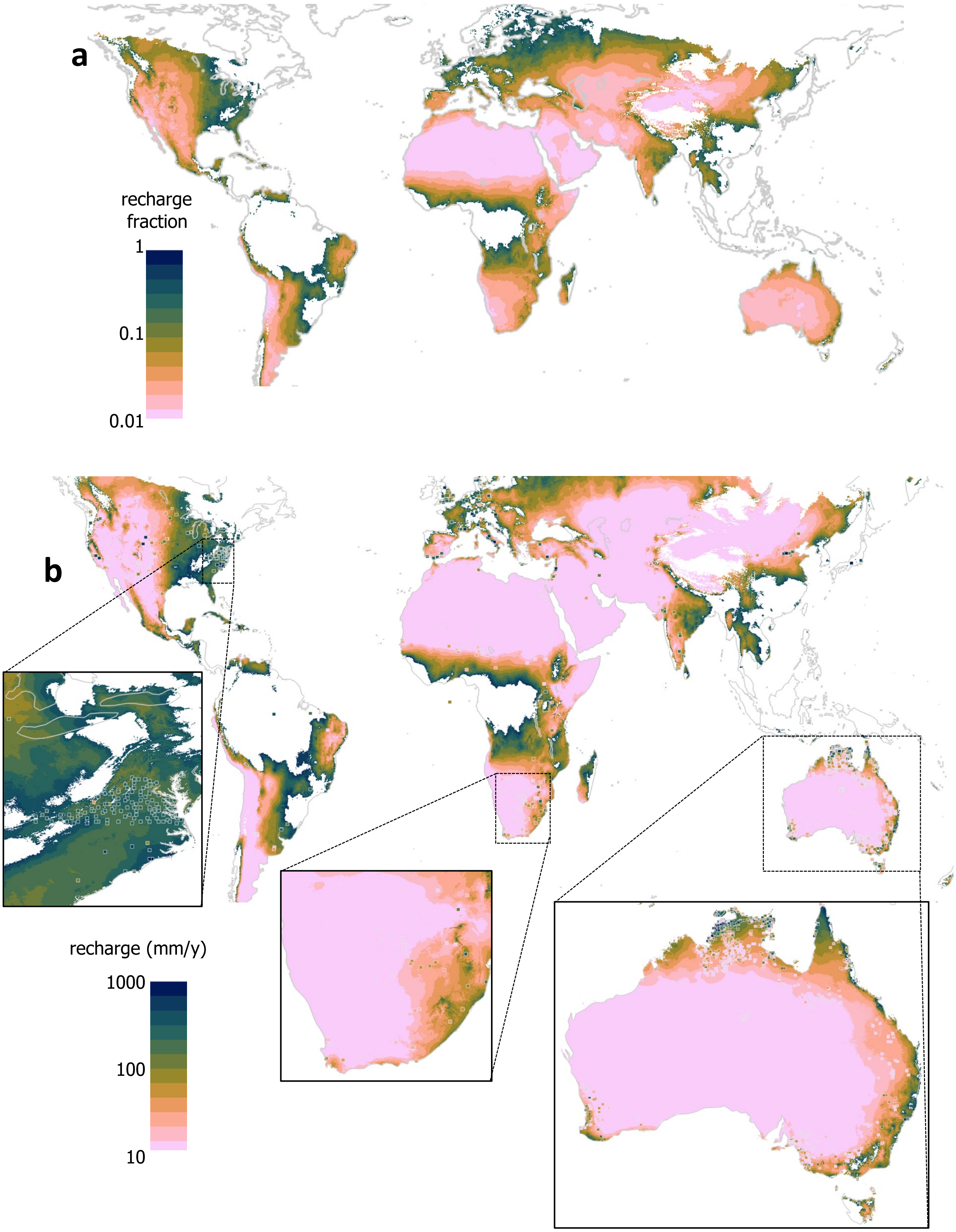

Figure 2. Estimated global patterns of groundwater recharge outside of permafrost regions. Estimates of groundwater recharge fractions vary regionally (a) and are based on global climate data and Equation 1. The absolute groundwater recharge values show high spatial variation because both the precipitation amount and the fraction of precipitation that becomes recharge are correlated with aridity (b) (note the logarithmic color scales). Markers indicate the observations at the 5237 sites (b). Permafrost regions are classified by having a mean annual temperature below −2°C. The estimates exclude regions with mean temperatures below −2°C because these regions lack observations, whereas regions with aridity below 1 are excluded indicating that the data in these very humid regions is limited.

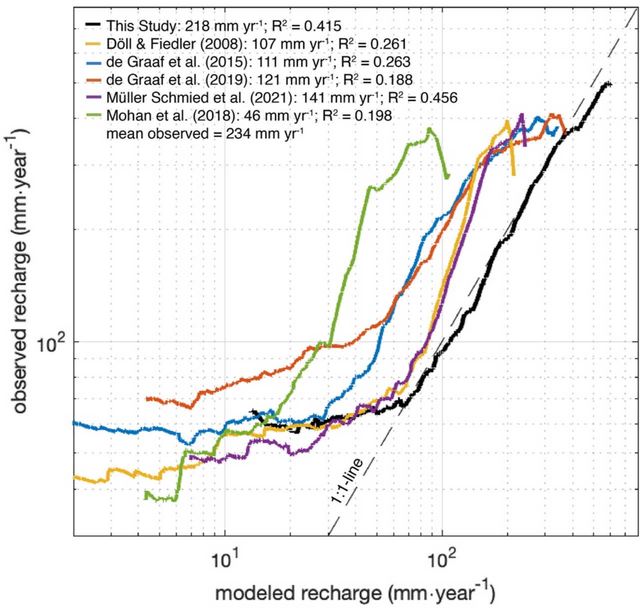

Figure 3. Comparison of observed versus predicted recharge for several global recharge predictions. Moving averages of recharge predicted by global models such as PCR-GLOB, WATER-GAP, and machine learning are systematically lower than recharge of the 5237 observation sites (as indicated by lines above the 1:1-line). The predictions by global models underestimate recharge by more than 50% compared to the recharge measurement. Using the sigmoid function (Equation 1) largely removes this bias and produces an overall average recharge of a very similar magnitude as global recharge estimates. The presented recharge rates are moving averages over 10% of the data. More detailed comparisons of modeled and observed recharge are presented in Figure S4 in Supporting Information S1.

consistent with the data set comprising observations from the 5237 sites (Figure 2a; Figure 1b). We exclude regions that can have permafrost (i.e., mean temperature below −2°C). Energy-limited regions with aridity below 1 are excluded from Figure 1 to indicate that the empirical climate aridity function poorly fits observations in these regions.

Estimated groundwater recharge fractions are low (<0.1) across roughly half of Earth's surface (excluding permafrost regions) (Figure 2a), as drylands are very prevalent across all continents but Europe (Figure 1a) (Berg & McColl, 2021). Recharge fractions increase across more humid parts of Earth such as most of Europe, eastern North America, central Africa, Southern Asia, and most of South America. These regional patterns are both present in observations and the estimated global pattern. Absolute recharge rates show largely similar regional patterns (Figure 2b), but the differences in estimated recharge are even greater between humid and arid regions. Estimated recharge would be highest in the equatorial wet regions and coastal regions of Central and North America, Europe, and Oceania (consistent with earlier global estimates), but large parts of these areas have aridities below 1 which means recharge estimates are hard to constrain because few data exist at these locations and the function starts to poorly fit the data. Nevertheless, even when recharge fractions are low, the potential of high absolute recharge rates will remain substantial in these regions as they experience high precipitation rates.

Observation-based recharge values more than double those of several previous global model estimates (Figure 3; Figure S4 in Supporting Information S1). Such model estimates have not been systematically evaluated with observed recharge data but rather with proxies such as streamflow measurements and groundwater levels, or only with a small amount of field data. If we compare the recharge rates from the widely used PCR-GLOB and WaterGAP global hydrological models with the recharge observations at the 5237 sites, we find that these models on average have 50% less recharge than the empirical data (Figure 3; Figures S4a–S4d in Supporting Information S1). A similar but even more substantial difference is present in another global recharge estimate based on 715 sites with recharge data (Figure 3; Figure S4e in Supporting Information S1). Split-sample tests do not show any such biases resulting from our aridity-recharge fraction relationship (Figure S2 in Supporting Information S1). An example realization of our relationship (Figure S4f in Supporting Information S1) shows how much better it explains observed recharge than other global hydrological models (Figures S4a–S4e in Supporting Information S1). The biases of the hydrological models arise from underestimations at both high and low recharge rates. The difference in modeled and field-estimated recharge may partly arise from the difference in the scales they represent. Global hydrological models simulate hydrological behavior at multiple km^2 per grid-cell scale, thereby covering both recharge and discharge zones. In contrast, most observations will be in recharge zones (Moeck et al., 2020), but discharge zones tend to cover only a small part of the Earth's surface (e.g., O'loughlin, 1981).

4. Implications and Conclusions

Aquifer storages are governed by the balance between recharge and discharge of groundwater to surface waters and vegetation, in addition to human abstractions (Alley et al., 2002). Where observations are available, field observations of recharge more than double most previous model estimates (Figure 3; Figure S4 in Supporting Information S1). This enhanced recharge does not counter the current understanding of regional groundwater overuse and its threats to global water security (Famiglietti, 2014) because groundwater overuse results in storage depletion and declining water levels that have been robustly documented in many more arid areas across the globe (e.g., Rodell et al., 2018).

Most recharge will resurface as evapotranspiration or river flow (Alley et al., 2002). Thus, higher recharge rates imply that groundwater's role in evapotranspiration and surface water fluxes is larger than previously modeled.

This also suggest that global hydrological models have overestimated (near) surface fluxes, such as overland flow, shallow subsurface flows through the unsaturated zone, and soil-moisture-fed evapotranspiration.

The implied greater role of groundwater in supplying streamflow and evapotranspiration is consistent with global observations that have shown that vegetation can source substantial parts of their water from groundwater, and vegetation disproportionally occurs near zones where it can access groundwater as a water source (Fan et al., 2017; Koirala et al., 2017). It is also consistent with the observation that most precipitation is stored in landscapes for at least several months before being observed in rivers (Jasechko et al., 2016), but note that older water can also have other sources as water also can reside in soils and reservoirs for months before being measured as streamflow (Messager et al., 2016; Sprenger et al., 2019). These dynamic connections with vegetation and streams likely predominantly occur in the upper layers of groundwater as deeper groundwaters mostly exchange slowly with the Earth's surface (Berghuijs & Kirchner, 2017; Jasechko et al., 2016, 2017).

Recharge and its main potential fates (i.e., streamflow vs. evapotranspiration) depend strongly on climate aridity (Budyko, 1974). How much precipitation becomes streamflow shrinks with increasing aridity, whereas the evaporative fraction grows with increasing aridity (Budyko, 1974) (Figure S5 in Supporting Information S1). In humid areas, which typically have substantial recharge, both streamflow and evapotranspiration can have groundwater contributions as streams typically have water levels below adjacent groundwater levels (Jasechko et a., 2021). Losing rivers are more common in drier climates (Jasechko et a., 2021), suggesting a smaller role for recharge in their streamflow and probably more recharge ultimately going to evapotranspiration. The relative contribution of groundwater for transpiration is also reported to grow with aridity (Evaristo & McDonnell, 2017) though conservation of mass dictates that groundwater will typically only be a small component of total evapotranspiration across arid landscapes (i.e., recharge << evapotranspiration). In mesic regions, the fraction of precipitation that recharges groundwater derived from the synthesis recharge data set tends to exceed the fraction that typically becomes streamflow (Figure S5 in Supporting Information S1), which suggests that also a part of evapotranspiration is supplied by groundwater. The gradients of recharge fraction with climate aridity may also help to assess the impacts of climate changes on groundwater recharge. The effects of climate change on recharge are currently highly uncertain and mostly unquantified (IPCC, 2021).

A strong connection of groundwater with surface water and plant transpiration remains absent from most diagrams of the global water cycle (Abbott et al., 2019; Dorigo et al., 2021; Oki & Kanae, 2006). Although such water cycle diagrams may not be intended as complete representations of the hydrological cycle, they often play an important role in teaching, research, communication, and policymaking (Abbott et al., 2019). Therefore, we need to consider revising those diagrams by increasing the rate at which groundwater is being replenished and discharged and strengthening the link of groundwater with incoming precipitation, surface waters, and vegetation (e.g., Miguez-Macho & Fan, 2021).

The underrepresentation of groundwater as a key contributor to evapotranspiration and river flows may be pervasive in hydrological models. Recharge is an internal flux that accumulates uncertainties and errors of other components of the budget (Reinecke et al., 2021), and models are often not designed to treat groundwater recharge as a main source of streamflow and evapotranspiration. Preferential flow paths that can recharge groundwaters are important in virtually any landscape (Beven & Germann, 2013; Nimmo, 2012) and contribute disproportionally to fluxes such as recharge (Berghuijs & Kirchner, 2017). Many of these pathways are absent in global hydrological models. Connections of groundwaters with streamflow and evapotranspiration could also be strengthened by including lateral groundwater flows (Maxwell & Condon, 2016). Many of these lateral connections between surface water and groundwater likely occur at scales smaller than the grid-cells of most models and thus require implicit sub-grid parameterizations (Fan et al., 2019). Strengthening the groundwater connection to surface fluxes in these models is essential, given that models are the foundation of our understanding of our planet, and underpin present-day environmental science and policymaking.

Data Availability Statement

All data used in this study are available via the cited sources. Precipitation data are available at https://www.worldclim.org/data/v1.4/worldclim14.html. Potential evapotranspiration and aridity data are available at https://cgiarcsi.community/data/global-aridity-and-pet-database/. Recharge data are available at https://opendata.eawag.ch/dataset/globalscale_groundwater_moeck.

Acknowledgments
We thank Dr. Ying Fan and Andrew Western for their constructive reviews that helped to improve this paper.

References

Abbott, B. W., Bishop, K., Zarnetske, J. P., Minaudo, C., Chapin, F. S., Krause, S., et al. (2019). Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, *12*(7), 533–540. https://doi.org/10.1038/s41561-019-0374-y

Alley, W. M., Healy, R. W., LaBaugh, J. W., & Reilly, T. E. (2002). Flow and storage in groundwater systems. *Science*, *296*(5575), 1985–1990. https://doi.org/10.1126/science.1067123

Berg, A., & McColl, K. A. (2021). No projected global drylands expansion under greenhouse warming. *Nature Climate Change*, *11*(4), 331–337. https://doi.org/10.1038/s41558-021-01007-8

Berghuijs, W. R., & Kirchner, J. W. (2017). The relationship between contrasting ages of groundwater and streamflow. *Geophysical Research Letters*, *44*(17), 8925–8935. https://doi.org/10.1002/2017gl074962

Beven, K., & Germann, P. (2013). Macropores and water flow in soils revisited. *Water Resources Research*, *49*(6), 3071–3092. https://doi.org/10.1002/wrcr.20156

Budyko, M. I. (1974). *Climate and life* (p. 508). Academic Press.

Crosbie, R. S., Jolly, I. D., Leaney, F. W., & Petheram, C. (2010). Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? *Hydrology and Earth System Sciences*, *14*(10), 2023–2038. https://doi.org/10.5194/hess-14-2023-2010

Crosbie, R. S., Peeters, L. J., Herron, N., McVicar, T. R., & Herr, A. (2018). Estimating groundwater recharge and its associated uncertainty: Use of regression kriging and the chloride mass balance method. *Journal of Hydrology*, *561*, 1063–1080. https://doi.org/10.1016/j.jhydrol.2017.08.003

Cuthbert, M. O., Taylor, R. G., Favreau, G., Todd, M. C., Shamsudduha, M., Villholth, K. G., et al. (2019). Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Nature*, *572*(7768), 230–234. https://doi.org/10.1038/s41586-019-1441-7

de Graaf, I. E. M., Gleeson, T., van Beek, L. R., Sutanudjaja, E. H., & Bierkens, M. F. (2019). Environmental flow limits to global groundwater pumping. *Nature*, *574*(7776), 90–94. https://doi.org/10.1038/s41586-019-1594-4

de Graaf, I. E. M., Sutanudjaja, E. H., van Beek, L. P. H., & Bierkens, M. F. P. (2015). A high-resolution global-scale groundwater model. *Hydrology and Earth System Sciences*, *19*(2), 823–837. https://doi.org/10.5194/hess-19-823-2015

De Vries, J. J., & Simmers, I. (2002). Groundwater recharge: An overview of processes and challenges. *Hydrogeology Journal*, *10*(1), 5–17. https://doi.org/10.1007/s10040-001-0171-7

Döll, P., & Fiedler, K. (2008). Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences*, *12*(3), 863–885. https://doi.org/10.5194/hess-12-863-2008

Döll, P., Mueller Schmied, H., Schuh, C., Portmann, F. T., & Eicker, A. (2014). Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research*, *50*(7), 5698–5720. https://doi.org/10.1002/2014wr015595

Dorigo, W., Dietrich, S., Aires, F., Brocca, L., Carter, S., Cretaux, J. F., et al. (2021). Closing the water cycle from observations across scales: Where do we stand? *Bulletin of the American Meteorological Society*, *102*(10), 1–95. https://doi.org/10.1175/bams-d-19-0316.1

Evaristo, J., & McDonnell, J. J. (2017). Prevalence and magnitude of groundwater use by vegetation: A global stable isotope meta-analysis. *Scientific Reports*, *7*(1), 1–12. https://doi.org/10.1038/srep44110

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, *4*(11), 945–948. https://doi.org/10.1038/nclimate2425

Fan, Y., Clark, M., Lawrence, D. M., Swenson, S., Band, L. E., Brantley, S. L., et al. (2019). Hillslope hydrology in global change research and Earth system modeling. *Water Resources Research*, *55*(2), 1737–1772. https://doi.org/10.1029/2018wr023903

Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B., & Otero-Casal, C. (2017). Hydrologic regulation of plant rooting depth. *Proceedings of the National Academy of Sciences*, *114*(40), 10572–10577. https://doi.org/10.1073/pnas.1712381114

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/joc.5086

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., & Cardenas, M. B. (2016). The global volume and distribution of modern groundwater. *Nature Geoscience*, *9*(2), 161–167. https://doi.org/10.1038/ngeo2590

Gleeson, T., Cuthbert, M., Ferguson, G., & Perrone, D. (2020). Global groundwater sustainability, resources, and systems in the anthropocene. *Annual Review of Earth and Planetary Sciences*, *48*(1), 431–463. https://doi.org/10.1146/annurev-earth-071719-055251

Gleeson, T., Wada, Y., Bierkens, M. F., & Van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197–200. https://doi.org/10.1038/nature11295

Hartmann, A., Gleeson, T., Wada, Y., & Wagener, T. (2017). Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. *Proceedings of the National Academy of Sciences*, *114*(11), 2842–2847. https://doi.org/10.1073/pnas.1614941114

IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change [Masson-Delmotte* In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, et al. (Eds.), Cambridge University Press.

Jasechko, S., Kirchner, J. W., Welker, J. M., & McDonnell, J. J. (2016). Substantial proportion of global streamflow less than three months old. *Nature Geoscience*, *9*(2), 126–129. https://doi.org/10.1038/ngeo2636

Jasechko, S., Perrone, D., Befus, K. M., Cardenas, M. B., Ferguson, G., Gleeson, T., et al. (2017). Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. *Nature Geoscience*, *10*(6), 425–429. https://doi.org/10.1038/ngeo2943

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., & Kirchner, J. W. (2021). Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature*, *591*(7850), 391–395. https://doi.org/10.1038/s41586-021-03311-x

Koirala, S., Jung, M., Reichstein, M., de Graaf, I. E. M., Camps-Valls, G., Ichii, K., et al. (2017). Global distribution of groundwater-vegetation spatial covariation. *Geophysical Research Letters*, *44*(9), 4134–4142. https://doi.org/10.1002/2017gl072885

Li, B., Rodell, M., Peters-Lidard, C., Erlingis, J., Kumar, S., & Mocko, D. (2021). Groundwater recharge estimated by land surface models: An evaluation in the conterminous United States. *Journal of Hydrometeorology*, *22*(2), 499–522. https://doi.org/10.1175/jhm-d-20-0130.1

MacDonald, A. M., Lark, R. M., Taylor, R. G., Abiye, T., Fallas, H. C., Favreau, G., et al. (2021). Mapping groundwater recharge in Africa from ground observations and implications for water security. *Environmental Research Letters*, *16*(3), 034012. https://doi.org/10.1088/1748-9326/abd661

Margat, J., & Van der Gun, J. (2013). *Groundwater around the world: A geographic synopsis*. Crc Press.

Maxwell, R. M., & Condon, L. E. (2016). Connections between groundwater flow and transpiration partitioning. *Science*, *353*(6297), 377–380. https://doi.org/10.1126/science.aaf7891

Messager, M. L., Lehner, B., Grill, G., Nedeva, I., & Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature Communications*, *7*(1), 1–11. https://doi.org/10.1038/ncomms13603

Miguez-Macho, G., & Fan, Y. (2021). Spatiotemporal origin of soil water taken up by vegetation. *Nature*, *598*(7882), 624–628. https://doi.org/10.1038/s41586-021-03958-6

Moeck, C., Grech-Cumbo, N., Podgorski, J., Bretzler, A., Gurdak, J. J., Berg, M., & Schirmer, M. (2020). A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships. *Science of the Total Environment*, *717*, 137042. https://doi.org/10.1016/j.scitotenv.2020.137042

Mohan, C., Western, A. W., Wei, Y., & Saft, M. (2018). Predicting groundwater recharge for varying land cover and climate conditions–a global meta-study. *Hydrology and Earth System Sciences*, *22*(5), 2689–2703. https://doi.org/10.5194/hess-22-2689-2018

Morris, B. L., Lawrence, A. R., Chilton, P. J., Adams, B., Cay-low, R. C., & Klinck, B. A. (2003). *Groundwater and its susceptibility to degradation: A global assessment of the problems and options for management* (Vol. 03–3). UNEP Early Warning & Assessment Report Series RS.

Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., et al. (2021). The global water resources and use model WaterGAP v2. 2d: Model description and evaluation. *Geoscientific Model Development*, *14*(2), 1037–1079. https://doi.org/10.5194/gmd-14-1037-2021

Nimmo, J. R. (2012). Preferential flow occurs in unsaturated conditions. *Hydrological Processes*, *26*(5), 786–789. https://doi.org/10.1002/hyp.8380

Obu, J. (2021). How much of the Earth's surface is underlain by permafrost? *Journal of Geophysical Research: Earth Surface*, *126*(5), e2021JF006123. https://doi.org/10.1029/2021jf006123

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, *313*(5790), 1068–1072. https://doi.org/10.1126/science.1128845

O'loughlin, E. M. (1981). Saturation regions in catchments and their relations to soil and topographic properties. *Journal of Hydrology*, *53*(3–4), 229–246. https://doi.org/10.1016/0022-1694(81)90003-2

Reinecke, R., Müller Schmied, H., Trautmann, T., Andersen, L. S., Burek, P., Flörke, M., et al. (2021). Uncertainty of simulated groundwater recharge at different global warming levels: A global-scale multi-model ensemble study. *Hydrology and Earth System Sciences*, *25*(2), 787–810. https://doi.org/10.5194/hess-25-787-2021

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M. H. (2018). Emerging trends in global freshwater availability. *Nature*, *557*(7707), 651–659. https://doi.org/10.1038/s41586-018-0123-1

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., & Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes: International Journal*, *20*(15), 3335–3370. https://doi.org/10.1002/hyp.6335

Siebert, S., Burke, J., Faures, J. M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation–a global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880. https://doi.org/10.5194/hess-14-1863-2010

Sprenger, M., Stumpp, C., Weiler, M., Aeschbach, W., Allen, S. T., Benettin, P., et al. (2019). The demographics of water: A review of water ages in the critical zone. *Reviews of Geophysics*, *57*(3), 800–834. https://doi.org/10.1029/2018rg000633

Sutanudjaja, E. H., Beek, R. V., Wanders, N., Wada, Y., Bosmans, J. H., Drost, N., et al. (2018). PCR-GLOBWB 2: A 5 arcmin global hydrological and water resources model. *Geoscientific Model Development*, *11*(6), 2429–2453. https://doi.org/10.5194/gmd-11-2429-2018

Trabucco, A., & Zomer, R. J. (2009). Global aridity and PET database (CGIAR consortium for spatial information. Retrieved from https://cgiarcsi.community/data/global-aridity-and-pet-database/

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic impacts of thawing permafrost—A review. *Vadose Zone Journal*, *15*(6), vzj2016.01.0010. https://doi.org/10.2136/vzj2016.01.0010