https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

The ISIMIP Groundwater Sector: A Framework for Ensemble Modeling of Global Change Impacts on Groundwater

Robert Reinecke[1], Annemarie Bäthge[1], Ricarda Dietrich[1], Sebastian Gnann[2], Simon N. Gosling[3], Danielle Grogan[4], Andreas Hartmann[5], Stefan Kollet[6], Rohini Kumar[7], Richard Lammers[4], Sida Liu[8], Yan Liu[6], Nils Moosdorf[9,10], Bibi Naz[6], Sara Nazari[9], Chibuike Orazulike[5], Yadu Pokhrel[11], Jacob Schewe[12], Mikhail Smilovic[13,14], Maryna Strokal[8], Yoshihide Wada[15], Shan Zuidema[4], Inge de Graaf[8]

Correspondence to: Robert Reinecke (reinecke@uni-mainz.de)

[1]Institute of Geography, Johannes Gutenberg-University, Mainz, Mainz, Germany
[2]Chair of Hydrology, University of Freiburg, Freiburg, Germany
[3]School of Geography, University of Nottingham, Nottingham, United Kingdom
[4]Institute for the Study of Earth, Oceans, and Space, University of New Hapshire, Durham, New Hampshire, USA
[5]Institute of Groundwater Management, TU Dresden, Dresden, Germany
[6]Agrosphere (IBG-3), Institute for Bio- and Geosciences, Research Centre Juelich, Juelich, Germany
[7]Department Computational Hydrosystems, Helmholtz Centre for Environmental Research GmbH - UFZ, Leipzig
[8]Earth Systems and Global Change Group, Wageningen University and Research, Wageningen, the Netherlands
[9]Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany
[10]Institute of Geosciences, Kiel University, Kiel, Germany
[11]Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Michigan, USA
[12]Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany
[13]Water Security Research Group, International Institute for Applied Systems Analysis, Laxenburg, Austria
[14]Chair of Hydrology and Water Resources, ETH Zurich, Zürich, Switzerland
[15]Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

Abstract

Groundwater serves as a crucial freshwater resource for people and ecosystems, vital in adapting to climate change. Yet, its availability and dynamics are affected by climate variations, changes in land use, and excessive extraction. Despite its importance, our understanding of how global change will influence groundwater in the future remains limited. Multi-model ensembles are powerful tools for impact assessments; compared to single-model studies, they provide a more comprehensive understanding of uncertainties and enhance the robustness of projections by capturing a range of possible outcomes. However, to this point no ensemble of groundwater models was available. Here, we present the new groundwater sector within ISIMIP which combines multiple global, continental, and regional-scale groundwater models. We describe the rationale for the sector, present the sectoral output variables, show first results of a model comparison, and outline the synergies with other existing ISIMIP sectors such as the global water sector and the water quality sector. Currently, eight models are participating in this sector, ranging from gradient-based groundwater models to specialized karst recharge models, each producing

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

up to 19 out of 23 modeling protocol-defined output variables. Utilizing available model outputs for a subset of participating models, we find that the arithmetic mean global water table depth varies substantially between models (6 - 127 m) and shows a shallower water table compared to other recent studies. Groundwater recharge also differs greatly in the global mean (78 - 228 mm/y), which is consistent with recent studies on the uncertainty of groundwater recharge but with different spatial patterns. Groundwater recharge changes between 2001 and 2006 show plausible patterns that align with droughts in Spain and Portugal during this period. The simplified comparison highlights the value of a structured model intercomparison project which will help to better understand the impacts of climate change on the world's largest accessible freshwater store – groundwater.

1 Introduction

Groundwater is the world's largest accessible freshwater resource, vital for human and environmental well-being (Huggins et al., 2023; Scanlon et al., 2023), serving as a critical buffer against water scarcity and surface water pollution (Foster and Chilton, 2003; Schwartz and Ibaraki, 2011). It supports irrigated agriculture, which supports 17% of global cropland and 40% of food production (Döll and Siebert, 2002; Perez et al., 2024; United Nations, 2022; Rodella et al., 2023). However, unsustainable extraction in many regions has led to declining groundwater levels, the drying of rivers, lakes and wells, land subsidence, seawater intrusion, and aquifer depletion (e.g., Bierkens and Wada (2019); de Graaf et al. (2019); Rodell et al. (2009)).

The pressure on groundwater systems intensifies due to the combined effects of population growth, socioeconomic development, agricultural intensification, and climate change, e.g., through a change in groundwater recharge (Taylor et al., 2013; Reinecke et al., 2021). Rising temperatures and altered precipitation patterns are already reshaping water availability and demand, with significant implications for groundwater use. For instance, changing aridity is expected to influence groundwater recharge rates (Berghuijs et al., 2024), yet the consequences for groundwater levels dynamics remain limited (Moeck et al., 2024; Cuthbert et al., 2019). It is further unclear how these shifts will affect groundwater's role in sustaining ecosystems, agriculture, and human water supplies.

Understanding the impacts of climate change and the globalized economy on groundwater systems requires a large-scale perspective (Haqiqi et al., 2023; Konar et al., 2013; Dalin et al., 2017). While groundwater management traditionally occurs at local or regional scales, aquifers often span administrative boundaries, and over-extraction in one area can have far-reaching effects not captured by a local model. Moreover, groundwater plays a critical role in the global hydrological cycle, influencing surface energy distribution, soil moisture, and evapotranspiration through processes such as capillary rise (Condon and Maxwell, 2019; Maxwell et al., 2016) and supplying surface waters with baseflow (Winter, 2007; Xie et al., 2024). These interactions underscore the importance of groundwater in buffering climate dynamics over extended temporal and spatial scales (Keune et al., 2018) and require a global perspective on the water-climate cycle. While large-scale climate-groundwater interactions are starting to become understood (Cuthbert et al., 2019), current global water and climate models may not always capture these feedbacks as most either do not consider groundwater at all or only include a simplified storage bucket, limiting our understanding of how climate change will affect the water cycle as a whole.

The inclusion of groundwater dynamics in global hydrological models remains a considerable challenge due to data limitations and computational demands (Gleeson et al., 2021). Simplified representations, e.g. linear reservoir (Telteu et al., 2021), often fail to capture the complexity of groundwater-surface water interactions, lateral flows at local or regional scales, or the feedback between groundwater pumping and streamflow (de Graaf et al., 2017; Reinecke et al., 2019). These processes are crucial for evaluating water availability, particularly in regions heavily dependent on groundwater. For instance, lateral flows sustain downstream river baseflows and groundwater availability, impacting water quality and ecological health (Schaller and Fan, 2009; Liu et al., 2020) and not including head dynamics may lead to overestimation of groundwater depletion (Bierkens and Wada, 2019). Multiple continental to global-scale groundwater models have been developed in recent years to represent these critical processes (for an overview see also Condon et al. (2021); Gleeson et al. (2021).

While current model ensembles of global water assessments have not yet included gradient-based groundwater processes, they have already advanced our large-scale understanding of the groundwater system. The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), analogous to the Coupled Model Intercomparison Project (CMIP) for climate models (Eyring et al., 2016), is a well-established community project to carry out model ensemble experiments for climate impact assessments (Frieler et al., 2017). The current generation of models in the Global Water Sector of ISIMIP often represents groundwater as a simplified storage that receives recharge, releases baseflow, and can be pumped (Telteu et al., 2021). Still, it lacks lateral connectivity and head-based surface-groundwater fluxes. Nevertheless, the ISIMIP water sector provided important insights on, for example, future changes and hotspots in global terrestrial water storage (Pokhrel et al., 2021), environmental flows (Thompson et al., 2021), the planetary boundary for freshwater change (Porkka et al., 2024), uncertainties in the calculation of groundwater recharge (Reinecke et al., 2021) and the development of methodological frameworks to compare model ensembles (Gnann et al., 2023).

Here, we present a new sector in ISIMIP called the ISIMIP Groundwater Sector, which integrates currently available groundwater models that operate at regional (at least multiple km² (Gleeson and Paszkowski, 2014)) to global scales. The groundwater sector aims to provide a comprehensive understanding of the current state of groundwater representation in large-scale models, identify groundwater-related uncertainties, enhance the robustness of predictions regarding the impact of global change on groundwater and connected systems through model ensembles, and provide insight into how to most reliably and efficiently model groundwater on regional to global scales. The new groundwater sector is a separate but complementary to the existing global water sector.

Specifically, the ISIMIP groundwater sector will compile a model ensemble that enables us to assess the impact of global change on various groundwater-related variables and quantify model and scenario-related uncertainties. These insights can then be used to quantify the impacts of global change on, e.g., water availability and in relation to other sectors impacted by changes in groundwater. The ISIMIP groundwater sector has natural linkages with other ISIMIP sectors, such as global water, water quality, regional water, and agriculture. This paper will highlight the connections between groundwater and these other sectors, providing an opportunity to improve our understanding of how modeling choices affect groundwater simulation dynamics.

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

2 The ISIMIP framework

ISIMIP aims to provide a framework for consistent climate impact data across sectors and scales. It facilitates model evaluation and improvement, enables climate change impact assessments across sectors, and provides robust projections of climate change impacts under different socioeconomic scenarios. ISIMIP uses a subset of bias-adjusted climate models from the CMIP6 ensemble. The subset is selected to represent the broader CMIP6 ensemble while maintaining computational feasibility for impact studies (Lange, 2021).

ISIMIP has undergone multiple phases, with the current phase being ISIMIP3. The simulation rounds consist of two main components: ISIMIP3a and ISIMIP3b, each serving distinct purposes. ISIMIP3a focuses on model evaluation and the attribution of observed climate impacts, covering the historical period up to 2021. It utilizes observational climate and socioeconomic data and includes a counterfactual "no climate change baseline" using detrended climate data for impact attribution. Additionally, ISIMIP3a includes sensitivity experiments with high-resolution historical climate forcing. In contrast, ISIMIP3b aims to quantify climate-related risks under various future scenarios, covering pre-industrial, historical, and future projections. ISIMIP3b is divided into three groups: Group I for pre-industrial and historical periods, Group II for future projections with fixed 2015 direct human forcing, and Group III for future projections with changing socioeconomic conditions and representation of adaptation. Despite their differences in focus, time periods, and data sources, both ISIMIP3a and ISIMIP3b require the use of the same impact model version to ensure consistent interpretation of output data, thereby contributing to ISIMIP's overall goal of providing a framework for consistent climate impact data across sectors and scales.

In the short term, the groundwater sector will focus on the historical period 1901-2019 in ISIMIP3a (https://protocol.isimip.org/#/ISIMIP3a/water_global/groundwater) with the climate-related forcing based on observational data (obsclim) and the direct human forcing based on historic data (histsoc). We aim to utilize these simulations for an in-depth model comparison, including a comparison to observational data such as time series of groundwater table depth (e.g., Jasechko et al. (2024)) and by utilizing functional relationships (Reinecke et al., 2024). This will yield a new understanding of how these models differ, what the reasons for these differences are, and how they could be improved. In addition, it will provide a basis for implementing impact analyses with ensemble runs based on future scenarios using ISIMIP3b inputs.

3 The current generation of groundwater models in the sector

Many large-scale groundwater models are already participating in the sector (Table 1), and we expect to expand further. The current models are mainly global-scale, with some having a particular regional focus, and primarily using daily timesteps.

While the main modeling purpose of most models is to simulate parts of the terrestrial water cycle, they all focus on different aspects (such as karst recharge or sea-water intrusion), most investigate interactions between groundwater and land surface processes, and account for human water uses. Two models (V2KARST and GGR) have distinct purposes in modeling groundwater recharge and do not model any head-based groundwater fluxes. Conceptually, the models may be classified according to Condon et al. (2021) into five categories: lumped models with static groundwater configurations of long-term mass balance (a), saturated groundwater flow with recharge,

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

and surface water exchange fluxes as upper boundary conditions without later fluxes (b), quasi 3D models with variably saturated flow in the soil column and a dynamic water table as a lower boundary condition (c), saturated flow models solving mainly the Darcy equation (d), and variably saturated flow which is calculated as three-dimensional flow throughout the entire subsurface below and above the water table (e). See Condon et al. (2021) and also Gleeson et al. (2021) for a more detailed overview and discussion of approaches. Half of the models (Table 1) simulate a saturated subsurface flux (d), V2KARST and GGR mainly use a 1D vertical approach (b), and others simulate a combination of multiple approaches (ParFlow, Table 1) or can switch between different approaches (CWatM, Table 1).

The sector protocol is defined at https://protocol.isimip.org/#/ISIMIP3a/groundwater and will be updated over time. We have defined multiple joint outputs for this sector (23 variables in total), but not all models can yet provide all outputs (Table 2). Models can provide 1-19 outputs (11 on average), and multiple models have further outputs that are under development. The global water sector also contains groundwater-related variables (Table A2), enabling groundwater-related analysis. We list them here to show their close connection to the global water sector and facilitate an overview of future groundwater-related studies.

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Table 1: Summary of all models participating in the ISIMIP groundwater sector. This table lists only models that add new variables to the ISIMIP protocol. Models already part of the global water sector and providing other groundwater-related variables are not listed here. (GMD discussion formatting requires a portrait instead of a landscape table)

Model name	**Main model purpose**	**Coupling with other models**	**Spatial domain and resolution**	**Temporal resolution**	**Hydrogeological configuration, e.g. number of layers**	**Conceptual model according to Condon et al.**	**Calibrated**	**Representation of groundwater use**	**Main Reference**
Water Balance Model (WBM)	Representation of the terrestrial hydrologic cycle, including human interactions.	-	Global and regional. Spatial resolution defined by the input river network.	Sub-daily, Daily, Multi-day	1 soil layer, 2 groundwater layers	d.	Globally: no, regional: yes (NE, US)	Through calculated abstractions from groundwater.	Grogan et al. (2022) With groundwater methods based on de Graaf et al. (2015); de Graaf et al. (2017).
Community Land Model (CLM)	To simulate surface and sub-surface hydrologic processes, including crop growth, irrigation, and groundwater withdrawal.	Community Earth System Model (CESM)	Global and regional (0.05 (regional), 0.1, 0.25, and 0.5 degree (global))	Sub-Daily	20 soil layers extending up to 8.5 m; 1 aquifer layer, unconfined	c.	No	Yes	Felfelani et al. (2021) Lawrence et al. (2019)
Community Water Model (CWatM)	To reproduce main hydrologic processes, including water	MODFLOW (optional)	Global, regional, subbasin (30 arcseconds, 1 km, 1 arc-min, 5 arc-min,	Daily	Standard: 1 with MODFLOW: variable	Standard: a./b. With MODFLOW: d.	Globally: yes (with discharge), regional: tailored	Yes	Guillaumot et al. (2022); Burek et al. (2020)

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

	management on regional to global scales.		30 arc-min)						
Global Gradient-based Groundwater Model (G³M)	Understanding of surface water, coastal, and ecosystem interaction with groundwater.	WaterGAP (Müller Schmied et al., 2016)	Global (5 arc minutes)	Daily, monthly, or yearly	2 layers, second layer with a reduced hydraulic conductivity	d.	No	Through calculated net abstractions from groundwater of WaterGAP	Reinecke et al. (2019); Kretschmer et al. (2025)
VIC-WUR-MODFLOW (VIC-wur)	Grid-based macro-scale hydrological model that solves both the surface energy balance and water balance equations.	WOFOST (WOrld FOod STudies) (Droppers et al 2021)	Regionally and globally: 5 arcminutes	Sub-daily to monthly	3 soil layers (variable thickness), 2 groundwater layers (variable thickness, confined/unconfined systems.	d.	Globally: no, regional: yes	Through calculated demands and allocation to surface water/ groundwater.	Liu et al in prep.; Droppers et al. 2020.; Liang et al. (1994)
V2KARST	A grid-based vegetation–recharge model for the global karst areas.	-	Globally: 0.25 arc degree	Daily	three soil layers and one epikarst layer	b.	Yes, based on global karst landscapes	no	Sarrazin et al. (2018)

GGR	A grid-based three-layer water balance model to estimate the daily global rain-fed groundwater recharge	-	180.0°W to 180.0°E longitudes and 60.0°N to 60.0°S latitudes, 0.1 degree	Daily	2 soil layers and 1 groundwater layer of variable thickness	b.	No	No	Nazari et al. (2025)
ParFlow	3D continuum simulations of variably saturated groundwater-surface water and land surface processes.	Common Land Model, CLM (Maxwell and Miller, 2005; Kollet and Maxwell, 2008), Terrestrial Systems Modeling Platform (Gasper et al., 2014), WRF (Maxwell et al., 2011)	Regionally and globally, 10^0 – 10^1km	Variable	Variable	a. - e.	Yes, in engineering applications	Yes	Kuffour et al. (2020)

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Table 2: List of output variables in the ISIMIP3a global groundwater sector. The spatial resolution is five arcminutes (even if some models simulate at a higher or coarser resolution), and the temporal resolution is monthly. Most models also simulate daily timesteps, but as most groundwater movement happens across longer time scales, we unified the unit to months. A "*" indicates that a model is able to produce the necessary output. A "+" indicates that this output is currently under development. (GMD discussion formatting requires a portrait instead of a landscape table)

Groundwater sector output variables		Unit	WBM	*CLM*	*CWatM*	G^{3}M	*VIC-wur*	V2KARST	*GGR*	*ParFlow*
Name	**Description**									
Capillary rise	Upward flux from groundwater to soil (leaving aquifer = negative value).	m3 m-2 month-1		*	*		*			*
Diffuse groundwater recharge	Downwards flux from soil to groundwater (entering aquifer = positive value). The unit kg m^{-2} s^{-1} is equal to mm s^{-1}. Unit is kept equal to the global water sector.	kg m-2 s-1	*	*	*		*	*	*	*
Groundwater abstractions	Groundwater pumped from the aquifer.	m3 m-2 month-1	*	*	*		+		+	
Groundwater abstractions (domestic)	*Groundwater abstractions* that are intended for domestic water use.	m3 m-2 month-1	*		*		+		+	
Groundwater abstractions (industries)	*Groundwater abstractions* that are intended for industrial water use.	m3 m-2 month-1	*		*		+		+	
Groundwater abstractions (irrigation)	*Groundwater abstractions* that are intended for irrigational water use.	m3 m-2 month-1	*	*	*		+		+	
Groundwater abstractions (livestock)	*Groundwater abstractions* that are intended for livestock water use.	m3 m-2 month-1	*		*		+			
Groundwater demands	Gross water demand	m3 m-2 month-1	*	*	*		+			
Groundwater depletion	Long-term losses from groundwater storage	m3 m-2 month-1	*	*		*	+			*

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Groundwater drainage/surface water capture	Exchange flux between groundwater and surface water. Groundwater leaving the aquifer = negative value; entering the aquifer = positive value	m3 m-2 month-1	*	*	*	*	*			*
Groundwater drainage/surface water capture from lakes	Exchange flux between groundwater and surface water (lakes); if available, additional to the sum of exchange fluxes (Groundwater drainage/surface water capture) also separate components can be provided/ Leaving the aquifer = negative values; entering the aquifer = positive value.	m3 m-2 month-1				*	*			*
Groundwater drainage/surface water capture from rivers	Exchange flux between groundwater and surface water (rivers); if available, additional to the sum of exchange fluxes (Groundwater drainage/surface water capture) also separate components can be provided/ Leaving the aquifer = negative values; entering the aquifer = positive value.	m3 m-2 month-1	*			*	*			*
Groundwater drainage/surface water capture from springs	Exchange flux between groundwater and surface water (springs); if available, additional to the sum of exchange fluxes (Groundwater drainage/surface water capture) also separate components can be provided/ Leaving the aquifer = negative values; entering the aquifer = positive value.	m3 m-2 month-1				*	*			*
Groundwater drainage/surface water capture from wetlands	Exchange flux between groundwater and surface water (wetlands); if available, additional to the sum of exchange fluxes (Groundwater drainage/surface water capture) also separate components can be provided/ Leaving the aquifer = negative values; entering the aquifer = positive value.	m3 m-2 month-1				*	*			*
Groundwater return flow	Return flow of abstracted groundwater (not yet separated into different sources).	m3 m-2 month-1	*	*			.		.	*
Groundwater storage	Mean monthly water storage in groundwater layer in kg m^{-2}. The spatial resolution is 0.5° grid.	m3 m-2 month-1	*	*		*	*			*

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Hydraulic head	Head above sea level in m. If more than one aquifer layer is simulated, report the heads on the top productive aquifer (confined or unconfined).	m	*			*	*			*
Lateral groundwater flux (front face)	Cell-by-cell flow (front)	m3 m-2 month-1	*	*		*	*			*
Lateral groundwater flux (right face)	Cell-by-cell flow (right)	m3 m-2 month-1	*	*		*	*			*
Lateral groundwater flux (net)	Net cell-by-cell flow	m3 m-2 month-1	*	*		*	*			*
Lateral groundwater flux (lower face)	Cell-by-cell flow (lower) when more than 1 groundwater layer is simulated.	m3 m-2 month-1	*			*	*			*
Submarine groundwater discharge	Flow of groundwater into oceans. The definition may vary by model. But in principle also models without density driven flow can submit this variable.	m3 m-2 month-1	*			*				*
Water table depth	Depth to the water table below land surface (digital elevation mode, DEM) in m.	m	*	*		*	*			*
Number of groundwater output variables in model	Counting only currently available		**19**	**13**	**9**	**14**	**14**	**1**	**1**	**17**

176

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

4 Unstructured experiments point out model differences that should be explored further

The ISIMIP groundwater sector is in an early development stage, and we hope that an ensemble of groundwater models driven by the same meteorological data will be available soon. Yet, to provide first insights into the models, their outputs, and how these can be compared we collected existing outputs from the participating models (see Table A1 for an overview). We opted for a straightforward initial comparison due to the various data formats, model resolutions, and forcings that complicate a more thorough examination of a specific scientific inquiry. Thus, this descriptive analysis serves as an introductory overview that highlights the present state of the art and identifies model discrepancies warranting further investigation. In addition, relevant output data are not yet available for all models. We focused on the two variables with the largest available ensemble: water table depth (G^{3}M, CLM, WBM, and VIC-wur; Table 1) and groundwater recharge (CLM, CWatM, GGR, VIC-wur, V2KARST, WBM; Table 1), only on historical periods rather than future projections.

The arithmetic mean (not weighted by cell area) global water table depth varies substantially (6 m – 127 m) between the models at the start of the simulation (1980 or steady-state) (Fig. 1a). On average, the water table of G^{3}M (28 m) and CLM (6 m) are shallower than WBM (127 m) and VIC-wur (81 m), whereas the latter two also show a larger standard deviation (WBM: 133 m, VIC-wur: 105 m) than the other two models (G^{3}M: 49 m, CLM: 3 m). The consistently shallower WTD of CLM impacts the ensemble mean WTD (Fig. 1b), which is shallower compared to other model ensembles (5.67 m WTD as global mean here compared to 7.03 m in Reinecke et al. (2024)). This difference in ensemble WTD points to conceptual differences between the models, which should be investigated further, for example, by exploring spatial and temporal differences and relationships with important groundwater drivers (Reinecke et al., 2024).

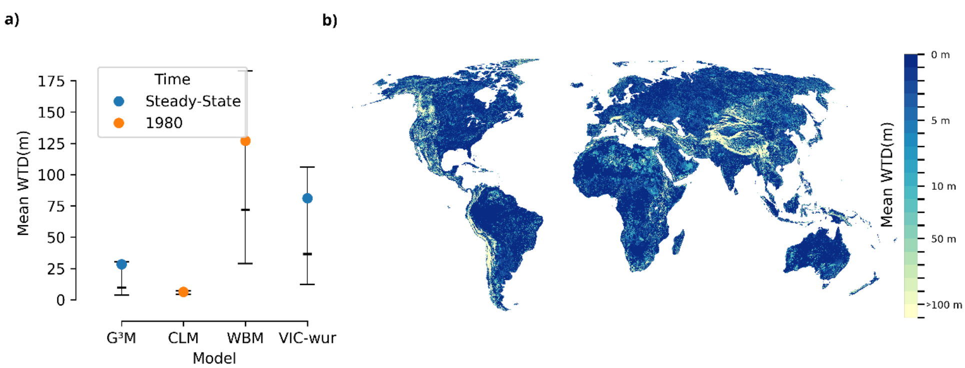

Figure 1: Global water table depth (WTD) at simulation start (1980) or the used steady-state. The simplified boxplot (a) shows the arithmetic model mean as a colored dot and the median as a black line. Whiskers indicate the 25th and 75th percentiles, respectively. The global map (b) shows the arithmetic mean of the model ensemble.

Similarly, the global arithmetic mean groundwater recharge (not weighted by cell area) differs by 332 mm/y between models (150 mm/y excluding V2KARST since it calculates recharge in karst regions only) (Fig. 2a). This

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

difference in recharge is more pronounced spatially (Fig. 2b) than differences in WTD shown before (Fig. 1b). Especially in drier regions such as in the southern Africa, central Australia, and the northern latitudes show coefficient of variation of 1 or greater (white areas). In extremely dry areas such as the east Sahara and southern Australia, the model spread is close to 0 (dark green). While the agreement is higher in Europe and western South America, the map differs slightly from other recent publications (e.g., compared to Fig. 1b in Gnann et al. (2023)). In light of other publications, highlighting model uncertainty in groundwater recharge (Reinecke et al., 2021) and the possible impacts of long-term aridity changes on groundwater recharge (Berghuijs et al., 2024), an extended combined ensemble of the global water sector and the new groundwater sector could yield valuable insights.

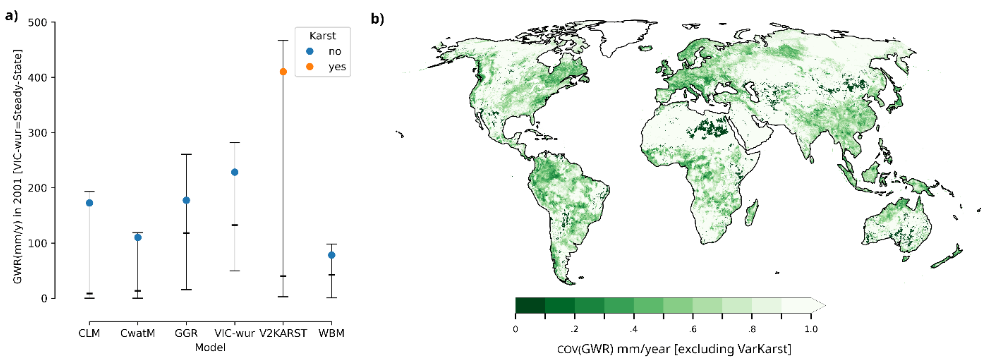

Figure 2: Global groundwater recharge (GWR) in 2001 or at steady-state (only VIC-wur). The simplified boxplot (a) shows the arithmetic model mean as a colored dot and the median as a black line. Whiskers indicate the 25th and 75th percentiles, respectively. The global map (b) shows the coefficient of variation of the model ensemble without V2KARST.

We further calculated relative changes in groundwater recharge between 2001 and 2006 (Fig. 3) with an ensemble of 7 models (CLM, CWatM, GGR, VIC-wur, V2KARST, WBM, and ParFlow). The ensemble includes two models that only simulate specific regions (V2KARST: regions of karstifiable rock, ParFlow: Euro CORDEX domain). This result shows a potential analysis that should be repeated within the new groundwater sector. Intentionally, we do not investigate model agreement on the sign of change or compare them with observed data. The ensemble still highlights plausible regions of groundwater recharge changes, such as in Spain and Portugal, which aligns with droughts in the investigated period (Paneque Salgado and Vargas Molina, 2015; Coll et al., 2017; Trullenque-Blanco et al., 2024). Relative increases in groundwater recharge are mainly shown for arid regions in the Sahara, the Middle East, Australia, and Mexico. However, it is likely that because we investigate relative changes, this might be related to the already low recharge rates in these regions.

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

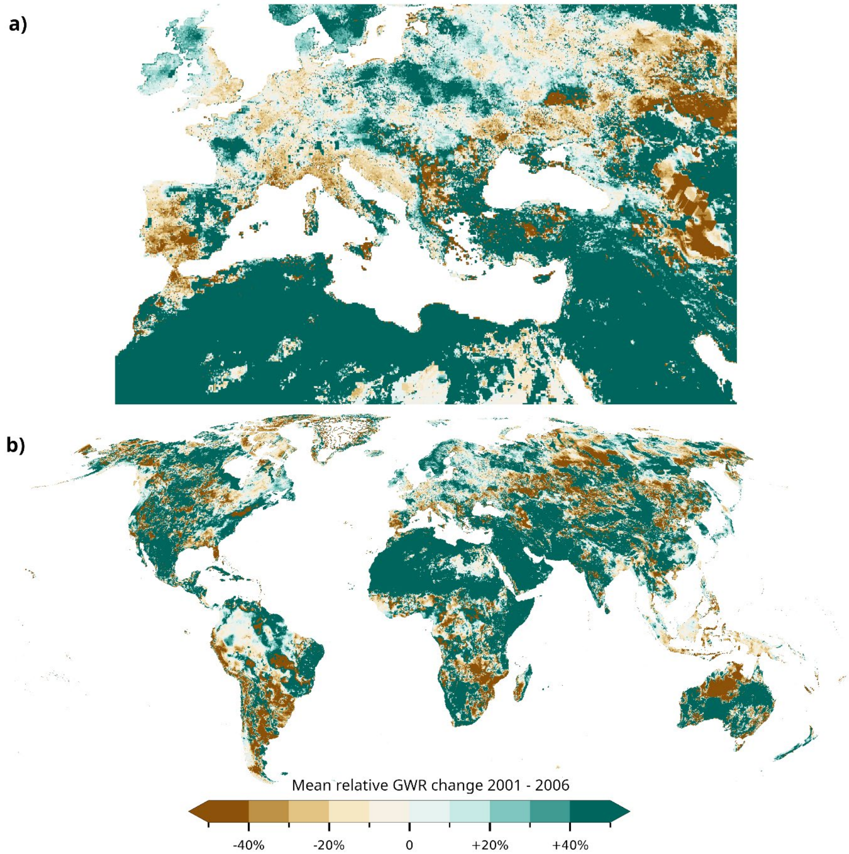

Figure 3: Mean relative percentage change of yearly groundwater recharge between 2001 and 2006 for Europe (a), and all continents except Antarctica (b). The ensemble consists of all models that provided data for the years 2001 and 2006 (CLM, CWatM, GGR, VIC-wur, V2KARST, WBM, and ParFlow). V2KARST (only karst) and ParFlow (only Euro CORDEX domain) were only accounted for in regions where data is available.

5 Groundwater as a linking sector in ISIMIP

ISIMIP encompasses a wide variety of sectors. Currently, 18 sectors are part of the impact assessment effort. The groundwater sector offers a new and unique opportunity to enhance cross-sectoral activities within ISIMIP, foster interlinkages within ISIMIP, and thus deliver interdisciplinary assessments of climate change impacts.

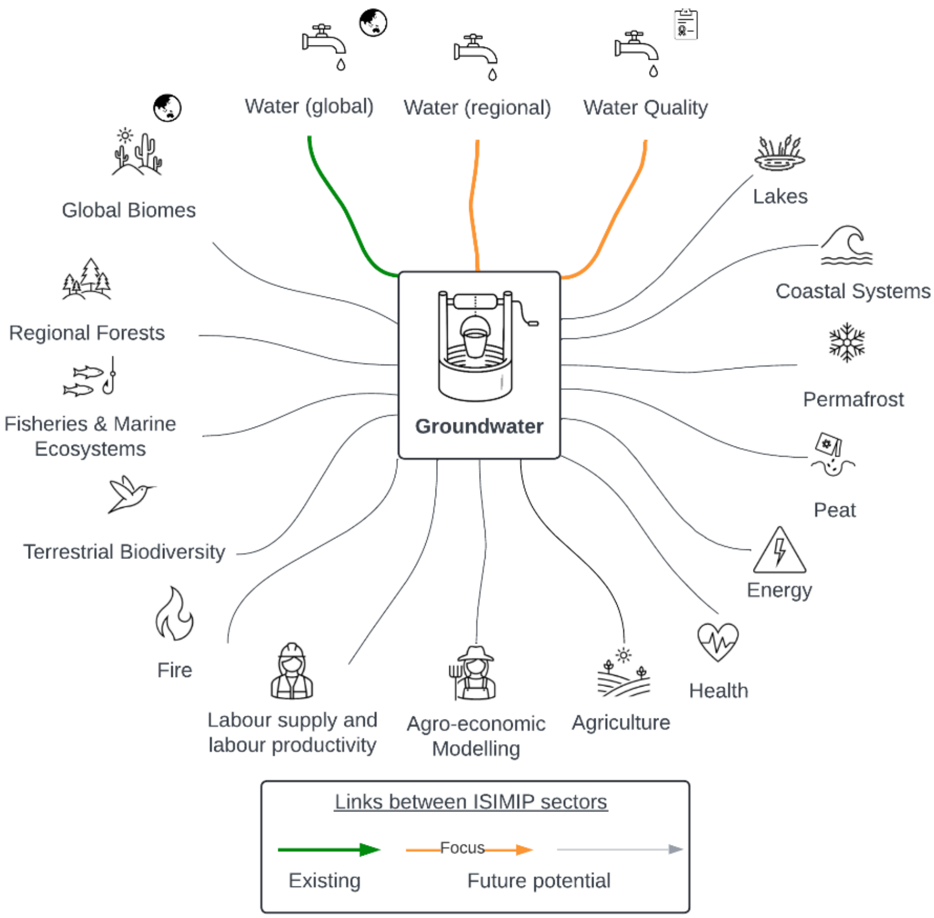

Figure 4: The groundwater sector provides the potential for multiple interlinkages between different sectors within ISIMIP. In the coming years, we will focus on links to three sectors (green and orange): water (global), water (regional), and water quality. Other cross-sectoral linkages between non-groundwater sectors (i.e. linkages between the outer circle) are not shown.

Some links with other sectors within ISIMIP are more evident than others with regard to existing scientific community overlaps or existing scientific questions (Fig. 4). For example, the new groundwater sector will focus on large-scale groundwater models, some of which are already part of global water models participating in the global water sector or using outputs (such as groundwater recharge) from the global water sector (see also existing groundwater variables in the global water sector Table A2). However, the groundwater sector will also feature non-global representations of groundwater. Thus, collaborating with the regional water sector could provide opportunities to share outputs and pursue common assessments. For example, the outputs of the groundwater model ensemble, such as water table depth variations or surface water groundwater interactions, could be used as input for some regional models that consider groundwater only as a lumped groundwater storage. Conversely, global and continental groundwater models can learn from validated regional hydrological models, which may provide insights into local runoff generation processes and impacts of water management. Furthermore, the relevance of groundwater for water quality assessments is widely recognized (e.g., for phosphorous transport from groundwater to surface water (Holman et al., 2008), or for salinization (Kretschmer et al., 2025)), or as a link between warming groundwater and stream temperatures (Benz et al., 2024). Leveraging such connections will provide valuable insights beyond groundwater itself.

Specifically, considering groundwater quality, a collaboration between both sectors could be achieved in multiple aspects. Integrating groundwater availability with water quality helps ensure sufficient and safe drinking and irrigation water. Focusing on aquifer storage levels and pollutant loads can help maintain groundwater resilience, safeguard food security, and protect public health under changing climate and socioeconomic conditions. Further, integrating groundwater quantity data with pollution source mapping helps prioritize remediation efforts where aquifers are most vulnerable, ensuring both water availability and quality. Concerning observational data, a unified approach to collecting and developing shared databases for groundwater levels and water quality measurements across multiple agencies reduces bureaucratic hurdles and ensures consistent, comparable data. Using standardized procedures for dealing with observational uncertainties such as data gaps, scaling issues, and measurement inconsistencies would support collaborative research further.

Research opportunities arise in other sectors as well. Groundwater is connected to the water cycle and social, economic, and ecological systems (Huggins et al., 2023). For example, health impacts (such as water- and vector-borne diseases) are closely related to water quantity and quality (e.g. Smith et al. (2024)), and the roles of groundwater for forest resilience (regional forest sector, (Costa et al., 2023; Esteban et al., 2021)) and forest fires (fire sector) under climate change are yet to be explored (Fig. 4). To prioritize our efforts and set a research agenda for the groundwater ISMIP sector, we will first focus on existing and more straightforward connections to the global water sector, regional water sector, and the water quality sector and then expand to collaboration with other sectors (Fig. 4).

6 A vision for the ISIMIP groundwater sector

Given groundwater's importance in the Earth system and for society, it is imperative to expand our knowledge of groundwater and (1) how it is impacted by global change and (2) how in turn this will affect other systems connected to groundwater. This enhanced understanding is essential to equip us with the knowledge needed to address future challenges effectively. The ISIMIP groundwater sector serves as a foundation for examining and measuring the effects of global change on groundwater systems worldwide. It facilitates cross-sector investigations, such as those concerning water quality, examines the influence of various model structures on groundwater dynamics simulations, and supports the collaborative creation of new datasets for model parameterization and assessment.

Already in the short term, the creation of the groundwater sector has substantial potential to enhance large-scale groundwater research by developing better modeling frameworks for reproducible research (running the multitude of experiments targeted in ISIMIP requires an automated modeling pipeline) and forge a community that can critically examine current modeling practice. The simple model comparison presented here sparks first questions

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

on why models differ and invites us to explore model differences in more depth. Such model intercomparison studies will enable us to quantify uncertainties and identify hotspots for model improvement. They will also allow us to assess the impact of climate and land use change on different groundwater-related variables, such as groundwater recharge and water table depth, and allow ensemble-based impact assessments on future water availability.

In the long term, the sector will enable us to jointly reflect on processes that we currently do not model or that need improvement, possibly also through new modeling approaches such as hybrid machine-learning models tailored to the large-scale representation of groundwater. Since groundwater is connected to many socio-ecological systems, groundwater models could also emerge as a modular coupling tool that can be integrated into multiple sectors. The newly founded groundwater sector already provides a first step in that direction by standardizing output names and units. If models are modular enough and define a standardized Application Programming Interface (API), they could also serve as a valuable tool for other science communities.

In summary, the ISIMIP groundwater sector aims to enhance our understanding of the impacts of climate change and direct human impacts on groundwater resources and a range of related sectors.

Data availability

The ensemble mean WTD and groundwater recharge trends are available at Reinecke (2025). For the original model data publications, see Table A1.

Author contribution

RR led the writing and analysis of the manuscript. RR and IG conceived the idea. All authors reviewed the manuscript and provided suggestions on text and figures.

Competing interests

None.

Appendix

Table A1: Original publications that describe the model outputs used in section 4.

Model	Simulation setup and used forcings	Reference
G³M	Steady-state model of WTD on 5 arcmin without any groundwater pumping, forced with WaterGAP 2.2d (Müller Schmied et al., 2021) groundwater recharge mean between 1901-2001.	Reinecke et al. (2019)

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

V2KARST	Global karst recharge model at 15 arcmin, forced with the MSWEP V2 (Beck et al., 2019) precipitation and GLDAS (Li et al., 2018) air temperature, shortwave and longwave radiation, specific humidity and wind speed for the period of 1990-2020	Sarrazin et al. (2018)
GGR	Global Groundwater Recharge model, A grid-based three-layer water balance model to estimate the daily global rain-fed groundwater recharge (2001-2020)	Nazari et al. (2025)
WBM	Time series simulation from 1980 to 2019 at 15 arc minutes, using the MERIT digital flow direction dataset (Yamazaki et al., 2019) including domestic, industrial, livestock, and irrigation water withdrawals. Forcings and key inputs: Climate: ERA5 (Prusevich et al., 2024), Reservoirs: GRanD v1.1 (Lehner et al., 2011), Inter-basin transfers (Lammers, 2022), Glaciers (Rounce et al., 2022), Impervious surfaces (Hansen and Toftemann Thomsen, 2020), Population density (Lloyd et al., 2019), Domestic and industrial water per capita demand: FAO AQUASTAT, Livestock density and water demand (Gilbert et al., 2018), Cropland: LUH2 (Hurtt et al., 2020), Aquifer properties (de Graaf et al., 2017) aquifer depth gap-filled with terrain slope data from Yamazaki et al. 2019, Soil available water capacity: FAO soil map, Root depth (Yang et al., 2016)	Multiple, see left column.
VIC-wur	Global Hydrological model simulating the GWR and streamflow from 1970-2014 in natural condition. The mean GWR and streamflow were used to simulate the GWT in steady-state MODFLOW model in 5 arcmin. The model is forced by: GFDL-ESM4 climate model (Dunne et al., 2020), Aquifer properties (de Graaf et al., 2017).	Droppers et al. (2020)
CLM	The model was spun up for 1979 and subsequently simulated from 1979 to 2013 using	Akhter et al. (2024) (under review in WRR)

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

	the GSWPv3 atmospheric forcing dataset at a 0.1-degree resolution. Recharge, capillary rise, drainage, irrigation pumping and cell-to-cell lateral flow were simulated within the model.	
ParFlow	The data provided here are based on Naz et al. (2023). In version 2 of the data, we provide variables including water table depth and groundwater recharge for time period of 1997-2006 at monthly time scale.	Naz et al. (2023)
CWatM	Community Water Model at 5 arcmin. Climate forcing with chelsa-W5E5v1.0 (5 arcmin) for temperature (average, maximum, minimum), precipitation, and shortwave radiation, and GSWP3-W5E5 (30 arcmin spline downscaled to 5 arcmin) for longwave radiation, wind speed, and specific humidity. Updates to Burek et al. (2020) include river network based on MERIT Hydro and upscaling with Eilander et al. (2021).	Burek et al. (2020)

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Table A2: List of groundwater related output variables in the ISIMIP3a global water sector (https://protocol.isimip.org/#/ISIMIP3a/water_global). The unit of all variables is kg m^{-2} s^{-1}, the spatial resolution is 0.5° grid and the temporal resolution is monthly.

Groundwater-related output variable of the Global Water Sector	**Description**
Groundwater runoff	Water that leaves the groundwater layer. In case seepage is simulated but no groundwater layer is present, report seepage as *Total groundwater recharge* and *Groundwater Runoff.*
Total groundwater recharge	For models that consider both diffuse and focused/localised recharge this should be the sum of both; other models should submit the groundwater recharge component that the model simulates. See also the descriptions in *Focused/localised groundwater recharge* and *Diffuse groundwater recharge*.
Focused/localised groundwater recharge	Water that directly flows from a surface water body into the groundwater layer below. Only submit if the model separates focused/localised recharge from diffuse recharge.
Potential irrigation water withdrawal (assuming unlimited water supply) from groundwater resources	Part of *Potential Industrial Water Withdrawal* that is extracted from groundwater resources.
Actual irrigation water withdrawal from groundwater resources	Part of *Actual Irrigation Water Withdrawal* that is extracted from groundwater resources.
Potential Irrigation Water Consumption from groundwater resources	Part of *Potential Irrigation Water Consumption* that is extracted from groundwater resources.
Actual Irrigation Water Consumption from groundwater resources	Part of *Actual Irrigation Water Consumption* that is extracted from groundwater resources.
Potential Domestic Water Withdrawal from groundwater resources	Part of *Potential Domestic Water Withdrawal* that is extracted from groundwater resources.
Actual Domestic Water Withdrawal from groundwater resources	Part of *Actual Domestic Water Withdrawal* that is extracted from groundwater resources
Potential Domestic Water Consumption from groundwater resources	Part of *Potential Domestic Water Consumption* that is extracted from groundwater resources.

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Actual Domestic Water Consumption from groundwater resources	Part of *Actual Domestic Water Consumption* that is extracted from groundwater resources.
Potential Manufacturing Water Withdrawal from groundwater resources	Part of *Potential Manufacturing Water Withdrawal* that is extracted from groundwater resources.
Actual Manufacturing Water Withdrawal from groundwater resources	Part of *Actual Manufacturing Water Withdrawal* that is extracted from groundwater resources.
Potential manufacturing Water Consumption from groundwater resources	Part of *Potential manufacturing Water Consumption* that is extracted from groundwater resources.
Actual Manufacturing Water Consumption from groundwater resources	Part of *Actual Manufacturing Water Consumption* that is extracted from groundwater resources.
Potential electricity Water Withdrawal from groundwater resources	Part of *Potential electricity Water Withdrawal* that is extracted from groundwater resources.
Actual Electricity Water Withdrawal from groundwater resources	Part of *Actual Electricity Water Withdrawal* that is extracted from groundwater resources.
Potential electricity Water Consumption from groundwater resources	Part of *Potential electricity Water Consumption* that is extracted from groundwater resources.
Actual Electricity Water Consumption from groundwater resources	Part of *Actual Electricity Water Consumption* that is extracted from groundwater resources.
Potential Industrial Water Withdrawal from groundwater resources	Part of *Potential Industrial Water Withdrawal* that is extracted from groundwater resources.
Actual Industrial Water Withdrawal from groundwater resources	Part of *Actual Industrial Water Withdrawal* that is extracted from groundwater resources.

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

Potential Industrial Water Consumption from groundwater resources	Part of *Potential Industrial Water Consumption* that is extracted from groundwater resources.
Actual Industrial Water Consumption from groundwater resources	Part of *Actual Industrial Water Consumption* that is extracted from groundwater resources.
Potential livestock Water Withdrawal from groundwater resources	Part of *Potential livestock Water Withdrawal* that is extracted from groundwater resources.
Actual Livestock Water Withdrawal from groundwater resources	Part of *Actual Livestock Water Withdrawal* that is extracted from groundwater resources.
Potential livestock Water Consumption from groundwater resources	Part of *Potential livestock Water Consumption* that is extracted from groundwater resources.
Actual livestock Water Consumption from groundwater resources	Part of *Actual livestock Water Consumption* that is extracted from groundwater resources.
Total Potential Water Withdrawal (all sectors) from groundwater resources	Part of *Total Potential Water Withdrawal* that is extracted from groundwater resources.
Total Actual Water Withdrawal (all sectors) from groundwater resources	Part of *Total Actual Water Withdrawal* that is extracted from groundwater resources.

References

Beck, H. E., Wood, E. F., Pan, M., Fisher, C. K., Miralles, D. G., van Dijk, A. I. J. M., McVicar, T. R., and Adler, R. F.: MSWEP V2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment, Bulletin of the American Meteorological Society, 100, 473–500, https://doi.org/10.1175/BAMS-D-17-0138.1, 2019.

Benz, S. A., Irvine, D. J., Rau, G. C., Bayer, P., Menberg, K., Blum, P., Jamieson, R. C., Griebler, C., and Kurylyk, B. L.: Global groundwater warming due to climate change, Nature Geosci, 17, 545–551, https://doi.org/10.1038/s41561-024-01453-x, 2024.

Berghuijs, W. R., Collenteur, R. A., Jasechko, S., Jaramillo, F., Luijendijk, E., Moeck, C., van der Velde, Y., and Allen, S. T.: Groundwater recharge is sensitive to changing long-term aridity, Nature Clim Change, 14, 357–363, https://doi.org/10.1038/s41558-024-01953-z, 2024.

Bierkens, M. and Wada, Y.: Non-renewable groundwater use and groundwater depletion: a review, Environ. Res. Lett., 14, 63002, https://doi.org/10.1088/1748-9326/ab1a5f, 2019.

Burek, P., Satoh, Y., Kahil, T., Tang, T., Greve, P., Smilovic, M., Guillaumot, L., Zhao, F., and Wada, Y.: Development of the Community Water Model (CWatM v1.04) – a high-resolution hydrological model for global and regional assessment of integrated water resources management, Geosci. Model Dev., 13, 3267–3298, https://doi.org/10.5194/gmd-13-3267-2020, 2020.

Condon, L. E. and Maxwell, R. M.: Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion, Science advances, 5, eaav4574, https://doi.org/10.1126/sciadv.aav4574, 2019.

Condon, L. E., Kollet, S., Bierkens, M. F. P., Fogg, G. E., Maxwell, R. M., Hill, M. C., Fransen, H.-J. H., Verhoef, A., van Loon, A. F., Sulis, M., and Abesser, C.: Global Groundwater Modeling and Monitoring: Opportunities and Challenges, Water Resources Research, 57, https://doi.org/10.1029/2020WR029500, 2021.

Costa, F. R. C., Schietti, J., Stark, S. C., and Smith, M. N.: The other side of tropical forest drought: do shallow water table regions of Amazonia act as large-scale hydrological refugia from drought?, The New phytologist, 237, 714–733, https://doi.org/10.1111/nph.17914, 2023.

Coll, J. R., Aguilar, E., and Ashcroft, L.: Drought variability and change across the Iberian Peninsula. *Theoretical and Applied Climatology*, *130*(3–4), 901–916. https://doi.org/10.1007/s00704-016-1926-3, 2017.

Cuthbert, M. O., Gleeson, T., Moosdorf, N., Befus, K. M., Schneider, A., Hartmann, J., and Lehner, B.: Global patterns and dynamics of climate-groundwater interactions, Nature Clim Change, 9, 137–141, https://doi.org/10.1038/s41558-018-0386-4, 2019.

Dalin, C., Wada, Y., Kastner, T., and Puma, M. J.: Groundwater depletion embedded in international food trade, Nature, 543, 700–704, https://doi.org/10.1038/nature21403, 2017.

de Graaf, I. E. M., Sutanudjaja, E. H., van Beek, L. P. H., and Bierkens, M. F. P.: A high-resolution global-scale groundwater model, Hydrol. Earth Syst. Sci., 19, 823–837, https://doi.org/10.5194/hess-19-823-2015, available at: https://hess.copernicus.org/articles/19/823/2015/, 2015.

de Graaf, I., Rens L.P.H. van Beek, Tom Gleeson, Nils Moosdorf, Oliver Schmitz, Edwin H. Sutanudjaja, and Marc F.P. Bierkens: A global-scale two-layer transient groundwater model: Development and application to groundwater depletion, Advances in Water Resources, 102, 53–67, https://doi.org/10.1016/j.advwatres.2017.01.011, 2017.

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

Döll, P. and Siebert, S.: Global modeling of irrigation water requirements, Water Resources Research, 38, https://doi.org/10.1029/2001WR000355, 2002.

Droppers, B., Franssen, W. H. P., van Vliet, M. T. H., Nijssen, B., and Ludwig, F.: Simulating human impacts on global water resources using VIC-5, Geosci. Model Dev., 13, 5029–5052, https://doi.org/10.5194/gmd-13-5029-2020, 2020.

Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., Held, I. M., John, J. G., Krasting, J. P., Malyshev, S., Naik, V., Paulot, F., Shevliakova, E., Stock, C. A., Zadeh, N., Balaji, V., Blanton, C., Dunne, K. A., Dupuis, C., Durachta, J., Dussin, R., Gauthier, P. P. G., Griffies, S. M., Guo, H., Hallberg, R. W., Harrison, M., He, J., Hurlin, W., McHugh, C., Menzel, R., Milly, P. C. D., Nikonov, S., Paynter, D. J., Ploshay, J., Radhakrishnan, A., Rand, K., Reichl, B. G., Robinson, T., Schwarzkopf, D. M., Sentman, L. T., Underwood, S., Vahlenkamp, H., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, Y. and Zhao, M.: The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics. *J Adv Model Earth Syst*, *12* (11), e2019MS002015. https://doi.org/10.1029/2019MS002015, 2020.Eilander, D., van Verseveld, W., Yamazaki, D., Weerts, A., Winsemius, H. C., and Ward, P. J.: A hydrography upscaling method for scale-invariant parametrization of distributed hydrological models, Hydrol. Earth Syst. Sci., 25, 5287–5313, https://doi.org/10.5194/hess-25-5287-2021, 2021.

Esteban, E. J. L., Castilho, C. V., Melgaço, K. L., and Costa, F. R. C.: The other side of droughts: wet extremes and topography as buffers of negative drought effects in an Amazonian forest, The New phytologist, 229, 1995–2006, https://doi.org/10.1111/nph.17005, 2021.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

Felfelani, F., Lawrence, D. M., and Pokhrel, Y.: Representing Intercell Lateral Groundwater Flow and Aquifer Pumping in the Community Land Model, Water Resources Research, 57, https://doi.org/10.1029/2020WR027531, 2021.

Foster, S. S. D. and Chilton, P. J.: Groundwater: the processes and global significance of aquifer degradation, Philosophical transactions of the Royal Society of London. Series B, Biological sciences, 358, 1957–1972, https://doi.org/10.1098/rstb.2003.1380, 2003.

Frieler, K., Lange, S., Piontek, F., Reyer, C. P. O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Suzuki, T., Volkholz, J., Burke, E., Ciais, P., Ebi, K., Eddy, T. D., Elliott, J., Galbraith, E., Gosling, S. N., Hattermann, F., Hickler, T., Hinkel, J., Hof, C., Huber, V., Jägermeyr, J., Krysanova, V., Marcé, R., Müller Schmied, H., Mouratiadou, I., Pierson, D., Tittensor, D. P., Vautard, R., van Vliet, M., Biber, M. F., Betts, R. A., Bodirsky, B. L., Deryng, D., Frolking, S., Jones, C. D., Lotze, H. K., Lotze-Campen, H., Sahajpal, R., Thonicke, K., Tian, H., and Yamagata, Y.: Assessing the impacts of 1.5\,\degree C global warming - simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), Geosci. Model Dev., 10, 4321–4345, https://doi.org/10.5194/gmd-10-4321-2017, 2017.

Gasper, F., Goergen, K., Shrestha, P., Sulis, M., Rihani, J., Geimer, M., and Kollet, S.: Implementation and scaling of the fully coupled Terrestrial Systems Modeling Platform (TerrSysMP v1.0) in a massively parallel supercomputing environment – a case study on JUQUEEN (IBM Blue Gene/Q), Geosci. Model Dev., 7, 2531–2543, https://doi.org/10.5194/gmd-7-2531-2014, 2014.

Gilbert, M., Nicolas, G., Cinardi, G., van Boeckel, T. P., Vanwambeke, S. O., Wint, G. R. W., and Robinson, T. P.: Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010, Scientific data, 5, 180227, https://doi.org/10.1038/sdata.2018.227, 2018.

Gleeson, T. and Paszkowski, D.: Perceptions of scale in hydrology: what do you mean by regional scale?, Hydrological Sciences Journal, 59, 99–107, https://doi.org/10.1080/02626667.2013.797581, 2014.

Gleeson, T., Wagener, T., Döll, P., Zipper, S. C., West, C., Wada, Y., Taylor, R., Scanlon, B., Rosolem, R., Rahman, S., Oshinlaja, N., Maxwell, R., Lo, M.-H., Kim, H., Hill, M., Hartmann, A., Fogg, G., Famiglietti, J. S., Ducharne, A., Graaf, I. de, Cuthbert, M., Condon, L., Bresciani, E., and Bierkens, M. F. P.: GMD perspective: The quest to improve the evaluation of groundwater representation in continental- to global-scale models, Geosci. Model Dev., 14, 7545–7571, https://doi.org/10.5194/gmd-14-7545-2021, 2021.

Gnann, S., Reinecke, R., Stein, L., Wada, Y., Thiery, W., Müller Schmied, H., Satoh, Y., Pokhrel, Y., Ostberg, S., Koutroulis, A., Hanasaki, N., Grillakis, M., Gosling, S., Burek, P., Bierkens, M., and Wagener, T.: Functional relationships reveal differences in the water cycle representation of global water models, 1079–1090, https://doi.org/10.1038/s44221-023-00160-y, 2023.

Grogan, D. S., Zuidema, S., Prusevich, A., Wollheim, W. M., Glidden, S., and Lammers, R. B.: Water balance model (WBM) v.1.0.0: a scalable gridded global hydrologic model with water-tracking functionality, Geosci. Model Dev., 15, 7287–7323, https://doi.org/10.5194/gmd-15-7287-2022, 2022.

Guillaumot, L., Smilovic, M., Burek, P., Bruijn, J. de, Greve, P., Kahil, T., and Wada, Y.: Coupling a large-scale hydrological model (CWatM v1.1) with a high-resolution groundwater flow model (MODFLOW 6) to assess the impact of irrigation at regional scale, Geosci. Model Dev., 15, 7099–7120, https://doi.org/10.5194/gmd-15-7099-2022, 2022.

Hansen, M. and Toftemann Thomsen, C.: An integrated public information system for geology, groundwater and drinking water in Denmark, GEUS Bulletin, 38, 69–72, https://doi.org/10.34194/geusb.v38.4423, 2020.

Haqiqi, I., Bowling, L., Jame, S., Baldos, U., Liu, J., and Hertel, T.: Global drivers of local water stresses and global responses to local water policies in the United States, Environmental research letters ERL, 18, 65007, https://doi.org/10.1088/1748-9326/acd269, 2023.

Holman, I. P., Whelan, M. J., Howden, N. J. K., Bellamy, P. H., Willby, N. J., Rivas-Casado, M., and McConvey, P.: Phosphorus in groundwater—an overlooked contributor to eutrophication?, Hydrol. Process., 22, 5121–5127, https://doi.org/10.1002/hyp.7198, 2008.

Huggins, X., Gleeson, T., Castilla-Rho, J., Holley, C., Re, V., and Famiglietti, J. S.: Groundwater Connections and Sustainability in Social-Ecological Systems, Ground water, 61, 463–478, https://doi.org/10.1111/gwat.13305, 2023.

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren,

https://doi.org/10.5194/egusphere-2025-1181
Preprint. Discussion started: 2 April 2025

D. P., and Zhang, X.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geosci. Model Dev., 13, 5425–5464, https://doi.org/10.5194/gmd-13-5425-2020, 2020.

Jasechko, S., Seybold, H., Perrone, D., Fan, Y., Shamsudduha, M., Taylor, R. G., Fallatah, O., and Kirchner, J. W.: Rapid groundwater decline and some cases of recovery in aquifers globally, Nature, 625, 715–721, https://doi.org/10.1038/s41586-023-06879-8, 2024.

Keune, J., Sulis, M., Kollet, S., Siebert, S., and Wada, Y.: Human Water Use Impacts on the Strength of the Continental Sink for Atmospheric Water, Geophys. Res. Lett., 45, 4068–4076, https://doi.org/10.1029/2018GL077621, 2018.

Kollet, S. J. and Maxwell, R. M.: Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model, Water Resources Research, 44, https://doi.org/10.1029/2007WR006004, 2008.

Konar, M., Hussein, Z., Hanasaki, N., Mauzerall, D. L., and Rodriguez-Iturbe, I.: Virtual water trade flows and savings under climate change, Hydrol. Earth Syst. Sci., 17, 3219–3234, https://doi.org/10.5194/hess-17-3219-2013, 2013.

Kretschmer, D. V., Michael, H., Moosdorf, N., Essink, G. O., Bierkens, M. F. P., Wagener, T., and Reinecke, R.: Controls on coastal saline groundwater across North America, Environmental research letters, https://doi.org/10.1088/1748-9326/ada973, 2025.

Kuffour, B. N. O., Engdahl, N. B., Woodward, C. S., Condon, L. E., Kollet, S., and Maxwell, R. M.: Simulating coupled surface–subsurface flows with ParFlow v3.5.0: capabilities, applications, and ongoing development of an open-source, massively parallel, integrated hydrologic model, Geosci. Model Dev., 13, 1373–1397, https://doi.org/10.5194/gmd-13-1373-2020, 2020.

Lammers, R. B.: Global Inter-Basin Hydrological Transfer Database, 2022.

Lange, S.: Bias-correction fact sheet, https://www.isimip.org/gettingstarted/isimip3b-bias-adjustment/, last access: 2 March 2025, 2021.

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., van Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., Wieder, W. R., Xu, C., Ali, A. A., Badger, A. M., Bisht, G., van den Broeke, M., Brunke, M. A., Burns, S. P., Buzan, J., Clark, M., Craig, A., Dahlin, K., Drewniak, B., Fisher, J. B., Flanner, M., Fox, A. M., Gentine, P., Hoffman, F., Keppel-Aleks, G., Knox, R., Kumar, S., Lenaerts, J., Leung, L. R., Lipscomb, W. H., Lu, Y., Pandey, A., Pelletier, J. D., Perket, J., Randerson, J. T., Ricciuto, D. M., Sanderson, B. M., Slater, A., Subin, Z. M., Tang, J., Thomas, R. Q., Val Martin, M., and Zeng, X.: The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty, J Adv Model Earth Syst, 11, 4245–4287, https://doi.org/10.1029/2018MS001583, 2019.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., and Wisser, D.: High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Frontiers in Ecol & Environ, 9, 494–502, https://doi.org/10.1890/100125, 2011.

Li, B., Rodell, M., and Beaudoing, H.: GLDAS Catchment Land Surface Model L4 daily 0.25 x 0.25 degree, Version 2.0, 2018.

Liang, X., Lettenmaier, D. P., Wood, E. F., and Burges, S. J.: A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres*, *99*(D7), 14415–14428. https://doi.org/10.1029/94JD00483, 1994.

Liu, Y., Wagener, T., Beck, H. E., and Hartmann, A.: What is the hydrologically effective area of a catchment?, Environmental research letters ERL, 15, 104024, https://doi.org/10.1088/1748-9326/aba7e5, 2020.

Lloyd, C. T., Chamberlain, H., Kerr, D., Yetman, G., Pistolesi, L., Stevens, F. R., Gaughan, A. E., Nieves, J. J., Hornby, G., MacManus, K., Sinha, P., Bondarenko, M., Sorichetta, A., and Tatem, A. J.: Global spatio-temporally harmonised datasets for producing high-resolution gridded population distribution datasets, Big earth data, 3, 108–139, https://doi.org/10.1080/20964471.2019.1625151, 2019.

Maxwell, R. M. and Miller, N. L.: Development of a Coupled Land Surface and Groundwater Model, Journal of Hydrometeorology, 6, 233–247, https://doi.org/10.1175/JHM422.1, 2005.

Maxwell, R. M., Condon, L. E., Kollet, S. J., Maher, K., Haggerty, R., and Forrester, M. M.: The imprint of climate and geology on the residence times of groundwater, Geophys. Res. Lett., 43, 701–708, https://doi.org/10.1002/2015GL066916, 2016.

Maxwell, R. M., Lundquist, J. K., Mirocha, J. D., Smith, S. G., Woodward, C. S., and Tompson, A. F. B.: Development of a Coupled Groundwater–Atmosphere Model, Monthly Weather Review, 139, 96–116, https://doi.org/10.1175/2010MWR3392.1, 2011.

Moeck, C., Collenteur, R. A., Berghuijs, W. R., Luijendijk, E., and Gurdak, J. J.: A Global Assessment of Groundwater Recharge Response to Infiltration Variability at Monthly to Decadal Timescales, Water Resources Research, 60, https://doi.org/10.1029/2023WR035828, 2024.

Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., Peiris, T. A., Popat, E., Portmann, F. T., Reinecke, R., Schumacher, M., Shadkam, S., Telteu, C.-E., Trautmann, T., and Döll, P.: The global water resources and use model WaterGAP v2.2d: model description and evaluation, Geosci. Model Dev., 14, 1037–1079, https://doi.org/10.5194/gmd-14-1037-2021, 2021.

Müller Schmied, H., Adam, L., Eisner, S., Fink, G., Flörke, M., Kim, H., Oki, T., Portmann, F. T., Reinecke, R., Riedel, C., Song, Q., Zhang, J., and Döll, P.: Variations of global and continental water balance components as impacted by climate forcing uncertainty and human water use, Hydrol. Earth Syst. Sci., 20, 2877–2898, https://doi.org/10.5194/hess-20-2877-2016, available at: https://hess.copernicus.org/articles/20/2877/2016/, 2016.

Naz, B. S., Sharples, W., Ma, Y., Goergen, K., and Kollet, S.: Continental-scale evaluation of a fully distributed coupled land surface and groundwater model, ParFlow-CLM (v3.6.0), over Europe, Geosci. Model Dev., 16, 1617–1639, https://doi.org/10.5194/gmd-16-1617-2023, 2023.

Nazari, S., Kruse, I. L., and Moosdorf, N.: Spatiotemporal dynamics of global rain-fed groundwater recharge from 2001 to 2020, Journal of Hydrology, 650, 132490, https://doi.org/10.1016/j.jhydrol.2024.132490, 2025.

Paneque Salgado, P., and Vargas Molina, J.: Drought, social agents and the construction of discourse in Andalusia. Environmental Hazards, 14(3), 224–235. https://doi.org/10.1080/17477891.2015.1058739, 2015.

Perez, N., Singh, V., Ringler, C., Xie, H., Zhu, T., Sutanudjaja, E. H., and Villholth, K. G.: Ending groundwater overdraft without affecting food security, Nat Sustain, 7, 1007–1017, https://doi.org/10.1038/s41893-024-01376-w, 2024.

Pokhrel, Y., Felfelani, F., Satoh, Y., Boulange, J., Burek, P., Gädeke, A., Gerten, D., Gosling, S. N., Grillakis, M., Gudmundsson, L., Hanasaki, N., Kim, H., Koutroulis, A., Liu, J., Papadimitriou, L., Schewe, J., Müller Schmied, H., Stacke, T., Telteu, C.-E., Thiery, W., Veldkamp, T., Zhao, F., and Wada, Y.: Global terrestrial water storage and drought severity under climate change, Nature Clim Change, 11, 226–233, https://doi.org/10.1038/s41558-020-00972-w, 2021.

Porkka, M., Virkki, V., Wang-Erlandsson, L., Gerten, D., Gleeson, T., Mohan, C., Fetzer, I., Jaramillo, F., Staal, A., te Wierik, S., Tobian, A., van der Ent, R., Döll, P., Flörke, M., Gosling, S. N., Hanasaki, N., Satoh, Y., Müller Schmied, H., Wanders, N., Famiglietti, J. S., Rockström, J., and Kummu, M.: Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change, Nat Water, 2, 262–273, https://doi.org/10.1038/s44221-024-00208-7, 2024.

Prusevich, A. A., Lammers, R. B., and Glidden, S. J.: Delineation of endorheic drainage basins in the MERIT-Plus dataset for 5 and 15 minute upscaled river networks, Scientific data, 11, 61, https://doi.org/10.1038/s41597-023-02875-9, 2024.

Reinecke, R., Müller Schmied, H., Trautmann, T., Andersen, L. S., Burek, P., Flörke, M., Gosling, S. N., Grillakis, M., Hanasaki, N., Koutroulis, A., Pokhrel, Y., Thiery, W., Wada, Y., Yusuke, S., and Döll, P.: Uncertainty of simulated groundwater recharge at different global warming levels: a global-scale multi-model ensemble study, Hydrol. Earth Syst. Sci., 25, 787–810, https://doi.org/10.5194/hess-25-787-2021, available at: https://hess.copernicus.org/articles/25/787/2021/, 2021.

Reinecke, R., Foglia, L., Mehl, S., Trautmann, T., Cáceres, D., and Döll, P.: Challenges in developing a global gradient-based groundwater model (G^3M v1.0) for the integration into a global hydrological model, Geosci. Model Dev., 12, 2401–2418, https://doi.org/10.5194/gmd-12-2401-2019, 2019.

Reinecke, R., Gnann, S., Stein, L., Bierkens, M., Graaf, I. de, Gleeson, T., Essink, G. O., Sutanudjaja, E. H., Ruz Vargas, C., Verkaik, J., and Wagener, T.: Uncertainty in model estimates of global groundwater depth, Environmental research letters ERL, 19, 114066, https://doi.org/10.1088/1748-9326/ad8587, 2024.

Reinecke, R.: The ISIMIP Groundwater Sector: A Framework for Ensemble Modeling of Global Change Impacts on Groundwater, Zenodo, https://doi.org/10.5281/zenodo.14962512, 2025.

Rodell, M., Velicogna, I., and Famiglietti, J. S.: Satellite-based estimates of groundwater depletion in India, Nature, 460, 999–1002, https://doi.org/10.1038/nature08238, 2009.

Rodella, A.-S., Zaveri, E., and Bertone, F.: The Hidden Wealth of Nations: The Economics of Groundwater in Times of Climate Change. Washington, DC: World Bank, 2023.

Rounce, D., Hock, R., and Maussion, F.: Global PyGEM-OGGM Glacier Projections with RCP and SSP Scenarios, Version 1, 2022.

Sarrazin, F., Hartmann, A., Pianosi, F., Rosolem, R., and Wagener, T.: V2Karst V1.1: a parsimonious large-scale integrated vegetation–recharge model to simulate the impact of climate and land cover change in karst regions, Geosci. Model Dev., 11, 4933–4964, https://doi.org/10.5194/gmd-11-4933-2018, 2018.

Scanlon, B. R., Fakhreddine, S., Rateb, A., Graaf, I. de, Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Di Long, Mekonnen, M., Schmied, H. M., Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., Sun, A., Taylor, R. G., Villholth, K. G., Vörösmarty, C. J., and Zheng, C.: Global water resources and the role of groundwater in a resilient water future, Nat Rev Earth Environ, 4, 87–101, https://doi.org/10.1038/s43017-022-00378-6, 2023.

Schaller, M. F. and Fan, Y.: River basins as groundwater exporters and importers: Implications for water cycle and climate modeling, J. Geophys. Res., 114, https://doi.org/10.1029/2008JD010636, 2009.

Schwartz, F. W. and Ibaraki, M.: Groundwater: A Resource in Decline, Elements, 7, 175–179, https://doi.org/10.2113/gselements.7.3.175, 2011.

Smith, M. W., Willis, T., Mroz, E., James, W. H. M., Klaar, M. J., Gosling, S. N., and Thomas, C. J.: Future malaria environmental suitability in Africa is sensitive to hydrology, Science (New York, N.Y.), 384, 697–703, https://doi.org/10.1126/science.adk8755, 2024.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., Gurdak, J. J., Allen, D. M., Shamsudduha, M., Hiscock, K., Yeh, P. J.-F., Holman, I., and Treidel, H.: Ground water and climate change, Nature Clim Change, 3, 322–329, https://doi.org/10.1038/nclimate1744, 2013.

Telteu, C.-E., Müller Schmied, H., Thiery, W., Leng, G., Burek, P., Liu, X., Boulange, J. E. S., Andersen, L. S., Grillakis, M., Gosling, S. N., Satoh, Y., Rakovec, O., Stacke, T., Chang, J., Wanders, N., Shah, H. L., Trautmann, T., Mao, G., Hanasaki, N., Koutroulis, A., Pokhrel, Y., Samaniego, L., Wada, Y., Mishra, V., Liu, J., Döll, P., Zhao, F., Gädeke, A., Rabin, S. S., and Herz, F.: Understanding each other's models: an introduction and a standard representation of 16 global water models to support intercomparison, improvement, and communication, Geosci. Model Dev., 14, 3843–3878, https://doi.org/10.5194/gmd-14-3843-2021, 2021.

Thompson, J. R., Gosling, S. N., Zaherpour, J., and Laizé, C. L. R.: Increasing Risk of Ecological Change to Major Rivers of the World With Global Warming, Earth's Future, 9, https://doi.org/10.1029/2021EF002048, 2021.

Trullenque-Blanco, V., Beguería, S., Vicente-Serrano, S. M., Peña-Angulo, D., and González-Hidalgo, C.: Catalogue of drought events in peninsular Spanish along 1916–2020 period. Scientific Data, 11(1), 703. https://doi.org/10.1038/s41597-024-03484-w, 2024.

United Nations: The United Nations World Water Development Report 2022: groundwater: making the invisible visible, UNESCO, Paris, 2022.

Winter, T. C.: The Role of Ground Water in Generating Streamflow in Headwater Areas and in Maintaining Base Flow 1, J American Water Resour Assoc, 43, 15–25, https://doi.org/10.1111/j.1752-1688.2007.00003.x, 2007.

Xie, J., Liu, X., Jasechko, S., Berghuijs, W. R., Wang, K., Liu, C., Reichstein, M., Jung, M., and Koirala, S.: Majority of global river flow sustained by groundwater, Nature Geosci, 17, 770–777, https://doi.org/10.1038/s41561-024-01483-5, 2024.

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P. D., Allen, G. H., and Pavelsky, T. M.: MERIT Hydro: A High-Resolution Global Hydrography Map Based on Latest Topography Dataset, Water Resources Research, 55, 5053–5073, https://doi.org/10.1029/2019WR024873, 2019.

Yang, Y., Donohue, R. J., and McVicar, T. R.: Global estimation of effective plant rooting depth: Implications for hydrological modeling, Water Resources Research, 52, 8260–8276, https://doi.org/10.1002/2016WR019392, 2016.