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# Considerable gaps in our global knowledge of potential groundwater accessibility

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# Main Manuscript for

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**This PDF file includes:**

Main Text
Figures 1 to 4

## Abstract

At what depth groundwater can be found below the land surface is key to understanding whether it is potentially accessible to ecosystems and humans, or what role it plays in the water cycle. Knowledge of ground-water table depth (WTD) exists at regional scales in many places, but a bottom-up knowledge aggregation to obtain a coherent global picture is exceptionally challenging. Uncertainty in global-scale WTD knowledge severely affects our ability to assess groundwater's future role in a water cycle altered by changes in climate, land use, and human water use. Global groundwater models offer a top-down pathway to gain this knowledge. However, we find them highly uncertain: four models investigated show WTD disagreements of more than 100 m for one-third of the global land area. Averaged across the models, we estimate that 23% [most deviating model: 71%] of the land area contains shallow groundwater potentially accessible to ecosystems and humans, <10m depth, 57% [29%] is potentially accessible to humans through pumping, 10-100m, while 20% [0.01%] is potentially too costly to access or inaccessible, >100m. Depending on the model, +-63% of global forest coverage and +-54% of irrigated land is inside areas of potentially ecosystem-accessible water, and +-33% of the global population lives in areas with potentially human-accessible groundwater. These results add significant uncertainties to any global-scale analysis, which will not significantly reduce without dedicated efforts. We outline three pathways to reduce this uncertainty through better global datasets, alternative strategies for model evaluation, and greater cooperation with experts.


## Significance Statement

Global knowledge about groundwater is vital to assess its role in the global water cycle and how it will be impacted by future climate, water use, land use and population change. While regional groundwater knowledge is available in places, this is not the case everywhere in the world, and collating very different regional datasets is challenging. Global models offer an alternative perspective at the global scale, but we show here that they are still highly uncertain. As the scientific community already uses these models and their outputs, it is crucial to understand, consider, and address their limitations. To do so, we suggest three pathways to collect additional knowledge and improve currently available models.

## Main Text

### Introduction

Groundwater makes up 99% of all non-frozen freshwater on our planet(1, 2), sustaining ecosystems by providing water to vegetation(3, 4), rivers, lakes, and wetlands(5–8), and being a pivotal ecosystem by itself (9). Groundwater offers a relatively constant supply of freshwater to 43% of the world's irrigated agriculture(1, 10) and safe drinking water to an estimated 3.7 billion people(1, 10). While surface water supply is increasingly fragile due to climate change(11), groundwater is assumed to remain a reliable source of freshwater(12). Thus, groundwater is a critical element for ecosystem health by sustaining flow in surface water bodies and directly supplying vegetation, agriculture, and access to clean drinking water. With a rapidly changing climate, increasing population, and economic growth, the importance of groundwater will likely increase(12). However, the recent IPCC 6th assessment report concluded that "limitations in the spatio-temporal coverage of groundwater monitoring networks, abstraction data and numerical representations of groundwater recharge processes continue to constrain understanding of climate change impacts on groundwater"(11). This lack of knowledge has consequences in at least three critical aspects relevant to society: the accessibility of groundwater for terrestrial ecosystems, as drinking water, and for agricultural use.

Terrestrial ecosystems provide vital ecosystem services such as the supply of clean water(13), and they are essential to the carbon cycle(14). Groundwater is often connected to surface water bodies such as wetlands and supplies them with freshwater, which may sustain terrestrial ecosystems during dry periods (5). Knowledge of groundwater table depth is central in determining whether this connection exists and how fragile it might be to changing conditions. For example, recent work showed that a substantial amount of streams in the US are likely losing their water to groundwater already(6). Groundwater may also supply freshwater to coastal ecosystems through submarine groundwater discharge, and knowledge of the hydraulic gradient towards the coast is necessary to determine the potential influxes of salt water into coastal aquifers(15). As vegetation may rely on groundwater directly or through capillary rise(3), knowledge of the depth of the groundwater table is a central building block in developing global carbon policy(16). Recent studies showed that tropical forests may change from carbon sinks to carbon sources due to water stress(17), and that global land cover changes affect rooting depth and, thus, carbon and water cycling(18). Furthermore, groundwater systems themselves are important ecosystems, providing living space to a multitude of organisms. Groundwater depth is an essential indicator in determining potential groundwater ecosystem richness and is central in determining the connectivity to surface ecosystems(9).

Groundwater is the sole source of drinking water for 2.5 billion people today (1), but many of these wells are increasingly at risk of running dry(19). Deeper wells may provide additional resources by accessing deeper-lying aquifers(20), but (i) these wells will require more costly energy to build and operate(21, 22), (ii) water drawn from deeper aquifers might require desalinization(23, 24) for human consumption as well as for agricultural use(25, 26), and (iii) they likely to be less productive as the aquifer becomes less permeable with depth(22). If groundwater is pumped continuously causing a long-term WTD decline, we may experience groundwater depletion and complete loss of freshwater resources. Importantly, groundwater contamination can be a more important factor in restricting sustainable groundwater supplies than depletion(27), and historical context in assessing depletion is essential(28). Groundwater depletion is a global crisis(29), and examples like Cape Town's Day Zero(30) water crisis highlight the importance of groundwater in sustaining the human right to clean drinking water.

Irrigated agriculture is by far the largest global user of groundwater by volume(1). The increasing occurrence and intensity of heatwaves and droughts(11) leads to heightened irrigation demand(31), while non-renewable use already leads to widespread groundwater depletion(32). Groundwater abstractions may aggravate water loss in rivers and wetlands as lowered groundwater levels potentially decrease the influx of water of even led to losing conditions(33). Regions like the Central Valley in California(29), the Mekong River Basin(34), and northwestern India(35) have overused their groundwater resources steadily, leading to widespread depletion of groundwater storage and subsequent land subsidence. The continuing global expansion of agricultural areas (36) will further aggravate the stress on groundwater resources.

A key variable to understand groundwater in all three contexts (ecosystems, drinking water supply, agriculture) is water table depth (WTD). Here we define WTD as depth from the land surface to the top of the saturated zone(37). Groundwater can quickly become inaccessible for ecosystems if the WTD declines beyond the depth of vegetation roots(38) or below the bottom of rivers and lakes(5). Humans may build wells reaching down to hundreds of meters(22), yet below a certain depth, reduced permeability will decrease groundwater yield(21) in addition to the already mentioned considerations of economic viability and sustainability. We define groundwater as potentially accessible if the WTD is shallow enough to be used by ecosystems and/or humans. Notably, a potentially accessible WTD does not mean that (financial) resources are in place to access this water and to transport it to its destination, that the water is of adequate quality, or that the hydrogeological configuration allows for abstraction.

Understanding the role of groundwater in the terrestrial water cycle is a key component in understanding how Earth system dynamics may change with human interventions on continental and planetary scales (39). Through its connection to streams, wetlands, and lakes, understanding WTD enables us to understand, for example, how streamflow will be affected by climate change and groundwater abstractions(5), and how it will affect sea level rise and water available for atmospheric circulation. Critically, despite groundwater's crucial role in the Earth system, we cannot yet provide a robust global picture of current and potential future WTD, and thus potential accessibility. While other global products, such as GRACE(29), exist to determine the global state of groundwater, WTD remains central in validating and calibrating these products. Furthermore, GRACE measures total storage changes rather than actual storage, and requires additional hydrological model output to create a spatially coarse product of groundwater storage change estimates. Without reliable knowledge of WTD at the global scale, it is unclear where international investments (e.g., through the World Bank) and global water policy (e.g., specialized UN agencies such as the FAO) will be most needed and most impactful to safeguard this essential resource.

**Bottom-up and top-down strategies to assess potential groundwater availability at the global scale**

Two strategies may be used to obtain global-scale knowledge of groundwater accessibility (Fig. 1a): a bottom-up strategy that assembles regional data where they exist, and a top-down strategy that uses global groundwater models.

Advantages of the bottom-up strategy include its use of available regional observations and/or models that are specifically tailored to a region (e.g. a single aquifer system), as well as the possibility to include knowledge from local experts. However, it is not straightforward to synthesize these diverse sources to obtain a coherent global picture of groundwater accessibility and it will unavoidably contain large gaps (Fig. 1b). Current global datasets show significant spatial biases as data is either not available for a region (e.g., due to non-available resources or lack of local relevance) or is difficult or impossible to collect/access. Datasets might also be organized very differently and show distinctive differences on either side of administrative boundaries(40). There is also a lack of digital infrastructure to easily access these data (though it might be available for specific regions(41)) and other private or political interests prevent sharing of data. For example, Jasechko et al.(19) amassed 39 million groundwater level data points globally, but due to licensing or personal interests are not allowed to share it with the scientific community, apart from those datapoints already made public by national services. In addition to observations, regional models encode existing knowledge(42). However, they are not readily usable for global impact assessments as their approaches and assumptions differ widely (e.g., CVHM(43) and C2Vsim(44) in California are two models for the same regions that are based on very different perceptual models(45) e.g., on how to represent hydrogeology and human impacts). Global assessments of climate impact would entail the almost impossible task of running hundreds or thousands of regional models (if available) forced by an ensemble of climate models and socio-economic pathways (only on a relatively coarse spatial resolution) simultaneously. In addition, the analysis and interpretation of results would be an equally difficult task due to a lack in standardization of model setups (process representations, use of input data etc.).

In recent years, global groundwater models have emerged as a top-down strategy to obtain a global picture of groundwater resources and their temporal evolution. However, the reliability of current models for supporting water policy is highly debated within the community(46), and model estimates are challenging to evaluate given the data limitations discussed(40) (e.g., data biases affect our ability to evaluate and calibrate the models). Nevertheless, they are already broadly applied in different communities; for example, the results of Fan et al. (47) are used to conduct regional studies on groundwater accessibility for vegetation in the Amazon(48) or are included in datasets like the HydroATLAS(49).

Here we argue that both strategies are necessary and ultimately intertwined to improve global-scale knowledge and to critically assess the current status of the top-down approach. Increased community efforts in collecting existing knowledge will ultimately improve global models, and, even if global models are not yet fully able to reproduce regional conditions, they are capable of carrying out global impact assessments that are not otherwise possible to achieve(3, 5, 38, 50). Below, we analyze the current state-of-the-art by analyzing and comparing four global steady-state (non-time-dependent) groundwater models as well as available WTD observations. We chose steady-state models and observations as they currently represent the most extensive available global dataset of simulated and observed long-term WTD(47). Additionally, we would assume steady-state to be the simplest to simulate given that time varying factors such as changing climatic conditions are not taken into account. Any disagreement found in these simulations provide a baseline of what uncertainty can be expected for more complex model setups.

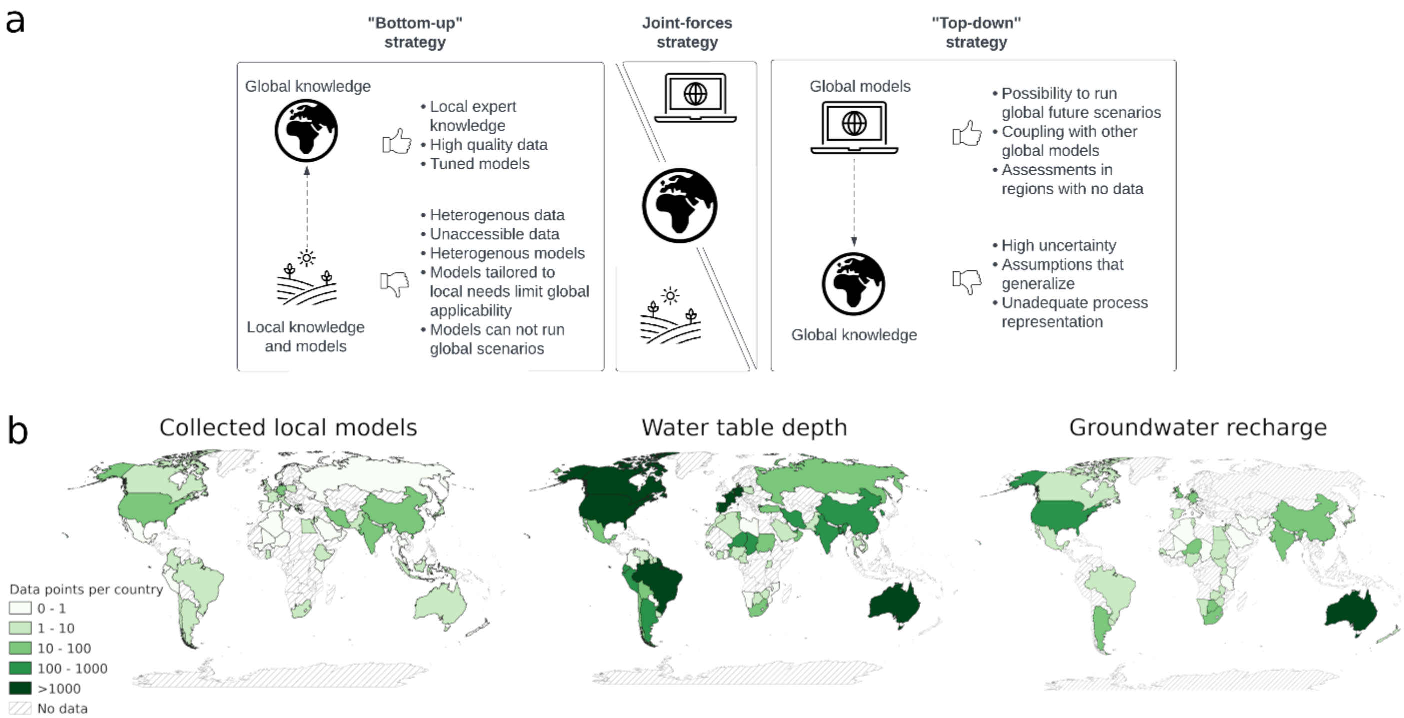


**Figure 1.** (a) Strategies to obtain global-scale groundwater knowledge, and (b) current available regional data. Data of local groundwater models are based on a global database of regional groundwater models(42), the water table depth data is taken from Fan et al.(47), and the groundwater recharge observations from Moeck et al. (51).

## Global variation of potential groundwater accessibility for ecosystems and humans

In the following sections, we define three categories of potential groundwater accessibility: (i) potentially accessible to ecosystems, (ii) potentially accessible for irrigation or drinking water supply, and (iii) costly to access or inaccessible. Potentially accessible to ecosystems implies that groundwater might also be a convenient human water source. We base these categories on an average WTD as a first order estimate, recognizing that water tables may fluctuate seasonally up to multiple meters (52, 53). Locally, accessibility of groundwater is not only controlled by WTD but also by geological setup (54), water quality (55), available infrastructure (56, 57), available equipment (58), monetary resources (59), and applied policies (28).

Globally, 96.9% of plants root no deeper than 10 m(38) and are projected to become shallower due to agricultural activities(18). We lack global data on groundwater connectivity to aquatic ecosystems, but two-thirds of US streams that potentially gain water from their surrounding aquifers lie in regions with water table depths no deeper than 10 m(6). We thus use a WTD shallower than 10 m to define accessibility for ecosystems, noting that this generalization might not apply to specific local settings (e.g., because deep roots are likely under-sampled(38), vegetation may adapt to fluctuating water tables(60, 61), and capillary rise delivers water above the water table(62)). We assume that with a groundwater table deeper than 10 m, surface water bodies (streams, lakes, wetlands) are likely not gaining and that vegetation does not have (direct) access to this groundwater(50, 63). Humans, on the other hand, can drill wells to access deeper groundwater, but these wells are mostly shallower than 100 m (the average well depth is 60 m(22) in the USA and 46 m globally(19)) due to economic constraints(22, 64). Thus, we categorize regions with water tables deeper than 100 m as costly or inaccessible. Humans may also access shallow groundwater (below 10 m). We acknowledge that both thresholds are somewhat arbitrary; they primarily indicate where groundwater is very deep or very shallow, which will impact accessibility and provides a useful first order estimate.

Following our definitions, we find that on average 23% of global groundwater is potentially accessible to ecosystems, 57% is potentially accessible to humans, and 20% is potentially costly or inaccessible. These numbers are calculated from the ensemble mean estimates of four global groundwater models(38, 65–67) (Fig. 2a, see Supplement and Methods). Shallow water tables accessible to ecosystems are located along coastlines and in regions with major aquifers, such as the Amazon Basin, the Central Valley aquifer, the Ganges-Brahmaputra Basin, and the Mississippi Alluvial Aquifer. Costly or inaccessible groundwater is mainly located in mountainous regions such as the Rocky Mountains, the Andes, and the Himalayas. The latter shows the limits of the coarse spatial representation used in the models (5 arcminutes), which may not be able to simulate local groundwater systems in topographically very diverse regions, even if groundwater provide a vital influx to streams in mountainous regions. It is important to remember that the mean WTD shown here represents the long-term average (steady-state) of a natural world without human impacts (e.g., pumping). A consequence is a tendency to see shallower water tables because they do not include an anthropogenic fingerprint(47). For example, a shallow water table in the Central Valley aquifer, as shown in Fig. 2a, is reasonable in a steady-state simulation if no groundwater abstraction is included. In general, due to their spatial resolution and limited global data to parameterize the models (for details see section Alternative strategies for model evaluation), all models used are not able to reproduce local convergence of groundwater(40).

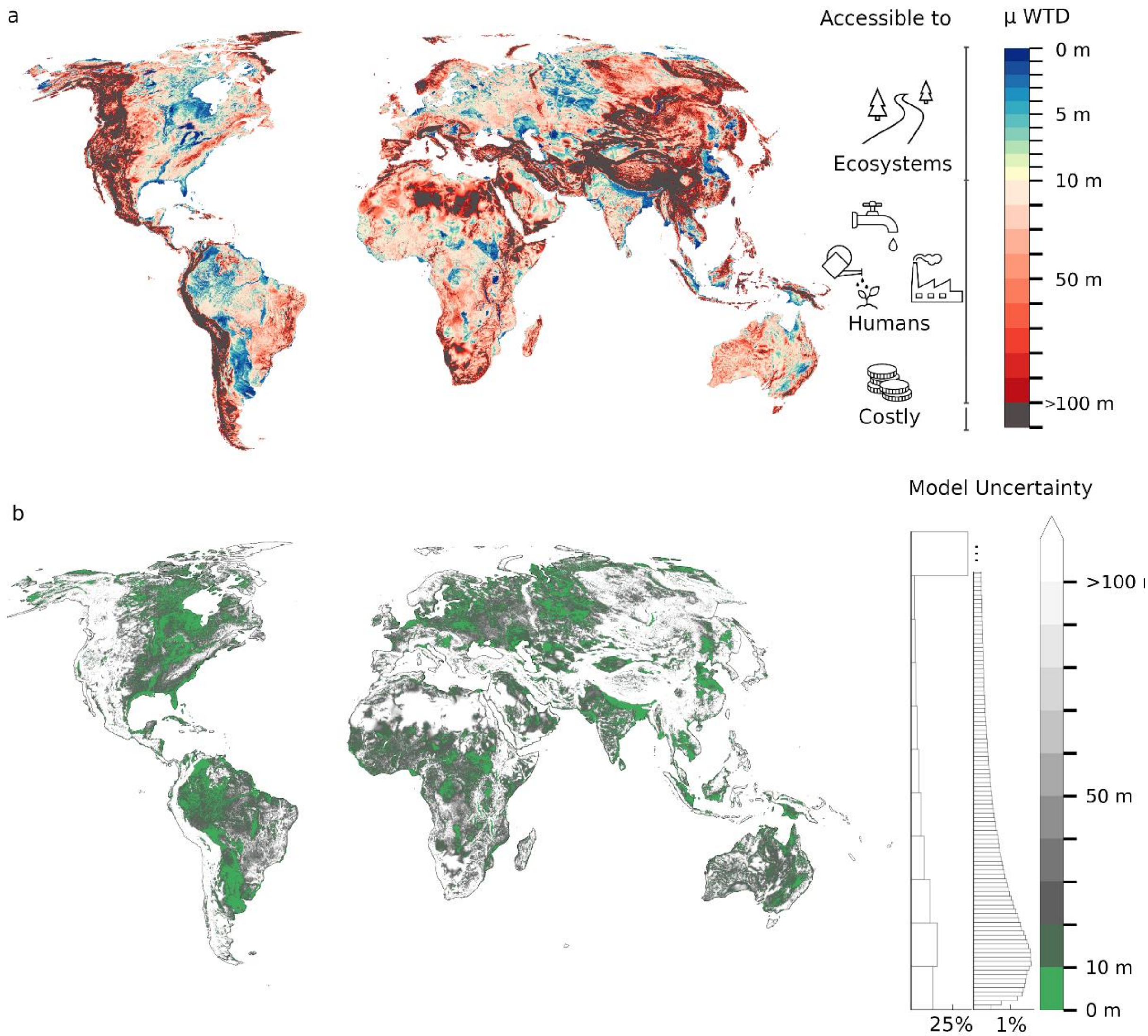


**Figure 2.** (a) Ensemble mean (µ) of steady-state Water Table Depth (WTD) calculated using four steady-state global groundwater models with categorization into three categories of potential accessibility: by ecosystems, humans, and costly or inaccessible. (b) Uncertainty in WTD (highest minus lowest value per grid cell), also represented by two histograms (based on number of grid cells not area) with a bin size of 1 m and 10 m. Blank spaces in the map indicate areas with large uncertainties(45).

**Global estimates of water table depth are highly uncertain**

While the ensemble mean WTD broadly shows patterns that agree with our general conceptual understanding of groundwater processes, such as deeper water tables in drier or more mountainous regions(63), the inter-model differences are substantial. We show areas of considerable uncertainty as blank spaces(45) in Fig. 2b. For one-third of the global land area, the models show disagreements in WTD of more than 100 m. Green places depict where models tend to agree in absolute terms, with differences no more than 10 m, amounting to only 12% of the global land area. Areas of high agreement include the Central Valley aquifer, the Mississippi Alluvial Aquifer, and the Ganges-Brahmaputra Basin.

Model differences broadly reflect topography and are exceptionally high in mountainous regions, such as the Rocky Mountains, the Andes, and the Himalayas. But we also see significant differences in flatter regions if they are located in dry climates, such as the Sahara, South Africa, and Australia. While models generally agree that water tables are deeper in these regions (> 100 m), the models strongly disagree on how deep, often by several hundreds of meters. There is a strong positive correlation between the depth of the mean groundwater table and uncertainty (Spearman rank correlation $\rho_s=0.96$, $p=0.00$; see Supplement). However, while the models agree more in regions with lower topographic slopes and shallower water tables, the uncertainty in these regions might be more consequential. Relative uncertainty (i.e., uncertainty in relation to the mean WTD, see Supplement) is less correlated with topography and thus more strongly highlights flatter areas where models disagree (in relative terms), such as parts of the Amazon basin and the West-Siberian plain. In these flatter regions, a difference in water table depth of 5 m can have an immense impact on the accessibility of water for roots(38), capillary rise(62), and surface water connectivity(5). Regions like the Central Valley aquifer of the Ganges-Brahmaputra Basin are also some of the regions where the largest human utilization of groundwater resources can be found(68), i.e. where the steady-state assumption is least likely to hold.

Even though the smallest uncertainties are found in areas with shallow water tables (Fig. 2), they are large enough to have major implications on the outcomes of global assessments of groundwater accessibility. Here we analyze forests as a critical terrestrial ecosystem and carbon sink(16), population as a proxy for where groundwater might be important to domestic use and industry(64), and (current) irrigated area as a proxy for the potential use of groundwater for agriculture(21). Figure 3 translates the uncertainty in WTD into uncertainty of potential groundwater accessibility for forests, population, and areas equipped for irrigation (note that these classes are not mutually exclusive and are different from the defined potential accessibility classes). It shows that the uncertainty is high for all three classes (forest, population, irrigation) and all three categories of potential accessibility. We find that the global area covered by forest located in regions with ecosystem-accessible groundwater (< 10 m) varies by 63% (compared to the global forest coverage) depending on what model estimate we use. How many people live in areas of potentially human-accessible groundwater (> 10 m and < 100 m) varies by 33%, and the uncertainty of how much irrigated land is in areas of potentially potential ecosystem accessible (< 10 m) groundwater is 54%. We do not suggest that forests, people, or agriculture necessarily depend on groundwater in these areas, but it highlights the potential lack of robustness of any subsequent application of these simulations without considering these uncertainties.

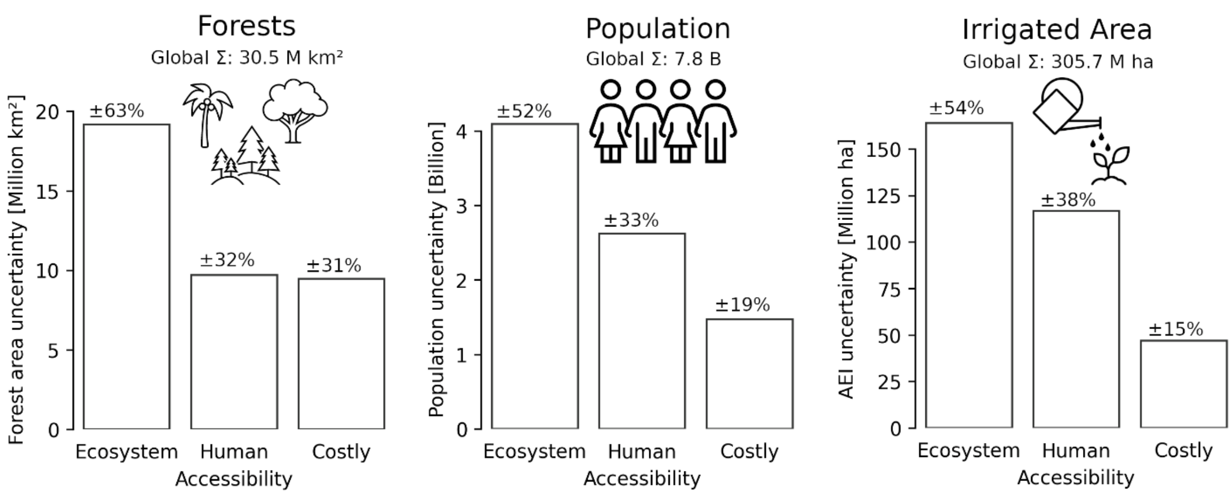


**Figure 3**. Uncertainties associated with, forest area, population, and area equipped for irrigation (AEI) with respect to uncertain regions of three categories of potential groundwater accessibility. Each plot quantifies the uncertainty of how much forest, population, or irrigation is potentially located in areas of ecosystem, human, or costly accessible groundwater. For example, the global area covered by forest situated in regions

with potentially ecosystem-accessible groundwater (< 10 m) varies by 63% (compared to the global forest coverage) depending on what model estimate we use. The uncertainty of the categories is calculated based on the ensemble range (highest minus lowest value per grid cell). Percentages shown relate to the respective global sums of forest area, population, and AEI.

This large uncertainty directly affects our ability to provide critical global assessments and support decision-making. For example, assessing the likelihood of ecosystems losing connection to groundwater is pivotal for carbon policy and ecosystem protection(9, 69). Mapping these potentially fragile ecosystems would indicate where ecosystem protection policy would provide the most impact(69). By limiting our ability to support such decisions, we are ultimately jeopardizing our ability to achieve multiple SDGs such as climate action (SDG 13), terrestrial ecosystems (SDG 15), and our ability to stay within planetary boundaries(39).

The uncertainty shown here also affects scientific experiments we can conduct with these models and it contextualizes existing studies. It is the first time these four models are analyzed and compared directly, and thus provides an important foundation for subsequent research. Previous studies focused on individual global groundwater models and applied sensitivity experiments to demonstrate that their conclusions are not sensitive to key uncertainties (5, 70). Our results suggest that future analyses would benefit from expressing uncertainty more widely using multiple models while utilizing sensitivity analysis strategies to consider both current and potential future conditions (71).

**A strategy of joint-forces towards reduced uncertainty in global groundwater knowledge**

The uncertainty in WTD estimated by global models currently compromises assessments of groundwater's crucial role in ecosystem health, in global water supply for food security, and in human health. We discuss three concrete pathways to reduce this uncertainty, including (i) better global datasets, (ii) alternative strategies for model evaluation, and (ii) joint gathering of regional knowledge.

**Better global datasets**

Uncertainty in global water table depth not only stems from model uncertainty but also from a lack of data which translates into an inability to parameterize, evaluate, or calibrate global models(40). Thus, the challenges of the bottom-up strategy (e.g., in combining available data) limit our capability to pursue the goals of the top-down strategy (Fig. 1).

Currently, only one global-scale observational dataset of WTD is available(47). However, it is highly biased towards the USA, Europe, and Australia (see Supplement Fig. 1). Furthermore, there is a slight under-representation of observations in water-limited (i.e. rather dry; PET/P > 1; see methods) regions (59% vs. 66% of the actual global land area) compared to energy-limited (i.e. rather wet; PET/P < 1; see methods) regions, and a clear over-representation of low elevations (93% of observations are taken at surface elevations below 1000 m vs. 80% globally) and flat regions (96% of observations are in regions flatter than 0.08m/m vs. 77% globally). Data availability is much worse if we go beyond the steady-state assumption since no consistent global-scale time series dataset for WTD is currently available. While models should correctly represent steady-state WTD, their fit to trends is of pivotal interest as this would allow investigating the consequences of a changing climate and/or anthropogenic impacts(5).

Furthermore, we require improved hydrogeological data, global datasets on groundwater abstraction over time, and better datasets on groundwater recharge(40). To this day, only one global permeability dataset is available(72, 73) and no data product is available on global aquifer schematization. No global dataset on groundwater pumping exists, and abstractions can only be estimated(32, 74). Currently available global groundwater recharge estimates are highly spatially biased(75), and modeled recharge is highly uncertain(76).

Apart from the technical challenges of collating such global datasets, there are various reasons why this data is not yet available: (i) non-willingness to share data (groundwater being a politically important resource, scientific imperialism of data collectors) and a general lack of sharing of data (even inside countries and institutions)(19), (ii) lack of resources (both in terms of financial resources and capacity)(1), (iii) duplicated, contradictory and/or non-existent mandates to collect groundwater data, (iv) poor data management without proper quality control and assurance(1), and (v) data simply not existing because there is no motivation to collect it, for example, in regions where population is sparse. Locally, groundwater level time series are available for many locations. However, these data need to be collated by the scientific community and/or parties already active in data gathering, i.e., the Global Groundwater Monitoring Network of the UNESCO centre IGRAC (International Groundwater Resources Assessment Centre) supported through the WMO Global Climate Observing System. Such an effort should ideally be in collaboration with other UN programs (e.g., UNICEF, UNEP, IHP) and supported scientifically through joint working groups with associations like the IAH (International Association of Hydrogeologists) and existing initiatives such as EGDI (European Geological Data Infrastructure). In this regard, groundwater needs to be recognized more prominently in SDG 6 (clean water and sanitation) and as a connecting building block among the SDGs(77), even though the UN has moved towards a recognition of groundwater in their recent report(1). Furthermore, local capacity-strengthening needs to be recognized as a vital aspect in generating data and a willingness to share local expertise.

**Alternative strategies for model evaluation**

The large disagreement in WTD estimates across current models (Fig. 2 b) suggests that there is something to be learned from comparing models and modeling choices. We can learn from comparing the models with each other, with our expectations, and with available observations(40). Model evaluation is commonly performed against small-scale observations of WTD (often converted to hydraulic head)(38, 47, 65, 66, 78–80). This approach, however, provides little insight into the reasons for model disagreement, is limited to few (geographically biased) locations relative to the simulated domain, and suffers from commensurability issues(81).

As an alternative, we can evaluate global-scale groundwater models by investigating so-called functional relationships between known drivers of groundwater flow and WTD(40, 71, 82), including how well models reproduce these relationships in comparison to our current process understanding. For example, using the concept of water table ratio(63, 83), we can conceptualize the water table as driven by four main natural factors: (i) climate (approximated by water-limited and energy-limited regions as an indicator for groundwater recharge; see Fig. 4b) (ii) topography (approximated by topographic slope), (iii) subsurface permeability, and (iv) interactions with surface water bodies. We would, for example, expect deep water tables in dry, steep, highly permeable regions, far away from perennial streams.

In the following, we briefly explore driver-WTD relationships between models and between models and the largest available dataset(47). The median observed WTD(47) (5.5 m) is relatively shallow and thus closer to Reinecke(65) (8.2 m) and Fan(38) (8.6 m), while de Graaf(66) (37.8 m) and Verkaik(67) (24.4 m) simulate a deeper median WTD (see Supplement). The models further exhibit strong differences in how their WTD estimates relate to topographic slope and aridity (see Fig. 4). In agreement with our conceptual understanding(63), observations suggest deeper water tables in water-limited regions than in energy-limited regions (6.1 m vs. 4.9 m, respectively), and deeper water tables for steeper slopes (Spearman rank correlations are $\rho_s$=0.21 and 0.25, for water-limited and energy-limited regions, respectively). Deeper water tables in arid regions are estimated by Fan (15.0 m vs. 4.2 m), but not by Verkaik (24.4 m vs. 24.5 m), Reinecke (6.9 m vs. 10.7 m) and de Graaf (34.8 m vs. 45.2 m). The model of Fan shows medium correlations with slope (0.29 and 0.55), while the models of Reinecke (0.85 and 0.88), de Graaf (0.73 and 0.77), and Verkaik (0.69 and 0.92) show high correlations with slope, particularly in energy-limited regions. We find weak inverse relationships between permeability and WTD for all models ($\rho_s$ ranges between -0.25

and -0.09 and is slightly higher for energy-limited regions; see Supplement), while observations show no clear relationship. Models also differ in how WTD correlates with distance to perennial streams, but there is no consistent pattern ($\rho_s$ between -0.19 and 0.38 for water-limited regions, and between -0.04 and 0.16 for energy-limited regions; see Supplement). In summary, we find topographic slope to be the dominant control in most models, while it is less pronounced in the observations.

Multiple reasons contribute to the differences between the four models investigated here, including (i) uncertainties in groundwater recharge estimates, (ii) spatial resolution of the models, (iii) model choices regarding model parameterization, and (iv) conceptual choices in model implementation (e.g., subsurface layering and assigned permeabilities). Groundwater recharge estimates (i) are highly uncertain(75, 76, 82, 84), and their evaluation is challenging due to sparse observations associated with significant uncertainties(85). The original spatial resolution (ii) of Reinecke and de Graaf is similar (5 and 6 arcmins), whereas Verkaik and Fan use a higher resolution (30 arcsec). Given that the Verkaik model is, in principle, a higher resolution version of the model by de Graaf, comparing these two models indicates the impact of resolution on WTD (see also(78, 86)). We find that aggregating to lower resolution has little effect on overall patterns of WTD (see Supplement), suggesting that model structure and forcing inputs might be more important than resolution (if no human impacts are considered). Regarding (iii), different elevations of the bottom of surface water bodies(70), the inclusion of and assumptions regarding wetlands in arid areas (in the steady-state version(65)), and approaches to parameterize the conductance of the streambed(5, 70) might impact modeled WTD. Lastly, some differences might be related to conceptual choices (iv), such as the use of Darcy on very coarse spatial resolutions (leading to unrealistic gradients (78) and thus possibly to the strong relation to slope), number of subsurface layers (two in Reinecke, de Graaf and Verkaik, 40 in Fan), or the assumption of decreasing permeability with depth (implemented by Fan and Reinecke).

Overall, these findings invite a more in-depth investigation to understand and explain inter-model and model-observation differences in the future(40, 46). Such a comparison would greatly benefit from a structured Model-Intercomparison Project (MIP) specifically focused on groundwater, comparable to the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)(87), to provide a consistent framework for model simulations (e.g., standardized forcing data, output resolution, and variable names)(40, 46).

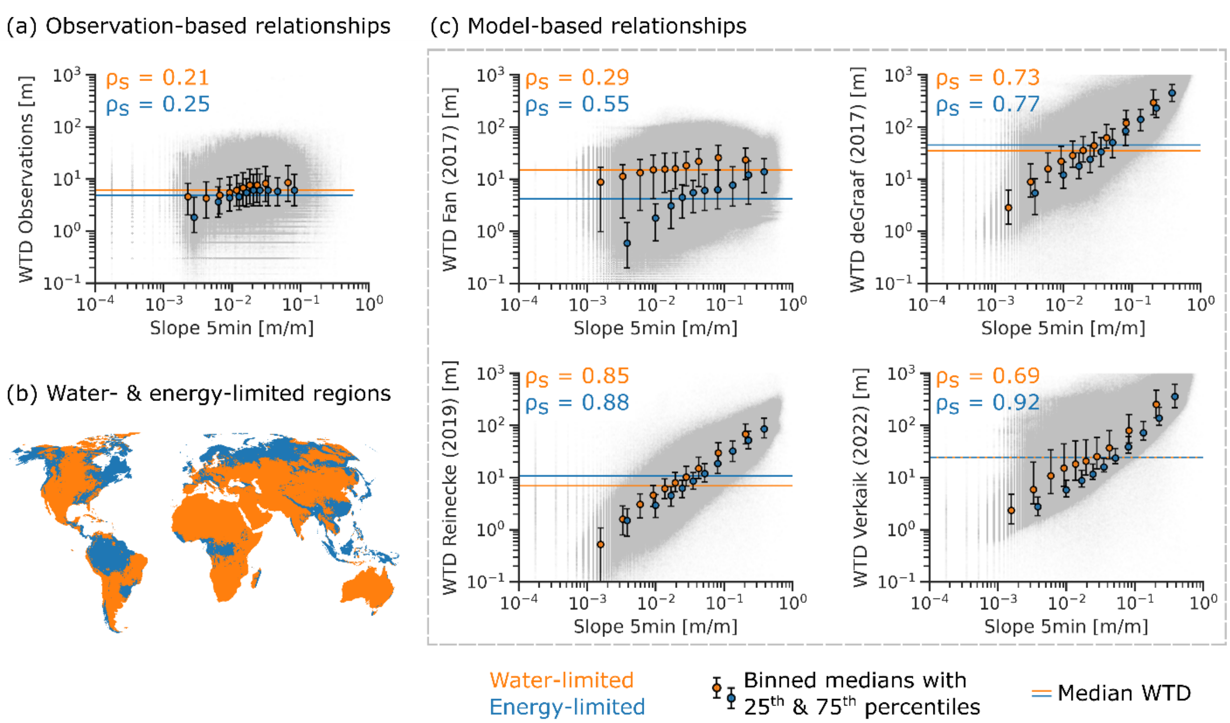

**Figure 4**. Relationship between topographic slope and (a) observed as well as (b) simulated WTD from four global models. (b) Location of water-limited (i.e. rather dry) and energy-limited (i.e. rather wet) regions. Spearman rank correlations shown in (a) and (c) are based on the point cloud, separated by aridity index. Bin averages are displayed as a visual aid and are separated based on the aridity index (orange and blue; see Methods for estimation and Supplement for a global map). Topographic slope, aridity, and modeled WTD have been aggregated to a resolution of 5 arcmin. For the observations, the WTD values were compared with the 5 arcmin values of the grid cell in which the observations are located.

## Gathering regional knowledge of groundwater systems

Global models are (at least for now) considered unsuitable tools to answer regional-scale water management questions due to a lack of specific tailoring to local conditions, though they are often the only source of information in data-scarce regions. Also, combining them with existing observations is challenging because of the immense spatial scale differences(88). However, they would profit from existing regional knowledge about groundwater systems and how humans interact with these systems (i.e. pumping and managed aquifer recharge)(40). Knowledge, for example, on preferential flow paths due to karst(89), volcanic rock, or deeply weathered soils (laterites)(90) is currently not embedded in any global dataset but available in regional models and expertise. Even though a global map of carbonate rock regions is available (91) it has not yet been included in any global groundwater model. Worldwide, thousands of regional groundwater models have been published in peer-reviewed articles and reports, often with accompanying data, and we have a rich base of expert knowledge within the heads of those who built these models. This knowledge base could be harnessed to build powerful new data sets for ground-truthing(84) global results and for improving the representation of groundwater processes in global models(40). First efforts have been made to build community portals to collect such information(42).

A global database of existing local and regional groundwater models would offer many opportunities to improve our scientific understanding and facilitate the connection of the groundwater community globally(40). Some national government organizations already openly share their groundwater models and all underlying data, for example, the USGS (US Geological Survey), the NHI (Netherlands Hydrological Instrument) and the GEUS (Geological Survey of Denmark and Greenland). A joint global collaboration between academics and national geological surveys, organized and supported by institutions such as the WMO, IGRAC, and IAH to create a globally accessible platform, would offer a powerful data portal. Bringing this information onto one platform would already yield the opportunity for standardization (e.g., data formats and terminology) and community exchange; additional conferences and workshops could strengthen the latter to facilitate knowledge exchange and the development of methods to analyze the data. Such a platform of local models and knowledge could then be used to ground truth conceptual assumptions of global models and datasets. More than that, it would make existing local models more accessible to other nations and regions that could tailor model setups to their own local settings. The goal of such a platform and other global data collection efforts always needs be a partnership of local communities that search for a shared understanding and not a “harvesting” of knowledge through the global-scale research community.

## Global-scale knowledge of groundwater table depth is necessary but not yet available

Groundwater is a pivotal source of freshwater for terrestrial ecosystems, it functions as an ecosystem, provides drinking water to humans, and remains a reliable source for irrigation during drought periods. To assess how global change (e.g., climate change, land use change, water abstractions) affects our water cycle and potentially freshwater sustainability, we require a global perspective on groundwater. However, we are currently lacking a coherent and robust global knowledge base to provide this perspective. With improved knowledge of global groundwater accessibility and threats (i.e., unsustainable abstractions), the United Nations could better guide action in protecting ecosystem health and developing effective carbon policies. Importantly, with better global models (including better representation of human impacts), we would be able to assess impacts of climate change on global groundwater resources more robustly, filling a current gap in the IPCC reports. Information on where groundwater is accessible, abstracted, and potentially remains accessible for future irrigation will enable international organizations like the FAO and the World Bank to guide programs on irrigation infrastructure and crop adaptation. To reach these goals, we need to acknowledge that current global-scale groundwater models must be improved and work jointly to compile existing local knowledge into global knowledge shared across communities.

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**Data and Code availability**:

The ensemble mean on 5 arcmin resolution including the uncertainty bounds can be accessed here: https://doi.org/10.5281/zenodo.7538161 CCby4.0.

The source code of the modeling framework of Reinecke et al.[45] can be accessed at:

http://globalgroundwatermodel.org

**Competing interests**: None.

## Methods

### Models

This analysis uses the outputs of four published global models: Verkaik(67), Fan(38), Reinecke(65), and de Graaf(66). The models exclude Greenland and Antarctica. All models used here represent a global steady-state WTD which is not influenced by anthropogenic change, e.g. no pumping is implemented. The steady-state version of the models does not implement pumping as it represents an equilibrium state without a time component. Abstraction in such a model could lead to infinite depletion if the abstraction rate is larger than the sum of inflows and if no rules are defined at which water level pumping should stop. The models used here implement water abstractions in their transient version, however, before moving to a time-varying analysis they should first agree on a natural steady-state. For the calculation of the ensemble mean, model results were aggregated (resampling method = average) to a spatial resolution of 5 arcmin using GDAL. We chose not to calculate the ensemble median because of the low number (four) of models used here. The uncertainty range was computed by calculating: Max(WTD) - Min(WTD) for every grid cell of the ensemble. All assessments regarding relative area are calculated with the correct cell areas based on a global equal area projection.

### Separation into three categories

We created water table accessibility categories based on global and large-scale datasets of rooting depth(38), potential groundwater-stream connectivity(6), and well depth(6) (see Supplement). The chosen categories such as rooting depth may not represent local systems. We assume a connectivity when surface water bodies are fed by groundwater, this excludes downward flow of surface water to the groundwater. The connectivity to lakes and rivers may also go beyond the chosen 10 m boundary for deeper lakes and streams.

**Uncertainty impact assessment**

Figure 2 uses three different data sources. Global tree cover data(92) on 30 m resolution was aggregated to 5 arcmin. The data representing the % coverage was then converted to area using the land mask covered by the model ensemble. Population data for the year 2020 (constrained version; https://hub.worldpop.org) on a 100 m resolution was aggregated (resampling method = sum) to 5 arcmin and cut to the land mask covered by the model ensemble. This resulted in a slight decrease of the global population as coastal areas are not as well represented by the coarser global model mask. Global irrigated areas on 5 arcmin resolution(93) were used to calculate the areas equipped for irrigation. The three 5 arcmin data products were spatially joined using GDAL with the calculated uncertainty range of the ensemble.

**Model evaluation**

WTD observations are from Fan et al. (2013)(47). Aridity data are based on CHELSA data at 30 arcsec resolution(94). Slope data are based on 250m slope data from the Geomorpho90m dataset(95) and elevation data (used in the Supplement) are based on 250m elevation data from(96); both are based on the MERIT DEM(97). For Figure 3, all rasters (aridity, slope, WTD from all models) were resampled to 5 arcmin resolution using GDAL (resampling method = median) and aligned to exactly overlay. Resampling may influence driver-WTD relationships as it smooths out variability. Overall, however, the patterns are only slightly affected (see Supplement). In Figure 3, each bin contains 10% of the data (spread evenly across all slope values). The correlations are calculated using all data points and are therefore unaffected by the bins, which are primarily there for visualization. Observational data used is possibly highly affected by water abstractions or return flows. The steady-state outputs of the models do not account for this anthropogenic impact.

Aridity was calculated by dividing potential evapotranspiration by precipitation (PET/P), both from CHELSA. Values below one indicate energy-limited, i.e. wetter, environments, values above on indicate water-limited, i.e. drier, environments. Using other data products, approaches and thresholds to calculate aridity will produce different aridity maps, however this will not substantially change the fact that we, for example, expect deeper water tables in regions which tent to be water-limited.

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