

Dear Dr. Cenlin He,

Thank you so much for handling our manuscript. Below, we respond to the three reviewers' feedback as well as comments from the community. We have improved the manuscript in several aspects:

- We have substantially revised the manuscript context to enhance the overall readability, and refined all color maps using the Scientific Colour Map 7.0 recommended by GMD;
- We have included the validation of groundwater table depth (WTD) to complement the previous evaluation based solely on groundwater head;
- We have further assessed the model performance across different climate regions and human activity gradients, to better understand the functional relationships underlying groundwater dynamics.
- We have added comparisons with ensemble mean results from other global groundwater models;
- And finally, we have clarified several technical details of the model implementation and elaborated the discussion of model limitations.

By incorporating these improvements, we hope that we have satisfactorily addressed all reviewer comments and that the revised manuscript will meet the standards for publication in GMD

Below, we provide our responses in blue text, while the reviewers' original comments remain as black.

Sincerely regards,  
Qing He  
on behalf of all coauthors

## **Reviewer #1, Dr. Robert Reinecke**

In their manuscript, He et al. present a steady-state groundwater model forced by outputs of the global hydrological model H08.

In general, this study is very timely, and it is nice that H08 is also approaching this difficult task of including a gradient-based groundwater component. However, there are also several areas where this manuscript needs improvement.

1) As already mentioned in an early community comment, some studies provide some more context for the finding presented here.

2) Instead of the global maps, a direct comparison to existing published results would significantly improve the scientific value of this study. I made a concrete suggestion further below. Parts section 3.5 adds not much and should either be extended or removed.

3) The sensitivity analysis is currently a manual calibration and not a classical sensitivity analysis. This needs either to be named manual calibration or the one traditional goal of sensitivity analysis needs to be achieved (see also more details below).

3) And finally, I suggest also reconsidering the framing of the study because what the authors present is not yet a coupled model but rather a global steady-state groundwater model forced by aggregated inputs from H08. Either the authors need to add at least ideas on how the complete two-way coupling can be implemented, or they need to adapt how the results are presented.

With regards,

Robert Reinecke

Response:

Dear Dr. Reinecke, we sincerely appreciate your constructive and insightful comments. We have carefully addressed all the points raised.

In particular, regarding your last comment, we agree that this paper only shows the steady-state groundwater simulation, which is stated in both the title and throughout the manuscript. To emphasize that the two-way coupling will be an indispensable part of our model development work in the future, we have added a discussion in Section 2.1 outlining our ongoing efforts and conceptual plans for the two-way dynamic coupling H08-MODFLOW simulation.

Detailed comments:

16: but then it is a manual calibration, not a sensitivity analysis

Response: Thank you for raising this point. We have revised the terminology to “Local One-At-A-Time (OAT) Sensitivity Tests” rather than “manual calibration”. See our detailed response to another comment below (Line 15).

18: Two previous studies? There is much more than that. Also, it is unclear what this refers to here. Studies on H08 or more generally global groundwater modeling

Response: Thank you. We have revised the wording here (Line 16-20).

17: Does this refer to WTD or head? This needs to be clarified because I suspect it is head.

Response: It is head. We have clarified accordingly (Line 16-20).

20: Did you mean shallow?

Response: We apologize for the typo. The original sentence has been removed to better fit the new abstract context.

35: Groundwater is also in itself an ecosystem Sacco et al (2023).

Response: Thanks. Citation added (Line 31).

40: You don't really model salinity here. I suggest removing this. Even if intrusion and discharge are critical processes, this deviates too much from the story you want to tell here

Response: Thanks. We have removed the sentence.

51 and following: I don't know if this focus on these specific models is necessary. An increasing number of models that represent the terrestrial global water cycle are starting to include groundwater as an explicit component. There is a plethora of models that we could call global water models (<https://wires.onlinelibrary.wiley.com/doi/full/10.1002/wat2.70025>). Especially since you then also discuss Parflow. A more general framing of the idea that there is an interest in better representing the global water cycle is better than trying to categorise H08 with two other models as the only global hydrological models out there, which is also not true.

Response: Thank you so much for this constructive suggestion. We have rephrased the context here and hope it is now of a broader interest to the global water model community (Line 46-58).

82: Reinecke instead of Reneicke

Response: We are terribly sorry for the typo. It is corrected (Line 66).

93: Does this refer to a 41-year mean of conditions that were used to force a steady-state model where time was removed from the model formulation to reach an equilibrium, or did you use a transient formulation to reach a defined steady-state? This is unclear here. Also, why this period and not, e.g., 1901, which is often the starting point for ISIMIP simulations?

Response: The steady-state in our study refers to the previous one, i.e., time was removed from the model formulation. We have clarified this in the revised manuscript. Also, we chose 1979 - 2010 as the simulation period just to align with an ongoing high-resolution H08 simulation project that uses the same time span. Because the main purpose of this study is model development, the chosen period is meant as a test case. For further analyses and integration into ISIMIP, we will no

doubt extend the simulation period to align with the protocol. We have clarified the definition of the steady-state in the revised manuscript (Line 78-79).

Also, the rest of the sentence is unclear - included in what?

Response: We meant “included in this study”. Corrected in the revised manuscript (Line 81).

112: This is a limitation that should be mentioned in the abstract.

Response: Thanks. We have revised the abstract accordingly (Line 25).

175: Why this exact period and not, e.g., 1901 or a mean of 100 years?

Response: We did it just to test our model performance and to align with one another’s H08 simulation study. See our previous response.

176? Why are the aggregated to monthly when you are running at monthly time steps (line 175)? Or does that mean you calculated the arithmetic mean over this period? Ah, it is described in the following sentence. Please be sure to improve the clarity in your manuscript.

Response: Thank you. We appreciate your careful reading.

203: This is not correct. It has not been proven in any scientific way other than that it provides decent results, however, not better than in models that don’t use this approach. Essentially, it is a calibration of transmissivity to observed heads. I am not saying it is wrong, but it should be introduced correctly.

Response: Thank you for pointing this out. We have revised the wording (Line 196).

Fig. 3a Please use appropriate colors - also in other figures.

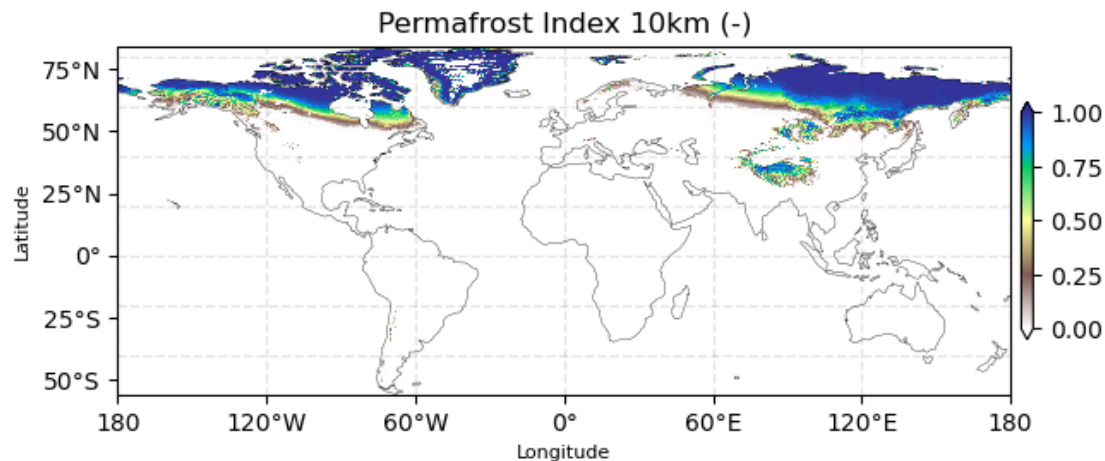
<https://hess.copernicus.org/articles/25/4549/2021/hess-25-4549-2021.html> is a good read concerning this. Also, the figure text does not include the units shown.

Response: We apologize for the inappropriate choice the colormap. We have now applied the colormaps from Scientific colour maps 7.0 to facilitate a more CVD-friendly visualization of our results for this figure and throughout the manuscript.

218: Is there a reason why you chose to not use the permafrost categorization to limit conductivity in the North?

Response:

Thank you for the suggestion. We have re-run all the simulations by constraining permafrost hydrological conductivity based on permafrost zone index (pzi) map from Gruber 2012 (see the spatial extent below), similar to Reinecke et al. 2019, HESS. However, constraints on hydraulic conductivity are only applied to regions with  $pzi > 0.5$ , as this threshold corresponds to continuous and extensive permafrost zones where temperature fluctuations and freeze–thaw dynamics strongly influence K values.



Different from Reinecke et al. (2019, HESS), we did not assign a uniform hydraulic conductivity (K) value of  $10^{-13}$  m/s to all permafrost grid cells. Instead, we applied a scale factor to the original K when the soil is unfrozen. This approach was adopted for two main reasons:

- (1) The model exhibited poor convergence performance when using an extremely small K, with many grid cells showing simulated groundwater heads higher than the land surface; and
- (2) The change in K within permafrost regions is controlled by multiple factors,

including soil temperature, freeze–thaw dynamics, and soil texture. Previous studies have shown that the K can decrease by one to four orders of magnitude when transitioning from unfrozen to frozen conditions (Watanabe and Flury, 2008, WRR, doi: 10.1029/2008WR007012; Watanabe and Osada, 2016, VZJ, doi: 10.2136/vzj2015.11.0154).

To maintain numerical stability in our simulations, we adopted a conservative estimate, representing a one-order-of-magnitude reduction in K. We admit this is a strong assumption, and we have explicitly acknowledged this in the revised manuscript (Line 214-217).

230: Which is consistent with <https://hess.copernicus.org/articles/23/4561/2019/>  
What does "1d" refer to?

Response: Thank you for recommending this paper. The river–aquifer exchange scheme in Reinecke et al. (2019) adopts the standard head-dependent conductance formulation, which is also used in MODFLOW. Our implementation follows the same formulation. Given this equivalence, we chose not to particularly highlight the scheme consistency here to avoid redundancy, while cite Reinecke et al. (2019) in the other part of this manuscript.

"1d" means "1 day". Corrected (Line 224).

Figure 4: Bad figure quality. The subfigure references have different sizes, and sometimes they are in the figure. C is missing a legend altogether.

Response: Thanks. We have adjusted them accordingly.

250: The DEM is at a higher resolution than 5-arcmin. How did you determine the river elevation exactly?

Response: The spatial resolution of DEM is aggregated to 5-arcmin using linear interpolation algorithm to ensure consistency with other dataset, similar to what has been done in Reinecke et al. (2024). The assumption is that the influence of the simplified upscaling method would only have effect on sub-grid topographic variability and only have negligible impact on the first-order global pattern of simulated head. We have clarified the data processing technique in the revised manuscript (Line 250 - 251).

280: While it is great that the authors did this. It is also important to frame it correctly. This is a local one-at-a-time SA which does not account for interactions. And since you don't achieve any of the traditional goals of SA, i.e., screening, ranking, or mapping <https://www.sciencedirect.com/science/article/pii/S1364815216300287>, I would say it is rather a manual calibration than a SA.

Response: We appreciate the reviewer's clarification. We agree the analyses here do not rigorously follow the traditional SA standard. However, we are hesitant to name this part as manual calibration since we did not define or minimize any objective function, nor perform iterative tuning. We'd rather prefer calling it "exploratory local (OAT) sensitivity tests" as the reviewer suggested, and explicitly state the limitation of our analyses.

282: see also Reinecke et al. (2021) for recharge, (2019) for other parameters, (2020) for spatial resolution, and (2024) regarding simulated WTD

Response: Thank you so much for the recommendation of the papers and the great contribution you've done. We have added relevant discussion in the revised manuscript (Line 283, Line 291, Sections 3.1 and 3.2).

285: RRB is upper case in the text and r\_rb in the table. Please be consistent. Also, what does "ref" mean? What is the baseline value for this?

Response: Thanks for the careful reading. ref for K indicates the mean hydrological conductivity from Gleeson et al. (2011); ref for Rch indicates the 40-year mean H08 recharge; ref for r\_rb. indicates 1 day. We have made the wording consistent and added explanation in Table 1's caption.

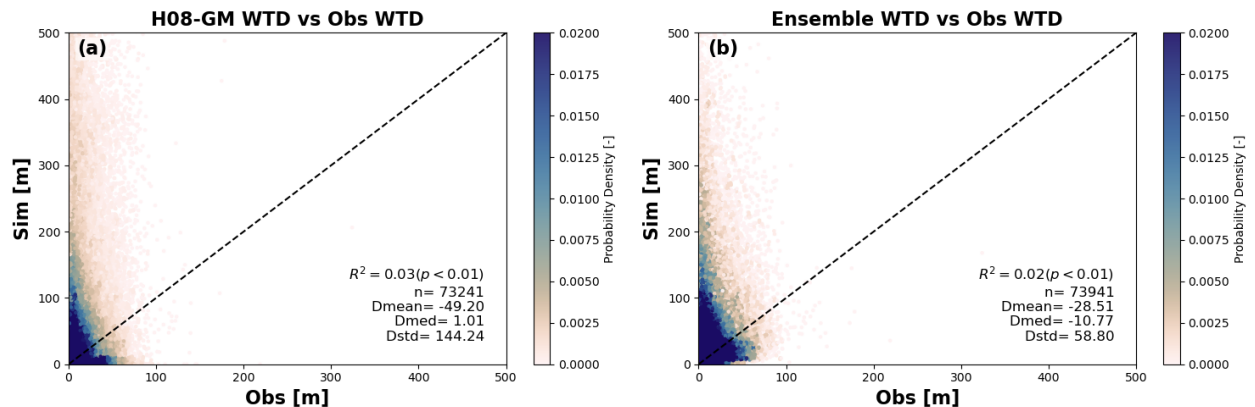
304: I would disagree with this. The head is what the model actually simulates, but what is relevant for many applications, e.g., in determining whether groundwater is available to humans or ecosystems, is WTD. Furthermore, calculating statistical metrics such as an error metric on the head is likely very biased by the topographic influence that is encoded in the head distribution. Scatterplots look very different depending on whether head or WTD is shown. Please show 1) scatterplots of simulated head vs. observed and scatterplots of simulated vs. observed WTD. See

also Reinecke (2020) for a related discussion. Furthermore, I suggest comparing your outputs to other existing steady-state simulations. You could even use the ensemble published with Reinecke et al. (2024).

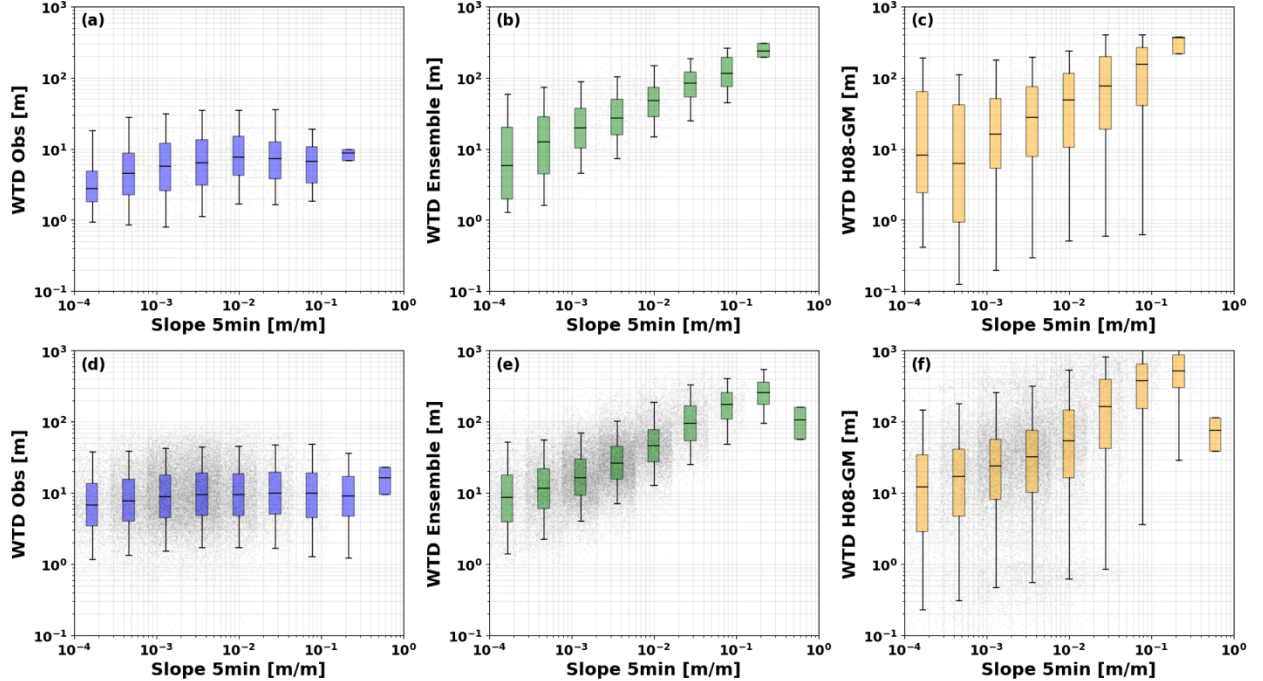
Response:

We thank the reviewer for highlighting this important point. We agree that water-table depth (WTD) is the more application-relevant metric (e.g., for human/ecosystem groundwater accessibility). We have therefore prepared the scatterplots of WTD between H08-GM and Observation, and compared it with the results with the ensemble-mean WTD from Reinecke et al. (2024) as well (Section 3.2 in the revised manuscript).

As expected, the model-simulated WTD, no matter from H08-GM or ensemble mean, compares poorly to the in-situ observations, suggesting this might be a common problem in all global groundwater models. Two reasons could be plausible: (1) WTD embeds biases from both DEM and groundwater head so that the bias of itself might be exacerbated; (2) The spatiotemporal inconsistency of WTD in Fan et al. (2013) and the model simulations, i.e., most observations of Fan et al. (2013) only have one reading, and since they are in-situ observations, they cannot represent the 10km x 10km footprint. See a more detailed discussion in the revised manuscript (Line 390 – Line 398).



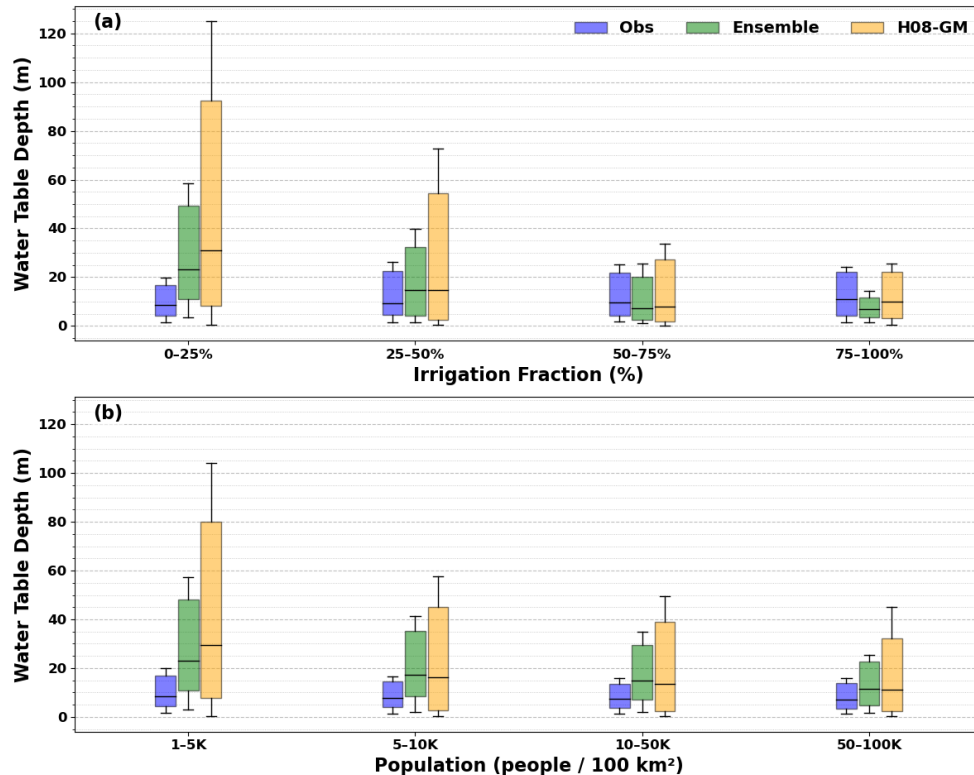
As the reviewer suggested in a later comment, we have also compared the WTD-slope functional relationships under different climate regimes in the figure below (top row for the energy-limited regime and bottom for the water-limited). H08-GM resembles the ensemble-mean in both water-limited and energy-limited regions, but neither of the models' results follow closely to the observations.



However, we believe the model can perform reasonably well in some regions, if not in the global sense. Inspired by Reinecke et al. (2024), we evaluated the performance of H08-GM and ensemble-mean in terms of different irrigation area fractions and population densities. The results suggest that in high irrigation fraction areas (e.g., >50%) and high population density areas (>10K/100km<sup>2</sup>), both H08-GM and ensemble-mean show closer median and model spread of WTD compared to the observations (Figure next page). This is important since it is in these areas the groundwater matters more to human and agricultural water accessibility.

In conclusion, we agree that the poor model-obs WTD problem in H08-GM, so as in other global groundwater models, but the models can perform reasonably well in densely populated and irrigated regions. This should be an important research

direction in the future for the global groundwater modeling community. To highlight topic, we have included the above content in the newly added Section 3.2 in the revised manuscript.



310: Again, this is an artifact of using head instead of WTD and suggests a much better model performance than actually is the case. Since the model is likely performing very well in shallow aquifers but much worse in deeper aquifers.

Response: We have revised the sentence to underscore this is for groundwater head (Line 335).

370: What is the impact of comparing human-impacted observation to simulation based only on a natural run? What deviation can be explained by this, and which are the model limitations?

Response:

This is an important point and we appreciate the reviewer's scrutinization. The observations in Fan et al. (2013) inevitably embed the influence of human activity, whereas our model simulation is purely a natural run. The simulated groundwater level should be deeper than the current natural run if human water withdrawal were taken into account (depends on region). This could lead to the model-observation gap being skewed: Where the model head is higher than the observations (shallower WTD), the model-observation gap is exaggerated; where the model head is lower than the observations (deeper WTD), the gap is underestimated. We have included these limitations in the revised manuscript (Line 435 - 440).

Fig. 5, 7: Please also adjust the color here.

Response: Thanks. Adjusted.

Fig.5: The small maps are not very helpful. How about showing the results of the manual calibration in terms of different error metrics (bias, root-mean squared, max deviation) and scatterplots of head and WTD here. This would be much more informative.

Response: Thank you for the suggestion. We believe that in addition to the scatterplots and error metrics, the maps here are important to show the spatial distribution of the simulated WTD. We have now included the scatterplots in Section 3.1 and 3.2, and moved the maps to the Section 3.3, which is specifically to show the spatial distribution of WTD.

Fig. 7: Instead of showing a direct comparison, e.g., as a difference map or scatter plots, to the existing results would be more informative than a global map. Consider comparing the functional relationships to the slope we propose in 2024 as well.

Response: Thanks. We have investigated this interesting relationship and show the results in Figure 9 in the revised manuscript. See our response to your previous comment.

Fig.8: Log scale of the river bed conductance? And where exactly is this zoom in from?

Response: Thank you. We have adjusted the map to show log-scale river bed conductance. The location is in lower Mississippi river basins, and we have clarified it in the caption (Line 543)

Section 3.5. The title mentions implications for megacities, but the section only discusses lateral fluxes computed by the model. This doesn't add much to the paper. Either the discussion of relevance to megacities needs to be addressed in much more detail, which would turn this into a completely different paper. Or I would remove this and write a specific paper about this another time - which would be great because the representation of megacities in global hydrological modeling is a topic we should talk about more. Also showing the later fluxes makes for interesting maps but currently provides no scientific insights. Either this needs a direct comparison to deGraaf and Stahl (2022) and others, such as [agupubs.onlinelibrary.wiley.com/doi/10.1029/2024WR038523](https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024WR038523) or I would remove this as well.

Response: We thank the reviewer for this constructive and inspiring comment. We agree that the discussion related to megacities was superficial in the current study. As suggested, we have now removed megacities from the section heading. We nonetheless kept a brief and clearly caveated discussion in the text because, as the reviewer suggested, the representation of megacities in global hydrological modeling is an emerging topic that needs to be addressed in future. Our intent is not to provide operational city-level assessments, but to use these examples as an exploratory illustration that the model may have potential for such global evaluations (Line 610 - 622).

Regarding the lateral groundwater flow analysis, we respectfully disagree that this component lacks scientific value. In fact, this section provides insightful global assessment of lateral groundwater fluxes simulated by a gradient-based steady-state MODFLOW model, which includes:

- Local OAT Sensitivity experiments revealing how lateral flux patterns and magnitudes are affected by key aquifer parameter setting (hydraulic conductivity), which was not reported in previous global groundwater studies.
- A qualitative intercomparison with recent global studies (e.g., de Graaf & Stahl, 2022); We have also included discussion relevant to the two recently published studies (Akhter et al. 2025 and Migueze-Macho and Fan 2025).

We agree that a more thorough analysis of lateral flows is necessary. However, given that the introduction of lateral flow was one of the core motivations behind extending H08 with a MODFLOW-based groundwater module, we believe that this section is an essential component of the current model development paper. We therefore position our current results as a starting point for further investigations into lateral groundwater processes in large-scale hydrological modeling in the future.

## Reviewer #2

Thank you for this great contribution. The paper presents a global groundwater modeling framework (H08-GM) that couples the H08 global hydrological model with MODFLOW version 6 at 5 arcmin resolution. The authors focus on steady-state simulations under natural conditions. The study includes sensitivity analysis on aquifer parameters, validates simulated groundwater heads against Fan et al. (2013) water table depth dataset, and produces global maps of groundwater table depth and lateral flow.

This study addresses the growing demand for a better groundwater representation in global hydrological modelling. I see it as a valuable and well-executed newly developed model with parameter sensitivity analysis. It provides useful global visualizations and emphasizes the importance of improving subsurface data and lateral flow.

Overall, I recommend Minor revisions, mainly to improve clarity and figure presentation.

Response: We sincerely thank the reviewer for the positive feedback, which has encouraged us to further refine the work. All suggestions regarding manuscript clarity and figure presentation have been fully addressed in the revision.

### Specific comments

The study is described as a coupled framework, but only a one-way coupling is implemented (H08 to MODFLOW). This limitation matters because groundwater feedback to surface processes is not represented. I suggest the authors be more explicit about this limitation and what it means for interpreting their results.

Response: Thank you for pointing out this important point. **The current one-way coupling framework could cause an underestimation (deeper) of the groundwater head than it should be if the two-way simulation were enabled.** The excessive groundwater is simply removed from the aquifer system, rather than entering to the surface water to strengthen its recharge to the aquifer. This could

cause underestimation of the simulated groundwater head (deeper groundwater levels) than it should be if the two-way simulation were enabled.

We have revised the methodological description in Section 2.1 to explicitly indicate this is a one-way coupled model (Line 104 - Line105), and added discussion of the possible consequences this may cause for the model simulation results in Conclusions (Line 615-619).

For the Aquifer thickness section (lines 196–210): I found this part hard to follow. The motivation for introducing aquifer thickness is not clearly connected to the model setup. Since the model simulates an unconfined aquifer, the authors should make the link between the aquifer thickness map, bottom elevation, and groundwater head more explicit.

Response: We apologize for the unclear description. The aquifer thickness refers to the depth between land surface elevation and aquifer bottom, and is a necessary input variable to MODFLOW. We have revised the diagram in Figure 1(b) to illustrate the relations between aquifer thickness, aquifer bottom elevation, and groundwater head. We have also revised the relevant text in Section 2.3.1 for a better clarification.

Figures could be improved with a few adjustments:

Many maps use red/blue scales that are not colorblind-friendly.

Response: We have adjusted all the maps with palette from Scientific colour maps 7.0, as seen in the revised manuscript.

b. Some captions are overly dense and read like mini-methods sections (e.g., Figure 2), while others don't give enough description or citations (e.g., Figure 3). Captions should primarily tell the reader what the figure shows; technical details can stay in the text.

Response: Thank you for your suggestion. We have revised the captions accordingly.

c. Units: Please make sure all colorbars explicitly show units.

Response: Thank you. We have added the colorbar labels for all figures.

The manuscript is too wordy in several places, with very long sentences that were difficult to follow. For example, lines 54–56, 85–90, 365–370. Breaking these into shorter sentences would make the paper easier to read.

Response: Thank you. We have revised them accordingly.

A few minor comments related to typos, clarity, and style (these are just examples, not a complete list):

Line 20: Typo — “hallow WTD” → “shallow WTD.”

Response: We sincerely apologize for the typo. They are corrected now.

Line 28: “...compared to the two previous studies” — unclear which studies are meant; please name them explicitly.

Response: Thank you. As suggested by Referee #1, we have revised the sentence to include more global groundwater studies here.

Lines 54–56: Sentence too long. Suggest splitting into two: one on natural hydrology (supply), one on human use (demand).

Response: Thank you. The original sentence has been revised both linguistically and scientifically to fit a broader topic.

Line 67: ParFlow is also a groundwater model, not a land surface model.

Response: We have revised the sentence to highlight the coupling of ParFlow to CLM (Line 68).

Lines 85–90: Break into two sentences.

Response: Thank you. Revised (Line 70-74)

Lines 140–144: Too wordy and dense; hard to follow.

Response: We have revised them (Line 134-136).

Lines 175–176: “...monthly timestep ... aggregated to a monthly step” — I assume this is a typo; should be daily timestep aggregated to monthly.

Response: Thank you so much for pointing out this. The model is run at the monthly step. We have removed the latter sentence.

Lines 196–210 (Aquifer thickness): Hard to follow.

Response: We have revised this paragraph for a better clarity.

Several inconsistent citations.

Response: We have carefully proofread the revised manuscript to make sure all citations are consistent.

Final comment

This paper has strong potential. With clearer writing, stronger justification for the aquifer thickness part and the one-way limitation, and improved figures/captions, I believe it will be a valuable contribution to the global hydrology community.

Response: Again, we sincerely appreciate your encouraging comments and will refine our work to further advance our understanding on groundwater dynamics and their interactions with human activities.

### Reviewer #3

This is an ambitious and timely global MODFLOW implementation that advances the representation of lateral groundwater flow. The manuscript is well organized and thoughtfully executed; addressing the points below would further strengthen its physical clarity and practical utility.

Response: We sincerely thank the reviewer for the positive comments, which have encouraged us to further refine the work. All suggestions have been fully addressed to improve the physical clarity and practical utility in the revised manuscript.

#### Major comments

H08 runs on a geographic grid, while MODFLOW uses a rectilinear grid in metric units. Please state if all areal and volumetric fluxes were converted.

Response:

We appreciate the reviewer's valuable comment. All the land surface variables in H08 relevant to MODFLOW model (e.g., recharge, runoff, etc.) are simulated at the flux density level (i.e., no grid cell area is involved). Therefore, we did not apply the areal and volumetric fluxes adjustment here. We have clarified this point in the revised manuscript (Lines 107-109).

Treating abstraction as a simple subtraction from net recharge neglects the spatial propagation of drawdown (cones of depression) and can bias heads even under steady state. Could you clarify this limitation? Do you intend to use the same approach in the transient runs? If so, wouldn't that undercut a key advantage of replacing a bucket model with an explicit groundwater model—namely, resolving spatially distributed drawdown and capture?

Response:

Thank you for this valuable comment. We would like to clarify two points here: (1) Our current steady-state run is under natural conditions without considering any pumping effect; and (2) For the transient run considering human pumping, we use MODFLOW's WEL package, rather than simply subtracting the pumping rate from recharge. The WEL package solves the flow field with point (or multi-node) sinks and

therefore produces the physically consistent drawdown cones. We will explicitly clarify this point in our upcoming manuscript. Thank you so much again for pointing out this issue.

Discuss biases expected where deep confined systems exist (e.g. North China Plain, Central Valley): vertical gradients, leakage from over/under-lying units, and coastal interfaces.

Response:

Thank you for this helpful suggestion. Omitting the water supply from underlying confined aquifer units and seawater intrusion in coastal areas can lead to an underestimation of the simulated groundwater head in our model. We have included a discussion of this limitation in the conclusion part (Lines 610 - 612).

For the net lateral groundwater flux, the current explanation is long and switches polarity to compare with other studies. consider adopt one sign convention throughout (and in captions) and move any polarity flips to the supplement.

Response:

Thank you for your comment. We have removed the description regarding the polarity switch to improve the manuscript clarity. We also condensed the relevant discussion regarding lateral flow, with only the most essential results retained to improve the overall clarity and readability of this section. See Section 3.5 in the revised manuscript.

Improve readability with a colorblind-safe palette. Consider annotating break values on the colorbar. Replace “aquifer conductivity” with “hydraulic conductivity (K)” throughout to avoid confusion.

Response:

We have adjusted all the colorbars with palette from Scientific colour maps 7.0, as seen in the revised manuscript. The terminology has also been revised throughout the manuscript

Minor comments

L20: Typo hallow-> shallow

Response: We apologize for the typo. It is now corrected.

L51–54: The list of global models is illustrative, not exhaustive. Rephrase to avoid implying exclusivity.

Response: We have revised the content accordingly (Line 46-50; Line 65-70).

L111–114: The absence of two-way coupling here stems from the steady-state design, not chiefly computational burden.

Response: We have revised it accordingly (Line 106-109).

L124–125: how to explain the reason behind? is it indicating that when the resolution is high enough, subgrid variation is not an important factor anymore?

Response:

We appreciate the reviewer's valuable thoughts. Here we meant H08 shows good behavior in representing the global hydrological regime, i.e., soil moisture dominates evapotranspiration in arid areas, and net radiation dominates ET in humid areas. We have revised the sentence for a better clarity (Line 123-124).

L141–142: Statement is unclear. I didn't understand.

Response:

We meant the original H08 groundwater module is bucket-type and can only simulate groundwater storage changes (no level information). We have revised the sentence for a better clarity (Line 135-136).

L173: For near-surface air temperature downscaling, consider a lapse-rate correction, which is preferable to purely linear interpolation in high-relief regions.

Response:

We appreciate this valuable suggestion. Implementing a lapse-rate correction would require reprocessing the meteorological forcing data and re-running the H08 simulations. Our current focus in this paper is on the groundwater module development. We will consider lapse-rate-based corrections for high-relief regions in

future work, especially when moving to transient, two-way H08–MODFLOW coupling.

L494: The claim about evaluating city-scale groundwater inflow/outflow from a global 5' (~10 km) model feels too strong. At this resolution—and given uncertainties in K, recharge, riverbed properties, and boundaries—such budgets are not robust. City-level assessments typically require carefully delineated regional/local models.

Response:

We appreciate the reviewer's important clarification regarding the limitations. We agree that such budgets are not robust. In response, we removed "megacity" from the subsection title and toned down the claims.

We nonetheless kept a brief and clearly caveated discussion in the text because the representation of megacities in global hydrological modeling is an emerging topic that needs to be addressed in the future. Our intent is not to provide operational city-level assessments, but to use these examples as an exploratory illustration that the model may have potential for such global evaluations (Lines 586 - 589).

## **Community Comments (Dr. Robert Reinecke)**

Dear Dr. Reinecke,

Thank you very much for your thoughtful comments and constructive suggestions. Please see our point-to-point reply below.

On the color schemes:

We sincerely apologize for the inappropriate palette choice. We have revised them accordingly based on Scientific Color Maps 7.0 for a more consistent and CVD-friendly visualization.

On the literature you mentioned:

We must admit that when we initiated this work, much of our time was invested in coding and in trying to better understand this relatively complex groundwater system. Your references on sensitivity analyses, spatial resolution effects, and uncertainty attribution in global groundwater modeling are highly relevant and very inspiring for our study. We have accommodated all of them and see them as an important foundation that will help us to interpret our model's current limitations more clearly. Please see the revised manuscript and our response to your referee's comments below

On the ISIMIP groundwater sector:

Thank you so much for your invitation. It is a truly an honor and valuable opportunity for us to join ISIMIP to learn from the ongoing efforts and to contribute our modeling results.

Thank you again for your valuable input, which has already helped us to strengthen our perspective.

## Community Comments #2 (Giacomo Medici)

Dear Giacomo Medici,

We sincerely thank you for your careful reading of our manuscript and your constructive suggestions. We will carefully consider your comments regarding literature references, figure presentation, and writing structure, and revise the manuscript accordingly. See the revised manuscript and our point-to-point response below.

### Specific comments

Lines 43-45. “Due to its large storage capacity and slow flow rate, groundwater contributes as the major and the most stable freshwater source to human water use in households, agriculture, and industry”. Insert recent literature on storage and low flow rate in areas devolved to agriculture and industry:

- Medici, G., Munn, J.D., Parker, B.L. 2024. Delineating aquitard characteristics within a Silurian dolostone aquifer using high-density hydraulic head and fracture datasets. *Hydrogeology Journal*, 32(6), 1663-1691.
- Mukate, S.V., Panaskar, D.B., Wagh, V.M. and Baker, S.J., 2020. Understanding the influence of industrial and agricultural land uses on groundwater quality in semiarid region of Solapur, India. *Environment, Development and Sustainability*, 22(4), 3207-3238.

Response: Thank you for recommending these papers. We have included them in the revised manuscript (Line 39).

Lines 101. Disclose the overall aim / or goal of your research at the end of your introduction.

Response: We appreciate your comment. The overall aim of our research has already been clearly stated in the last paragraph of the Introduction (Lines 75–76). We believe this placement effectively summarizes the study’s purpose and maintains

the logical flow of the section, so it does not necessarily need to appear at the very end.

Line 101. You need to describe the specify objectives of your research by using numbers (e.g., i, ii, and iii)

Response: We appreciate your suggestion to list the research objectives using numbered items. However, we believe the current paragraph already presents the objectives in a clear and logically connected manner. Therefore, we respectfully kept the narrative form to maintain the flow and coherence of the text.

Line 105. Do you need to specify a MODFLOW version?

Response: We believe that specifying the exact MODFLOW version is important for clarity and reproducibility, as different versions may use different numerical schemes and packages. Therefore, we have retained the version information in the manuscript.

Line 363. What about ME, MAE, RMS and R2 for the difference between model and observation?

Response: Thank you for your suggestion. We have indicated additional statistics in the newly added scatterplots (Figure 6 and Figure 7) and global validation map (Figure 8)

Lines 527-528. There should be no references in a conclusion.

Response: We appreciate your comment. However, we respectfully note that including references in the conclusion is acceptable in scientific writing, particularly when summarizing findings in the context of previous studies. We have therefore retained a few key citations to highlight the broader relevance of our results.

## Figures and tables

Figure 1a, b. Some words are unreadable. Please, make them larger and increase the graphic resolution.

Response: Thank you. We have adjusted them accordingly.

Figure 1a. Specify 2D diagram with a single layer?

Response: We have clarified that the illustration represents a single-layer aquifer (Line 129); however, the diagram itself is shown in 3D for better visualization.

Figure 1a. Specify structured grid?

Response: Thanks. Added (Line 129).

Figure 2. The three figures on the bottom can be closer and then can be enlarged.

Response: We appreciate your suggestion. We have carefully adjusted the layout of Figure 2 to improve spacing and readability. However, due to the limitations of the plotting library (Matplotlib) and the need to maintain consistent axis scales and colorbars across subplots, the current layout in the revised manuscript represents the best achievable configuration without compromising figure clarity.

Figure 3. Better “Aquifer Hydraulic Conductivity”

Response: Thanks. Adjusted.

Figure 6. Some issues here. The legends cover some parts of the figures and some details are un-readable.

Response: We have tested several alternative layouts to improve readability, but due to scaling and formatting constraints, the current configuration is the best achievable version. The legends are intentionally placed over regions with missing or sparse data, so no meaningful details are obscured.

Once again, we highly appreciate your time and effort in helping us improve our work.

# Development of A Global 5arcmin Groundwater Model (H08-GMv1.0): Model Setup and Steady-State Simulation

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**Abstract.** Groundwater plays a critical role in regulating the global hydrological cycle and serves as the most stable freshwater resource for human daily water consumption. However, many global water models, including H08, a global water model considering human water use activities, downplay the groundwater component, i.e., the underground aquifer is often described as a simple lumped model where no lateral groundwater movement or the water table is represented. Here, we present a global H08-MODFLOW groundwater model (H08-GM), built at a five-arcmin spatial resolution, aiming to enhance the capability of the original H08 model in simulating groundwater flows. We describe the basic model setups and simulations under steady-state conditions in this paper. The Local One-At-A-Time (OAT) Sensitivity Tests are first conducted to select the best-run model simulations against in-situ observations. At the global scale, all model runs demonstrate overall good performance of groundwater head, whereas perform poorly in simulating Water Table Depth (WTD, groundwater table below land surface), which is shown to be a common issue in other global groundwater models. However, the model's WTD behaviour is reasonably well in densely populated and irrigated areas, demonstrating its validity for application relevant to human water use activities.

20 We further use the model to reveal the mechanisms controlling groundwater flow dynamics and present the global cell-to-cell net groundwater lateral flow map. We found that the magnitude in some regions is non-negligible to annual groundwater recharge. This highlights the important role of the lateral groundwater flow in maintaining the regional water budget. The steady-state simulation from this study provides the necessary initial condition for the transient simulations, which is essentially important to analyze the global groundwater decline trends and will be presented in another paper. Although

25 developed in the one-way coupled manner, the H08-GM model can provide a powerful tool for large-scale groundwater studies, which enables direct comparison with other groundwater models joined the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), and is essential to advance the development of the next-generation global water models.

## 1 Introduction

Groundwater plays a critical role in the global hydrological cycle. The water exchange between aquifers and surface water bodies buffers the sharp seasonal fluctuations in river channels and lakes, maintaining the resilience of aquatic landscapes and

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ecosystems (Huggins et al., 2023; Jasechko et al., 2021; Otoo et al., 2025; Rohde et al., 2024a, b; [Saccò et al., 2024](#)). Such surface-groundwater exchange can also contribute to a significant amount of rainfall and evapotranspiration variability in arid and semi-arid regions (Bierkens and Van Den Hurk, 2007; Condon and Maxwell, 2019; Schaller and Fan, 2009), therefore mitigating the severity of droughts and heatwaves through land-atmosphere interactions (Keune et al., 2016; Kollet and Maxwell, 2008; Maxwell et al., 2007; Mu et al., 2022).

Groundwater serves as a natural freshwater reservoir to supply human water use activities. Due to its large storage capacity and slow flow rate, groundwater contributes as the major and the most stable freshwater source to human water use in households, agriculture, and industry (Gleeson et al., 2012; Kuang et al., 2024; [Medici et al., 2024](#); [Mukate et al., 2020](#); Scanlon et al., 2023; Wada et al., 2014). On a global average, more than 90% of freshwater availability excluding glaciers is contributed by groundwater storage (Margat and Gun, 2013). In extremely arid regions where no surface water is available, or during dry seasons when no rainfall recharges surface water bodies, groundwater could be the only water source for the local communities (Braune and Xu, 2010; Calow et al., 2010; Gee and Hillel, 1988). Therefore, understanding the spatial and temporal distribution of groundwater availability is key to addressing water scarcity at local, regional, and global scales.

Global Water Models (GWMs) (Reinecke et al., 2025) provide useful tools to understand the role of groundwater in terrestrial water cycle. However, at the early stage of GWMs development, the groundwater processes are often downplayed due to the computational resource limitation. For example, many GWMs such as WaterGAP (Döll et al., 2003), PCR-GLOBWB (van Beek et al., 2011), H08 (Hanasaki et al., 2008a, b), and CLM (Dai et al., 2003), etc., chose to simplify the aquifer as a bucket reservoir and only represent the vertical water exchanges. In the real world, the groundwater flows three-dimensionally, including both vertical flux exchanges with the upper unsaturated zones, and horizontal flows from areas of high hydraulic head to adjacent low-head regions. The groundwater lateral flows are proven to contribute a substantial amount to the total natural water budget, especially in high spatial resolution studies (Akhter et al., 2025; Krakauer et al., 2014; Miguez-Macho and Fan, 2025), and in regions of groundwater convergence and arid climates (de Graaf and Stahl, 2022). Such simplification could introduce considerable bias to the models' estimation of total water availability. The absence of explicit representation of the groundwater table also undermines the hydrological models' capability for direct and accurate evaluation of human water withdrawal impact on groundwater depletion, particularly over intensively exploited regions such as Ogallala Aquifer and North China Plain (Cao et al., 2013; Scanlon et al., 2012; Yang et al., 2022).

With the advancements in computational technologies, the representation of lateral groundwater flow in GWMs has re-invoked interest from the GWM communities in recent two decades (Condon et al., 2021; Gleeson et al., 2021). Among them, benchmark efforts have been made by the PCR-GLOBWB group (de Graaf et al., 2015, 2017; Sutanudjaja et al., 2011, 2018; Verkaik et al., 2024), where the original bucket groundwater module has been replaced by MODFLOW, a physical groundwater model with 3-Dimensional flowing processes based on Darcy's Law (Harbaugh, 2005; Harbaugh et al., 2000;

65 Langevin et al., 2017; McDonald and Harbaugh, 1988). Noteworthy efforts to address the lateral groundwater flow issues in GWMs are also seen in WaterGAP 2.0 (Müller Schmied et al., 2021; Reinecke et al., 2019a), where a gradient-based global groundwater flow parameterization scheme has been developed and implemented; [The development of 3-Dimensional saturate flow module in MATSIRO](#) (Koirala et al., 2014); [The coupling of ParFlow to CLM](#) (Maxwell et al., 2015; Maxwell and Miller, 2005); and a newly developed hydro-economic model CWatM (Burek et al., 2020; Guillaumot et al., 2022) ([The list of models here is illustrative, not exhaustive](#)). With explicit [lateral flow processes and](#) groundwater table represented, the current generation of GWMs is now able to estimate decadal groundwater storage changes and groundwater level declines caused by human water pumping activities. [This advancement](#) enables the direct comparison with the observation and estimations from data-driven approaches (Kuang et al., 2024; Scanlon et al., 2023).

75 Here, we present a global H08-MODFLOW model (H08-GM hereafter) to better represent groundwater lateral flow, thereby improving the realism of simulated groundwater availability and human-groundwater interactions in the original H08. We will first describe the basic model setups, including the coupling framework, parameterization schemes, and the hydrogeological data and in-situ validation data used in this paper. The global 41-year (1979-2019) steady-state simulation ([i.e., time was removed from the model formulation rather than using a transient simulation to reach an equilibrium](#)) results under pristine conditions (i.e., without human groundwater pumping), mainly the spatial distribution of the climatological groundwater depth and aquifer-river channel water flux exchange regime will be included [in this study](#). The steady-state simulation is useful for understanding the long-term balance between recharge and discharge, and provides initial conditions to the transient simulation, which will be discussed in another study. The development of the H08-GM model will allow direct assessments on how lateral flow from adjacent areas can mitigate groundwater decline in highly exploited aquifers, thus aiding in the evaluation of global water scarcity and informing water management strategies. The explicit representation of the groundwater table in the H08-GM model will also facilitate a more accurate comparison with outputs from other GWMs that joined the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).

## 2 Data and Methods

### 2.1 General Description: The Coupling Framework

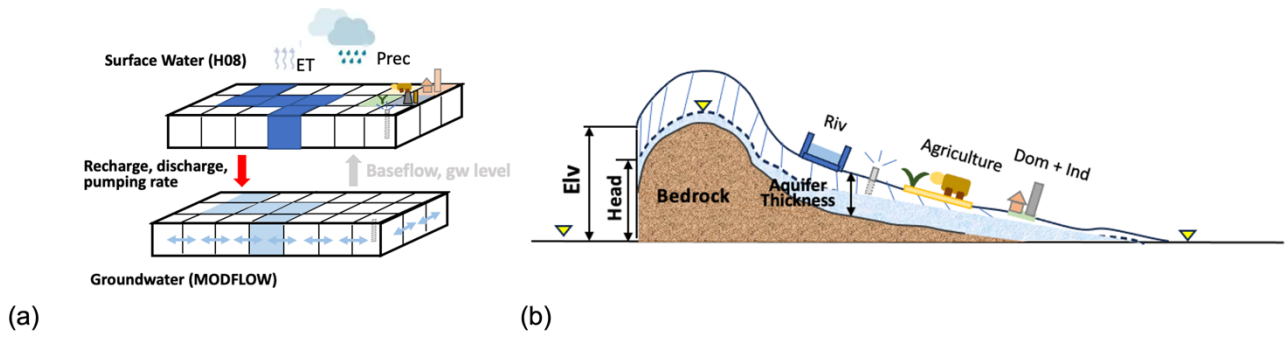
90 The H08-GM consists of two parts: the surface water processes simulated by H08, and the groundwater processes simulated by MODFLOW. In this section, we provide an overview of how the two models can be connected. Detailed descriptions of the individual models will be given in Sections 2.2 and 2.3, respectively.

[An illustration of the groundwater hydrology components \(land surface elevation \(Elev\), groundwater head \(Head\), aquifer bottom elevation and thickness, river-aquifer interaction, and pumping zones\) is shown in Figure 1b to help better understand the terminologies throughout the paper. The conceptual framework of the coupled model is shown in Figure 1a. The two](#)

models are connected through the water flux exchanges, i.e., at each model grid H08 provides total groundwater recharge, river discharge, and total groundwater withdrawal rate as the hydrological forcing to MODFLOW (red arrows, Figure 1a); Baseflow and groundwater level are then simulated by MODFLOW and outputted back to H08 (grey arrow, Figure 1a). An I/O interface that can store the output of H08 and MODFLOW is essential to achieve the two-way coupling goal, with functions of: (i) Time keeping; (ii) Variables and units converting (e.g., from groundwater levels to storage); and (iii) Exchange prognostic/diagnostic variables. From H08 to MODFLOW, the spatially distributed recharge, river stage/flow will be passed; From MODFLOW to H08, the groundwater heads, simulated baseflow to river channels, and root-zone capillary rise fluxes, which feedback to H08 evapotranspiration stress and to the dynamic water-allocation module. However, as an initial step, in this study we only present the offline simulation results (i.e., no feedback from MODFLOW to H08), in order to test whether the forcing from H08 can produce reasonable global groundwater simulation by driving MODFLOW. Both models are built on a 5 arcmin grid to ensure consistent spatial resolution. All the land surface variables in H08 relevant to MODFLOW model (e.g., recharge, runoff, etc.) are simulated at the flux density level (i.e., no grid cell area is involved). Therefore, we did not apply areal and volumetric fluxes adjustment here.

## 2.2 Surface Water Model H08

The H08 model is a global hydrological model considering human water use activities (Hanasaki et al., 2008a, b, 2018). The model considers natural hydrological processes maintaining a closed energy and water balance at each model grid. The soil column is described as a one-layer leaky bucket with a fixed depth of 1m and water draining consecutively at the bottom (subsurface runoff). Soil moisture is obtained through the water balance equation, considering rainfall, snowmelt, evapotranspiration, surface and subsurface runoff, and groundwater baseflow. Evapotranspiration is calculated linearly to the potential evapotranspiration based on a stress factor considering soil moisture. Surface runoff is described as the residual water exceeding soil capacity, while subsurface runoff is calculated as a power function of soil moisture. River discharge is accumulated from surface runoff by the river routing module at each grid. All grid cells within each Köppen climate zone share uniform parameter settings (e.g., soil wilting point and field capacity). Although there is no subgrid distinction between vegetated or bare soil fractions, neither is the soil capillary rise characterized in H08, the overall simulated hydrological regimes correspond reasonably well to the Budyko aridity framework on a global average, i.e., soil moisture dominates evapotranspiration in arid areas, while net radiation dominates in humid areas (Hanasaki et al., 2008a). Human water infrastructures, including reservoir operations, desalination plants, and inter-basin water transfer through aqueducts and canals, are also available options based on the users' purposes.

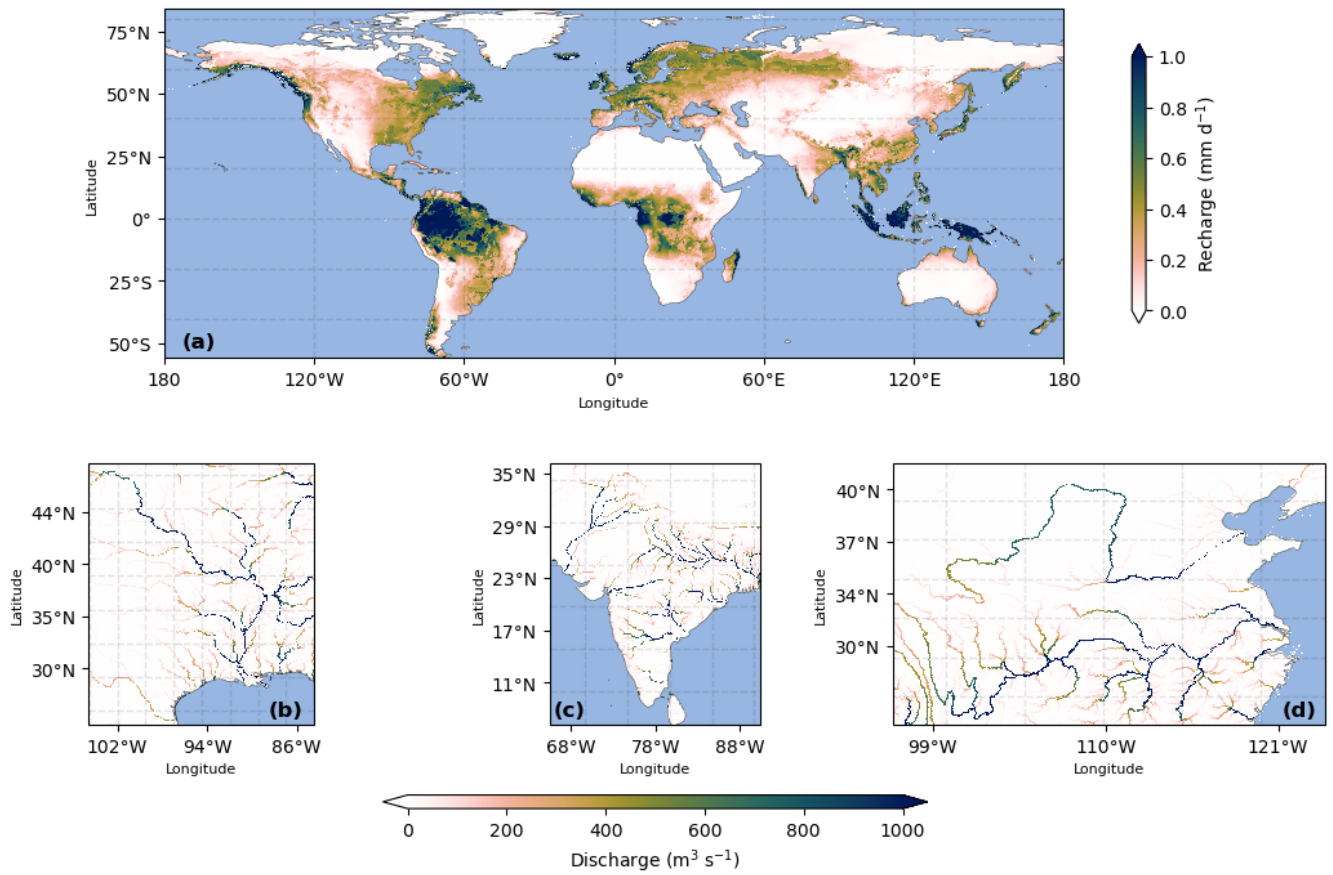


**Figure 1.** (a) Schematic diagram for H08-GM framework. The upper part of the raster represents the natural hydrological processes and human water withdrawal for different sectors in H08. The lower part of the raster represents groundwater processes. The red arrow indicates hydrological forcing input from surface water (H08) to a single-layer groundwater aquifer with structured grid (MODFLOW). The grey arrow indicates groundwater feedbacks to surface water. In the current model setting, only the red arrow part is enabled (one-way coupling). (b) Schematic diagram of groundwater hydrology components. Yellow triangles represent the phreatic surface. The difference between surface elevation and groundwater head is termed as Water Table Depth (WTD).

The groundwater aquifer is described as a single-layer reservoir, where the groundwater storage is fed with groundwater recharge ( $Q_{rc}$ , Eq. (1)) calculated proportionally to the total runoff. There is no characterization on the aquifer geometry; Only the storage changes are available. The groundwater discharge (baseflow) is calculated as a power function of the groundwater storage. Two types of aquifers are introduced: renewable and non-renewable. The renewable aquifers can receive water from groundwater recharge, whereas in the non-renewable aquifer, water can only be withdrawn but not replenished. Human water withdrawal is used for three sectors, i.e., household, industry, and agriculture. The total extracted water for agriculture is calculated dynamically based on irrigation water requirement during crop growth, while water withdrawal for the other three sectors is calculated based on the static sectoral water requirement maps provided by AQUASTAT (Food and Agriculture Organization, 2007). The fraction of groundwater use per sector per country from International Groundwater Resources Assessment Centre (IGRAC) database (IGRAC, 2004) is used to determine how much water is abstracted from surface water bodies and how much is from groundwater aquifers. Water abstraction from renewable aquifers has a higher priority than the non-renewable ones. For brevity we only summarize the key elements relevant to this study here, more details are referred to (Hanasaki et al., 2008a) and (Hanasaki et al., 2018).

$$Q_{rc} = \min(Q_{rc_{max}}, f_r \cdot f_t \cdot f_h \cdot f_{pg} \cdot Q_{tot}), \quad (1)$$

Where,  $Q_{rc_{max}}$  is the maximum groundwater recharge ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $f_r$  is a relief-related factor ( $0 < f_r < 1$ ),  $f_t$  is a soil-texture-related factor ( $0 < f_t < 1$ ),  $f_h$  is a hydrogeology-related factor ( $0 < f_h < 1$ ),  $f_{pg}$  is a permafrost/glacier-related factor ( $0 < f_{pg} < 1$ ), and  $Q_{tot}$  is the total runoff ( $\text{kg m}^{-2} \text{s}^{-1}$ ).  $Q_{rc_{max}}$ ,  $f_r$ ,  $f_t$ ,  $f_h$  and  $f_{pg}$  are determined by the look-up tables provided in Tables A1–A4 of Döll and Fiedler et al. (2008).



**Figure 2.** Long-term averaged groundwater recharge and river discharge from H08 (1979-2019). (a) Global distribution of the 41-year averaged groundwater recharge (unit: mm d<sup>-1</sup>). (b)–(d) for the 41-year mean river discharge (unit: m<sup>3</sup> s<sup>-1</sup>) in the southern Mississippi River basin (b), the India Peninsula (c), and the Yellow and the Yangtze River basins in China (d), respectively.

We first run H08 individually to obtain the groundwater recharge and river discharge to drive MODFLOW. Global meteorological forcing data including 8 variables, i.e., rainfall, 2 m air temperature, specific humidity, wind speed, surface air pressure, longwave and shortwave radiation, and snowfall, from the W5E5 dataset (Lange et al., 2021) are used. The W5E5 dataset was compiled based on version 2.0 of WATCH Forcing Data methodology applied to ERA5 data (WFDE5) (Cucchi et al., 2020; Weedon et al., 2014), ERA5 reanalysis data (Hersbach et al., 2020), and precipitation data from version 2.3 of the Global Precipitation Climatology Project (GPCP) (Adler et al., 2003). The WFDEI data is originally at 0.5 degrees and was post-processed to a 5 arcmin resolution using the linear interpolation function embedded in H08, i.e., the values of the four surrounding grid cells for a certain grid cell will be used to calculate a linear interpolated value by weighting each using the distance ratio. The model was run under the natural scenario at the monthly timestep from January 1, 1979 to December 31,

2019. For the steady-state simulation described in this paper, only groundwater recharge and river discharge are used and averaged over the simulation period to obtain the 40-year climatological means. The spatial distributions of these two variables are shown in Figure 2.

Groundwater recharge (Figure 2a) is generally higher in humid regions (e.g., the eastern United States, Europe, and southern China) and lower in arid regions (e.g., the western United States, Arabian Peninsula, and inland Eurasia), with maximum values observed in tropical areas such as the Amazon Basin, the Sahel, and the Indonesian archipelago. Figure 2(b)–2(d) shows the spatial distribution of river discharge across representative basins in the United States (lower Mississippi), India (Ganges–Brahmaputra), and China (Yangtze and Yellow Rivers). All three regions show a consistent pattern – the high discharge is mainly concentrated along major rivers and downstream reaches and lower values in upstream or small tributaries. The discharge values are also notably lower under drier climates (Yellow River) compared to other basins under more humid hydro-climatological conditions.

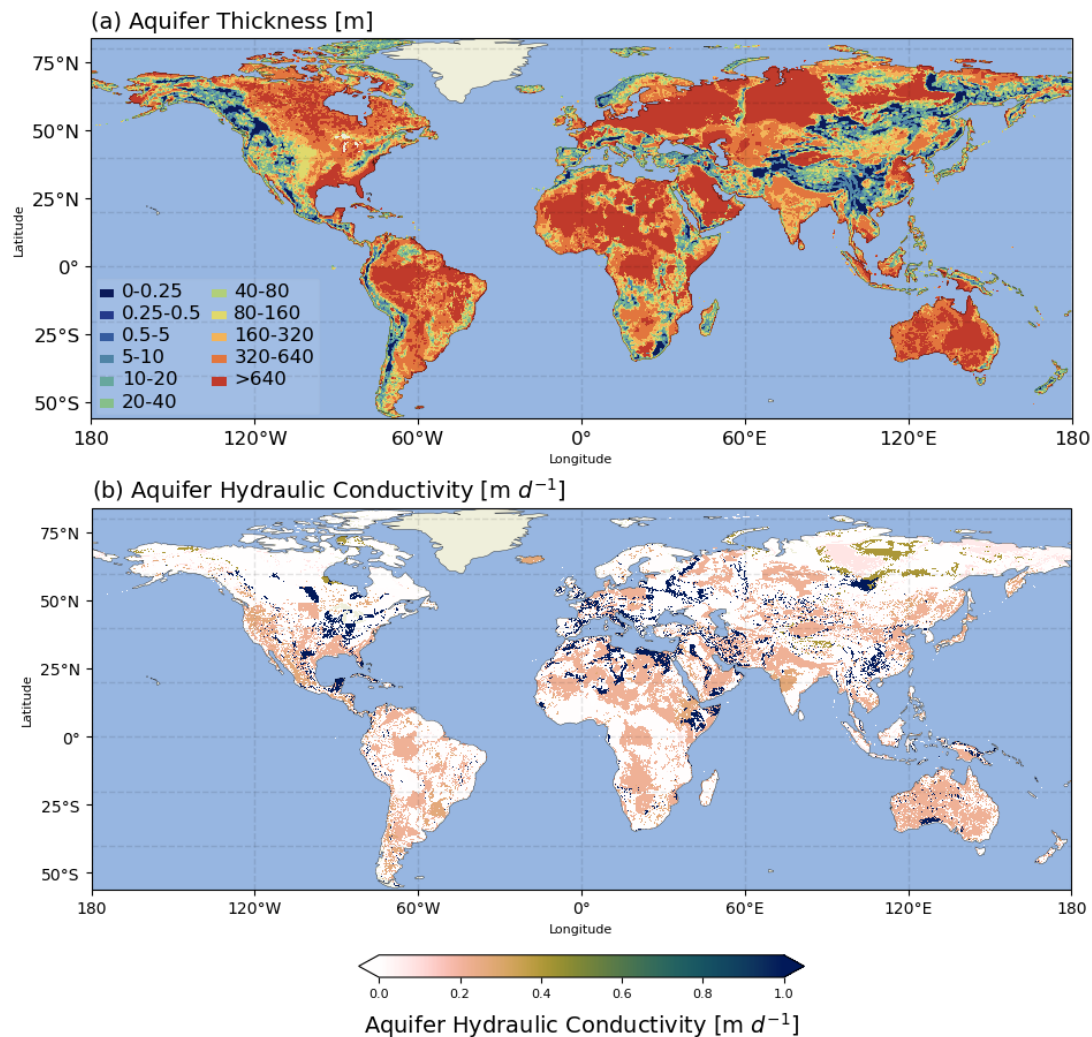
## 2.3 Groundwater Model MODFLOW

MODFLOW is the USGS's modular hydrologic model for simulating and predicting groundwater conditions (Langevin et al., 2017; McDonald and Harbaugh, 1988). The model uses a generalized control-volume finite-difference approach to solve the two- and three-dimensional groundwater flows based on Darcy's equation. Lateral flows and groundwater heads are explicitly simulated and provided as outputs. The modular structure also allows users to customize the model flexibly by adding packages of their research targets such as aquifer properties, recharge, rivers, and wells, etc. In this study, we use MODFLOW6 (version 6.4.0), to build a global single-layer unconfined groundwater model and replace the original groundwater store in H08. FloPy (Bakker et al., 2016) (version 3.3.6) is used as the interface to run the model.

### 2.3.1 Aquifer Properties

Two aquifer property parameters, i.e., aquifer thickness and hydraulic conductivity, are required to build an unconfined groundwater steady-state model at any spatial scale. Aquifer thickness refers to the vertical extent between the top and bottom boundaries of the aquifer (Figure 1b); For a given area, it indicates the aquifer's potential water storage capacity. This parameter is usually obtained from field experiments in local scale studies, while the global map is often delineated based on lithological categories. The GLobal HYdrogeology MaPS (GLHYMPS) (Gleeson et al., 2011, 2014; Huscroft et al., 2018) is one pioneering dataset of such a type. However, the GLHYMPS aquifer thickness only accounts for the shallow layer (thickness up to 100m), thus cannot reasonably represent the deep aquifers in the world. A terrain-based approach was then proposed by (de Graaf et al., 2015) and shown to be effective for deep aquifer characterization based on the calibration of transmissivity to observed heads. The hypothesis of this approach is that there is similarity in Coefficient of Variations (CV) of aquifer thickness all around the world. Therefore, it first generates a random distribution of the average aquifer thickness based on the land surface and floodplain elevation differences ( $\Delta z$ ) at each grid. Then, observed statistical values from 6

200 regional scale studies are used to constrain the corresponding log-normal transformation of  $\Delta z$  and a standard normal ordinate function (i.e.,  $\varphi(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2}$ ). The optimal guess is then derived as the final aquifer thickness product. In this study, we use this product to better represent the deep aquifers. The aquifer thickness map is shown in Figure 3(a).



205 **Figure 3.** Global distribution of aquifer thickness (a) and aquifer hydraulic conductivity (b). The aquifer thickness product is from de Graaf et al. (2015)(de Graaf et al., 2015), and aquifer hydraulic conductivity is based on GLiM lithological map (Hartmann and Moosdorf, 2012) and GLHYMPS (Gleeson et al., 2011, 2014)

Hydraulic conductivity controls the rate at which groundwater flows through the aquifer materials and is primarily determined by the aquifer’s lithological characteristics. The gridded 5arcmin GLiM global lithological map (Hartmann and Moosdorf, 2012) is used to define the spatial distribution of 16 lithologies (Figure C1, Appendix). For each lithological category, we

210

obtain the corresponding permeability value from GLHYMPS; when there are multiple values (for subcategories) within one lithology type, we take their means based on the subcategory sample numbers. The standard deviation for each category is also obtained for the following sensitivity analysis in Section 2.4. The aggregated permeability data for each lithological type is shown in Table B1 (Appendix). The permeability is then converted to hydraulic conductivity as a direct model input. For permafrost regions (i.e., permafrost zonation index>0.5) (Gruber, 2012), we reduce K by one-order-of-magnitude by considering the combined effects of soil temperature, soil texture and freeze-thaw dynamics (Watanabe and Flury, 2008; Watanabe and Osada, 2016), although we note this is a strong assumption to ensure the model's numerical stability.

### 2.3.2 River Channel Properties (position, level, bottom elevation, riverbed drainage conductivity)

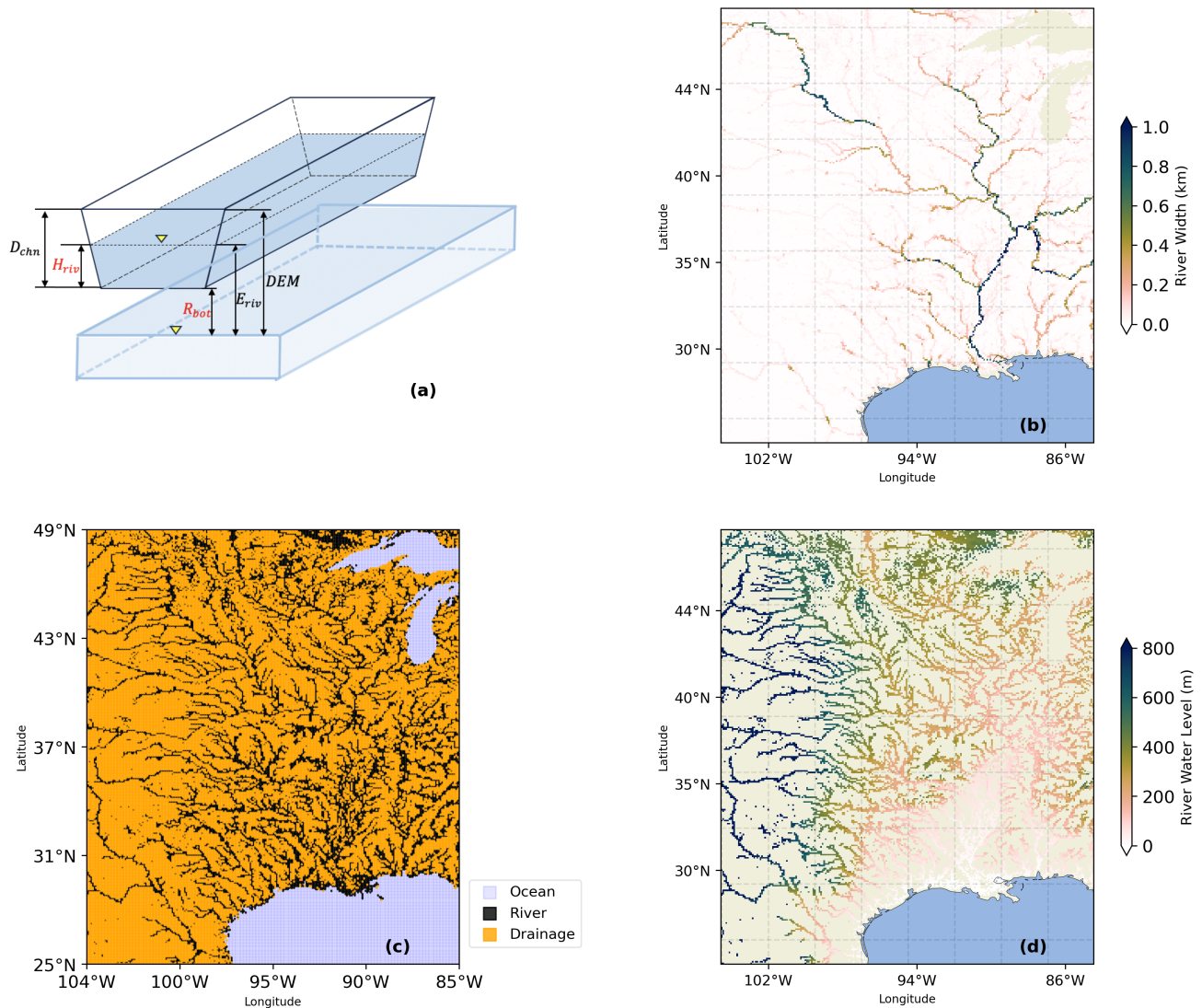
To investigate the river-aquifer exchanges, a river package (RIV) is used. The water flux exchanges are calculated based on the head difference between river channels and the aquifer cells, i.e., water leaks from the river channel to the aquifer when the river water level is higher than the groundwater head and vice versa, as:

$$Q_{flux} = c_{rb} \times (H_{riv} - h_{aq}) \quad (2)$$

Where,  $H_{riv}$  and  $h_{aq}$  refers to river water level (m) and groundwater head (m), respectively. When the groundwater table is below the river bottom, river bottom elevation ( $R_{bot}$ ) is used for  $h_{aq}$  to limit the maximum water flux exchanges.  $c_{rb}$  indicates the riverbed conductance ( $m^2d^{-1}$ ) and is calculated as:

$$c_{rb} = \frac{RIV_{wth} \times RIV_{len}}{r_{rb}} \quad (3)$$

Where,  $RIV_{wth}$  and  $RIV_{len}$  are the river channel width (m) and length (m), respectively, both of which are taken from (Yamazaki et al., 2011).  $r_{rb}$  is the riverbed resistance. In de Graaf et al. (2015), it is taken as 1 day. However, in our preliminary analyses we found the simulated head is rather sensitive to this parameter. Therefore, the appropriate value will be selected from several sensitivity experiments. See Section 2.4 for a detailed description.



**Figure 4.** Illustration of the groundwater model grid designations and river properties over the southern Mississippi river basin. (a) Schematic diagram of the river channel geometry.  $H_{riv}$  represents the river water level (unit: m) which serves as the input to calculate river-aquifer exchange; (b) Spatial distribution of river width (unit: km) from GWD-LR product (Yamazaki et al., 2014). Data over lake areas are not available; (c) Model designation of MODFLOW. Black, orange, and blue color represents river, drainage, and constant head grids, respectively; (d) Spatial distribution of river water levels (unit: m) calculated from Eq. (4).

We first use a combined satellite and empirical algorithm river width product GWD-LR to allocate the river grids in MODFLOW (Yamazaki et al., 2014). This product was constructed by applying the SRTM Water Body Database (SWBD) and the HydroSHEDS flow direction map, and shows high realism in representing river width for large river channels. To overcome its limitation in representing small rivers and overestimation of large rivers, we further constrained the results by

applying a power-law algorithm, as done in the latest version (v4.20) of the Hydrodynamic flood model CaMa-Flood (Yamazaki et al., 2011). See further description in Text S1 in Supplementary Materials. Because the river-aquifer exchange  
 245 can be negligible for small tributaries, we define river width larger than 10 m as river grids where water exchanges actually happen, similar to the criteria defined in de Graaf et al. (2015). An illustration of the river width result and the resulting river grid allocation in MODFLOW are shown in Figure 4(b) and (d).

Next,  $R_{bot}$  is calculated as the difference between land surface elevation (DEM) and river channel depth ( $D_{chn}$ ) (Figure 4(a)),  
 250 where the previous is taken from [30 arcsec](#) HydroSHEDS dataset (Lehner et al., 2008) [and aggregated to 5arcmin resolution using simple linear interpolation algorithm](#).  $D_{chn}$  is calculated based on the power-law algorithm as in CaMa-Flood model (Yamazaki et al. 2011) (Text S1 in Supplementary Materials).  $H_{riv}$  is then calculated as:

$$H_{riv} = R_{bot} + D_{riv} \quad (4)$$

Where,  $D_{riv}$  is the river water depth (m) and is calculated based on Manning's equation:

$$D_{riv} = \left( \frac{n \times Q_{chn}}{RIV_{wth} \times RIV_{slp}^{0.5}} \right)^{0.6} \quad (5)$$

Where,  $n$  is the Manning roughness coefficient and is taken as  $0.035 \text{ m}^{-1/3} \text{ s}^{-1}$ .  $RIV_{slp}$  refers to river channel slope (unitless) and is calculated as the ratio of the DEM difference between the current and next downstream river cells over the distance between the two cells. See (Oki and Sud, 1998) and (Yamazaki et al., 2009) for complete explanations about how the flow direction is decided and the distance between one cell and the next downstream cell is calculated.  $Q_{chn}$  refers to the river discharge ( $\text{m}^3/\text{s}$ ).  
 260 For the steady-state simulation in this study, it is calculated as 40yr mean of the monthly H08 simulation. See Figure 2 (b) – (d) for examples of the spatial distribution over southern Mississippi river basin, Indian Peninsula, and Yellow and Yangtze River basin in China.

### 2.3.3 Other Boundary Conditions (constant head, topography, drainage)

Unlike H08, MODFLOW requires land surface elevation data to calculate groundwater movement. We use DEM from  
 265 HydroSHEDS for this purpose. For all ocean grids, since the submarine flow is not our research focus, we set them as constant head (CHD) with the water level of 0 m, i.e., it can receive (release) unlimited water from (to) the terrestrial underground aquifer. We also do not separately consider evapotranspiration in the groundwater model because it is already included in the H08 simulation part. For small tributaries (river sequence number less than 10), since the water entering the aquifer system can be negligible, we apply the drainage package (DRN) to allow water to leave the groundwater system. When  $h_{aq}$  is above  
 270 a prescribed level, here set as DEM, water from the groundwater will form ponding areas and be removed from the aquifer system. The drainage rate is calculated based on land surface water conductance, calculated in the same form as Equation (2). No water flux exchange will happen when  $h_{aq}$  is below the drainage level (DEM). The allocation for DRN and CHD grids in MODFLOW is illustrated over an example region in Figure 4(c).

275 **Table 1.** Sensitivity experiment setting scenarios and the resulting groundwater head simulation statistics against observations.  
<sup>†</sup> Indicates the best-run experiment; ref for  $K$  indicates the mean hydrological conductivity from Gleeson et al. (2011); ref for  $Rch$  indicates the 40-year mean H08 recharge; ref for  $r_{rb}$  indicates 1 day. For the model and observation difference terms  $D_{mean}$  and  $D_{med}$ , positive values indicate the overall model head is shallower than observed head and vice versa.  $D_{std}$  is always positive; larger values indicate the overall simulated head deviates further from the observation.

|   | EXP                       | $K$                          | $Rch$                          | $r_{rb}$                        | $R_{cor}$   | $D_{mean}$ | $D_{med}$ | $D_{std}$ |
|---|---------------------------|------------------------------|--------------------------------|---------------------------------|-------------|------------|-----------|-----------|
| A | K0R0B0                    | ref                          | ref                            | ref                             | 0.67        | 452.79     | 294.53    | 494.67    |
|   | K1R0B0                    | +1 $\sigma$                  | ref                            | ref                             | 0.79        | 271.47     | 151.6     | 378.48    |
|   | K2R0B0                    | +2 $\sigma$                  | ref                            | ref                             | 0.88        | 34.29      | 33.14     | 255.29    |
|   | K0R1B0                    | ref                          | +0.5 $\sigma$                  | ref                             | 0.53        | 657.64     | 445.97    | 679.98    |
|   | K1R1B0                    | +1 $\sigma$                  | +0.5 $\sigma$                  | ref                             | 0.70        | 397.89     | 229.16    | 505.27    |
|   | K2R1B0                    | +2 $\sigma$                  | +0.5 $\sigma$                  | ref                             | 0.85        | 89.5       | 60.39     | 290.62    |
|   | K0R2B0                    | ref                          | -0.5 $\sigma$                  | ref                             | 0.80        | 240.37     | 133.58    | 334.19    |
|   | K1R2B0                    | +1 $\sigma$                  | -0.5 $\sigma$                  | ref                             | 0.85        | 123.08     | 63.22     | 283.06    |
|   | K2R2B0                    | +2 $\sigma$                  | -0.5 $\sigma$                  | ref                             | 0.83        | -68.92     | 2.58      | 297.93    |
| B | K0R0B1                    | ref                          | ref                            | $\times 0.1$                    | 0.95        | 90.81      | 65.27     | 168.24    |
|   | K1R0B1                    | +1 $\sigma$                  | ref                            | $\times 0.1$                    | 0.95        | 63.3       | 41.31     | 169.7     |
|   | K2R0B1                    | +2 $\sigma$                  | ref                            | $\times 0.1$                    | 0.93        | -23.99     | 5.71      | 200.46    |
|   | K0R1B1                    | ref                          | +0.5 $\sigma$                  | $\times 0.1$                    | 0.94        | 115.33     | 87.11     | 176.22    |
|   | K1R1B1                    | +1 $\sigma$                  | +0.5 $\sigma$                  | $\times 0.1$                    | 0.94        | 85.92      | 56.44     | 175.47    |
|   | K2R1B1                    | +2 $\sigma$                  | +0.5 $\sigma$                  | $\times 0.1$                    | 0.93        | 1.24       | 13.09     | 189.78    |
|   | K0R2B1                    | ref                          | -0.5 $\sigma$                  | $\times 0.1$                    | 0.95        | 57.91      | 40.62     | 165.09    |
|   | K1R2B1                    | +1 $\sigma$                  | -0.5 $\sigma$                  | $\times 0.1$                    | 0.94        | 20.71      | 22.24     | 179.68    |
|   | K2R2B1                    | +2 $\sigma$                  | -0.5 $\sigma$                  | $\times 0.1$                    | 0.90        | -76.58     | -6.22     | 247.33    |
| C | K0R0B2                    | ref                          | ref                            | $\times 0.01$                   | 0.95        | 47.82      | 23.73     | 161.55    |
|   | K1R0B2                    | +1 $\sigma$                  | ref                            | $\times 0.01$                   | 0.95        | 30.97      | 17.35     | 162.61    |
|   | K2R0B2                    | +2 $\sigma$                  | ref                            | $\times 0.01$                   | 0.93        | -31.18     | 0.98      | 193.91    |
|   | K0R1B2                    | ref                          | +0.5 $\sigma$                  | $\times 0.01$                   | 0.95        | 51.18      | 26.86     | 162.27    |
|   | K1R1B2                    | +1 $\sigma$                  | +0.5 $\sigma$                  | $\times 0.01$                   | 0.95        | 37.94      | 21.06     | 161.89    |
|   | <b>K2R1B2<sup>†</sup></b> | <b>+2<math>\sigma</math></b> | <b>+0.5<math>\sigma</math></b> | <b><math>\times 0.01</math></b> | <b>0.94</b> | -17.98     | 4.24      | 184.88    |
|   | K0R2B2                    | ref                          | -0.5 $\sigma$                  | $\times 0.01$                   | 0.95        | 36.95      | 19.35     | 161.82    |
|   | K1R2B2                    | +1 $\sigma$                  | -0.5 $\sigma$                  | $\times 0.01$                   | 0.95        | 10.59      | 11.78     | 172.13    |
|   | K2R2B2                    | +2 $\sigma$                  | -0.5 $\sigma$                  | $\times 0.01$                   | 0.92        | -51.92     | -4.33     | 211.04    |

280 **2.4 Local One-At-A-Time (OAT) Sensitivity Tests**

Since uncertainties in the groundwater recharge and key aquifer parameters (i.e., aquifer hydraulic conductivity and thickness) are reported to be high (Gleeson et al., 2011; Reinecke et al., 2019b, 2021; Wada et al., 2010), we conducted several sensitivity tests to ensure the robustness of the simulated steady-state groundwater head. Additionally, our preliminary analyses show that the river geometry parameters, such as riverbed resistance, can also play an important role in the resulting groundwater head simulation. Therefore, in total, we select 3 parameters, i.e., groundwater recharge  $RCH$ , aquifer hydraulic conductivity  $K$ , and

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riverbed resistance  $r_{rb}$ , for sensitivity analyses. The aquifer thickness  $D$  is not considered explicitly here because MODFLOW actually applies aquifer transmissivity ( $KD$ ) for simulation, therefore the effect can be implicitly reflected in the variation in  $K$ . We note that the analyses here are local One-at-A-Time (OAT) only and do not address interaction effects; they therefore fall short of full sensitivity analyses objectives (screening, ranking, mapping) (Pianosi et al., 2016). The more rigorous global sensitivity analyses, as in (Reinecke et al., 2019b), will be pursued in future investigations.

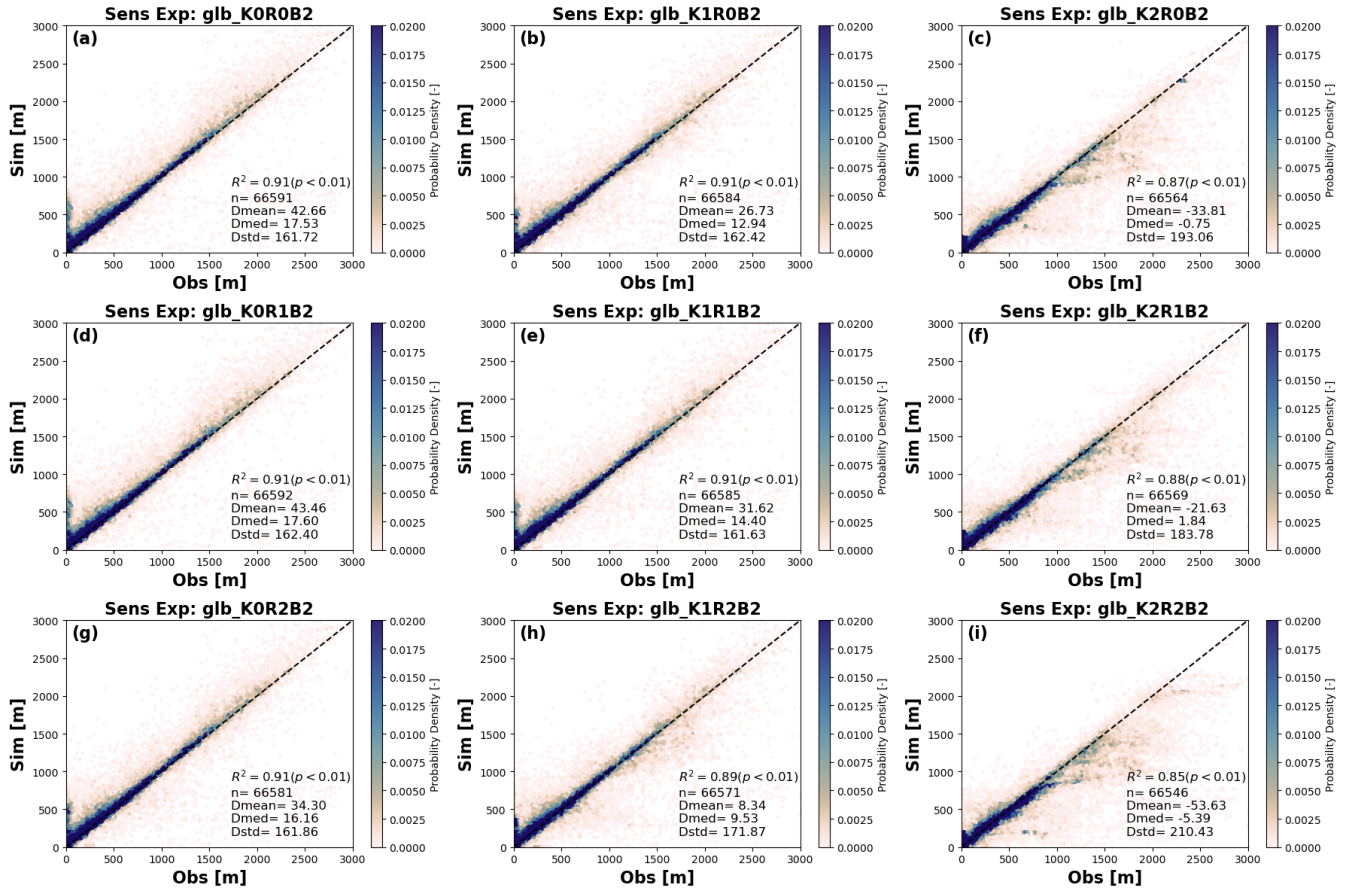
To maintain computational efficiency, for each parameter we did three sensitivity analyses. Together this results in 27 experiments in total (Table 1). We take K0R0B0 as the reference experiment (ref), and use Correlation Coefficient ( $R$ ), Mean, Median, and Standard Deviation of the difference between simulation and observation ( $Dmean$ ,  $Dmedian$ ,  $Dstd$ ) to evaluate the performance of each experiment against observations. For parameters of  $K$  and  $RCH$ , one and two standard deviations are added individually for each relevant experiment. The statistic for  $K$  is from Gleeson et al. (2011) directly, while for  $RCH$  it is calculated based on groundwater recharge from H08 monthly simulation output (1979.01 – 2019.12). Note that although the aquifer thickness data we use is for deep aquifers while Gleeson et al. (2011) only provides such information for the shallow, here we assume there is similarity in aquifer thickness statistics between the two layers, similar to the assumption in the derivation of the dataset we use. For  $RRD$ , because there is no global reference of how its statistics should look like, rather simplistic scale factors are applied, i.e., 0.1 day and 0.01 day are taken for different experiment settings.

## 2.5 Validation

To validate the simulation results, we use the equilibrium water table level observations from (Fan et al., 2013). In total, this dataset comprises 1,603,781 WTD readings, along with their corresponding elevation and geographic information. We then average the observations within the same model grid cell to mitigate the influence of the point-grid scale gaps as much as possible. We evaluate both the groundwater head and WTD, since the previous provides a more physically meaningful metric fundamental to groundwater flow dynamics (de Graaf et al. 2015), and the latter is more directly relevant to human and ecosystem water accessibility (Reinecke et al., 2024). The global scale model performance is evaluated first; Then, we evaluate the model behaviours in terms of different irrigation intensity and population density. Here, the irrigation intensity is represented by the global 10km irrigation area fraction map from (Siebert et al., 2015), and the population density is aggregated from the 1km global population dataset of year 2020 (<https://hub.worldpop.org/geodata/summary?id=80026>). Observations with invalid elevation readings are excluded. The total number of aggregated observations is 75,386.

In addition to the direct comparison between the simulated WTD against observations, we also compare the functional relationship between known drivers of groundwater flow (e.g., climatic aridity and topography) and WTD (Gleeson et al., 2021; Gmann et al., 2023; Reinecke et al., 2024; Wagener et al., 2022). The climatic aridity is calculated as the ratio of potential evapotranspiration to precipitation (PET/P, or Aridity Index (AI)), based on Global Land Data Assimilation System (GLDAS) Noah Land Surface Model L4 dataset (Rodell et al., 2007). AI>1 indicates the water-limited regime where atmospheric water

320 demand is larger than precipitation supply (dry climate in general); whereas  $AI < 1$  indicates the energy-limited regime where precipitation water supply can sufficiently meet the atmospheric water demand (humid climate in general). The spatial distribution of water- and energy-limited regions is shown in Figure C3. The topography effect is represented by slope, which is calculated based on HydroSHEDS DEM in the same way as described in Section 2.3.2. Moreover, we further compare our results with the ensemble mean WTD from four other global groundwater models, i.e., 5 arcmin GLOBGM (de Graaf et al., 2015, 2017), 30 arcsec GLOBGM (Verkaik et al., 2024), G3M (Reinecke et al., 2019a), and ASAP (Fan et al., 2013). The ensemble mean data is obtained directly from the model assessment paper in (Reinecke et al., 2024).



330 **Figure 5.** Scatterplots of the simulated groundwater head under different parameter settings (Experiment group C). Inserted texts refer to statistics between model simulation (y-axis) and observation from Fan et al. (2013) (x-axis).  $R^2$ ,  $n$ ,  $Dmean$ ,  $Dmed$ , and  $Dstd$  refers to coefficient of determination, sample size, mean, median and standard deviation of the simulation-observation difference.

### 3 Results and Discussion

#### 3.1 Validation of Simulated Groundwater Head And the Sensitivity to Hydrogeological Parameters

335 The statistics of groundwater head from each sensitivity experiment result against observations are shown in Table 1 and Figure 5. The simulation-observation correlation coefficient of groundwater head ranges between 0.66 and 0.95 across experiments ( $p < 0.01$ ), suggesting our model works reasonably well in simulating groundwater head regardless of the different parameter setting scenarios. However, the large difference of the absolute model-observation biases as represented by  $D_{mean}$ ,  $D_{median}$ ,  $D_{std}$  suggest that the accuracy of our simulated groundwater head is sensitive to  $RCH$ ,  $K$  and  $\mathcal{I}_{rb}$ .

340 The reference experiment where no adjustment on the two parameters is made shows the worst performance with three statistics of 452.76 m ( $D_{mean}$ ), 294.51 m ( $D_{med}$ ), and 494.59 m ( $D_{std}$ ), respectively (the lowest  $R$  as well, of 0.66). This means the simulated groundwater head is much shallower than the observations. This may be explained by the water balance at each grid cell: When  $K$  is low, the water exchange between adjacent cells is more difficult. With the amount of water entering each grid cell fixed (unchanged recharge) throughout the simulation, the slower water exchange between cells will result in more water

345 accumulation within the cells and therefore higher water levels.

The simulated groundwater head is more sensitive to  $K$  compared to other parameters. For instance, in Table 1, when comparing experiments with identical values of  $RCH$  and  $\mathcal{I}_{rb}$ , the simulation biases between experiments with different  $K$  values differ by several times, particularly when  $K$  is low. This is further seen in the spatial maps of model-observation bias

350 in Figures C4. The simulated groundwater head is more sensitive to  $K$  in shallow groundwater areas (blue and green coloured areas, western U.S., Amazon, Sahel, the southern-north Eurasia, etc.) than in areas with deeper water tables (orange and red coloured areas, Rocky and Andes mountains, Tibetan Plateau, etc.). This pattern is consistent with the findings of de Graaf et al. (2015). However, our model's sensitivity to  $K$  is notably higher than that reported by de Graaf et al. (2015) and Reinecke et al. (2019a,b). The Coefficient of Variation (CV) of the simulated heads exceeds 0.5 across most regions (not shown). We

355 attribute it to three primary reasons: First, the number of our sensitivity analyses is limited. This may result in amplified standard deviation from individual extreme cases. Second, the model is poorly converged toward equilibrium under low  $K$  scenarios, especially in shallow groundwater occurrence regions. As illustrated in Figure 5 (the first column), groundwater heads in many of these areas exceed the drainage level, resulting in surface ponding. This forces us to tune  $K$  more favourably toward higher values in the sensitivity analyses, whereas the very low  $K$  scenarios stay unexplored. Third, compared to

360 sensitivity analyses in Reinecke et al. (2019a), where only  $\pm 10\%$  perturbation on  $K$  is applied, our experiments feature a broader variability range of  $K$ .

The simulated head also shows sensitivity to groundwater recharge  $RCH$  and river bed conductance  $\mathcal{I}_{rb}$ , but the sensitivity is more evident under low  $K$  scenarios. For example, the bias differences among the K0R0B0, K0R1B0, and K0R2B0

365 experiments are significantly larger than those observed in the corresponding experiments within Group A (e.g., K1R0B0,

K1R1B0, and K1R2B0) (Table 1). Moreover, in comparison to the corresponding experiments in Group B and Group C, the differences among K0R0B0, K0R0B1, and K0R0B2 biases even show orders of magnitude. These findings indicate that  $K$  remains the dominant hydrogeological parameter controlling groundwater head. At the same time, they also suggest that groundwater–surface water interactions — particularly the role of rivers — become crucial in regulating groundwater level fluctuations when lateral groundwater flow into or out of the aquifer system is limited due to low permeability. As a result, the simulation performance gradually improves as  $K$  increases; The improvement is further seen when  $r_{rb}$  decreases (which means more rapid river-aquifer exchange). To ensure further analyses are based on simulation with the highest realism, we chose the experiment with the best performance against observations as the baseline run (i.e., K2R1B2) for analyses in the following context. We also note that the model's performance could be further improved if more suitable combinations of the parameters were used. This can be achieved through observation-based bias correction procedures such as PEST (Doherty et al. 2003) and SCE-UA (Duan et al. 1992; 1993; 1994). However, since applying these algorithms globally is particularly time-consuming and the concentration of this study is to test the feasibility the established framework, the statistics from the current best-run experiment are reasonable enough for the time being, therefore we will leave further model improvement in future work.

### **3.2 Validation of Simulated WTD And the Sensitivity to Hydrogeological Parameters**

The sensitivity of simulated WTD to the model's parameter settings does not follow the same way as the groundwater head (Table 2 and Figure 6 – Figure 7). Due to the small magnitude of WTD itself, an increasing of  $K$  yields only a marginal improvement in the median WTD bias ( $D_{med}$ ), while the bias in standard deviation ( $D_{std}$ ) increases significantly (K0R0B0, K1R0B0, K2R0B0). The mean bias ( $D_{mean}$ ) shows a U-shaped response: It decreases initially, but once  $K$  exceeds a threshold, the bias grows again with opposite sign. The WTD response to  $Rch$  and  $r_{rb}$  is also less sensitive than the groundwater head, with only minimal improvement of  $D_{med}$  and  $D_{mean}$ . However, the response directions are within expectation. An increase of  $Rch$  yields shallower simulated WTD (e.g., K0R0B2 vs K0R1B2), whereas an increase of  $r_{rb}$  produces deeper simulated WTD (i.e., the bias shifts toward zero or positive) by enhancing drainage to channels (e.g., K1R0B1 vs K1R0B2).

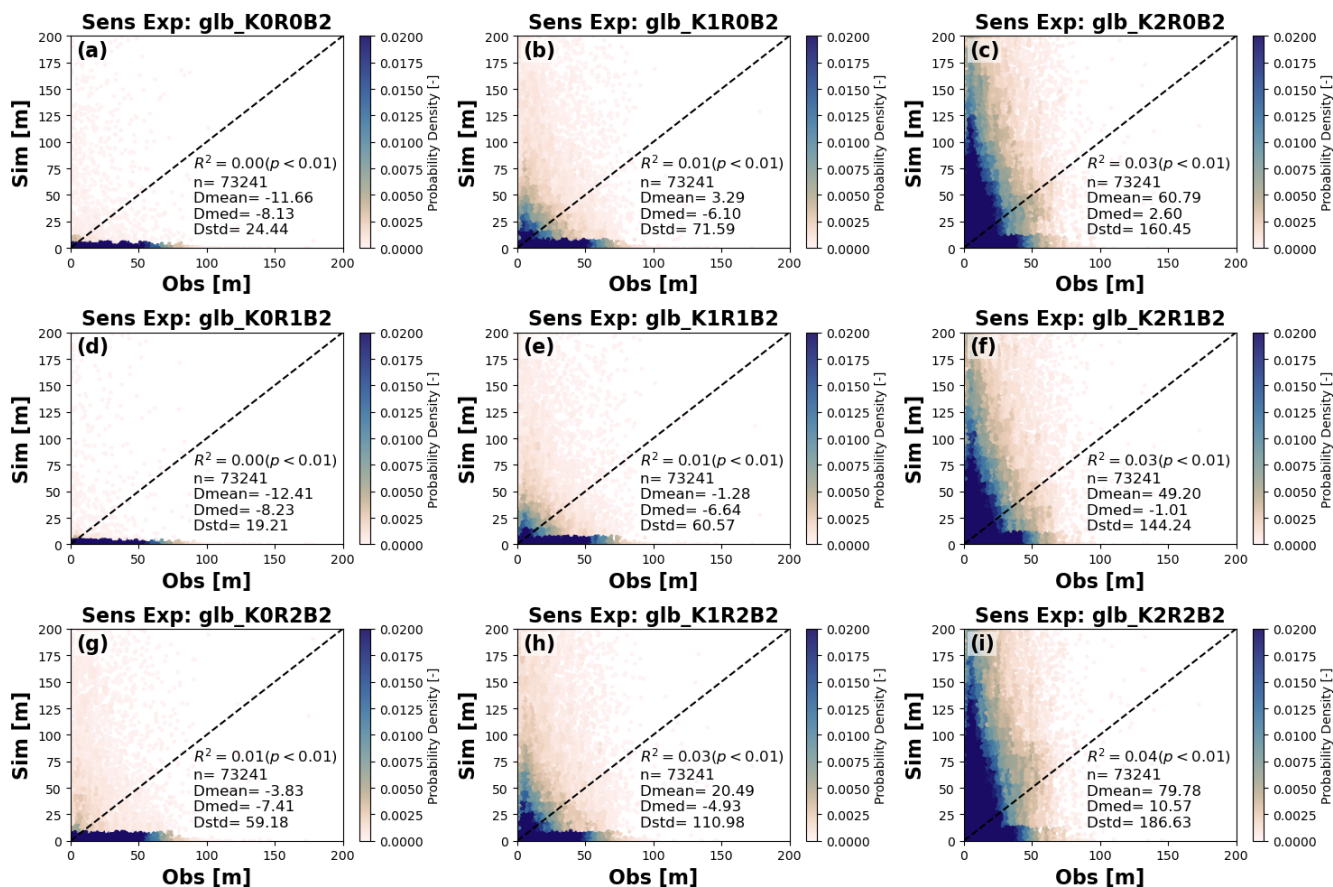
A notable difference from the groundwater head is that the simulated WTD compares poorly to observations in all experiment runs at the global scale ( $R_{cor} < 0.3$ ) (Table 2 and Figure 6). The same poor behavior is also observed in the ensemble mean WTD from Reinecke et al. (2024) (Figure 7), suggesting this is a common problem in all global groundwater models. In addition to the model structure and parameter biases, we attribute this to several possible reasons below. First, since WTD is calculated as DEM minus groundwater head, it inherits bias from both inputs, which may result in exacerbated biases that can be of the same order as WTD itself; Second, there is a spatiotemporal mismatch between simulated and observed WTD. The Fan et al. (2013) dataset aggregates measurements from different years, with ~90% of locations having only a single reading; Moreover, each monitoring well in Fan et al. (2013) is a snapshot of local conditions. WTD can be highly heterogeneous within a 10 km × 10 km grid cell, so a single well may poorly represent the grid mean.

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**Table 2.** Sensitivity experiment setting scenarios and the resulting WTD simulation statistics against observations. <sup>†</sup> Indicates the best-run experiment; ref for  $K$  indicates the mean hydrological conductivity from Gleeson et al. (2011); ref for  $Rch$  indicates the 40-year mean H08 recharge; ref for  $r_{rb}$  indicates 1 day. For the model and observation difference terms  $D_{mean}$  and  $D_{med}$ , positive values indicate the overall model head is deeper than observed head and vice versa.  $D_{std}$  is always positive; larger values indicate the overall simulated head deviates further from the observation.

|          | <u>EXP</u>                | <u>K</u>                     | <u>Rch</u>                     | <u><math>r_{rb}</math></u>      | <u><math>R_{cor}</math></u> | <u><math>D_{mean}</math></u> | <u><math>D_{med}</math></u> | <u><math>D_{std}</math></u> |
|----------|---------------------------|------------------------------|--------------------------------|---------------------------------|-----------------------------|------------------------------|-----------------------------|-----------------------------|
| <u>A</u> | <u>K0R0B0</u>             | <u>ref</u>                   | <u>ref</u>                     | <u>ref</u>                      | <u>0.03</u>                 | <u>-12.47</u>                | <u>-8.31</u>                | <u>20.44</u>                |
|          | <u>K1R0B0</u>             | <u>+1<math>\sigma</math></u> | <u>ref</u>                     | <u>ref</u>                      | <u>0.07</u>                 | <u>-5.65</u>                 | <u>-7.62</u>                | <u>53.31</u>                |
|          | <u>K2R0B0</u>             | <u>+2<math>\sigma</math></u> | <u>ref</u>                     | <u>ref</u>                      | <u>0.18</u>                 | <u>45.3</u>                  | <u>-3.68</u>                | <u>150.18</u>               |
|          | <u>K0R1B0</u>             | <u>ref</u>                   | <u>+0.5<math>\sigma</math></u> | <u>ref</u>                      | <u>0.02</u>                 | <u>-12.92</u>                | <u>-8.36</u>                | <u>16.3</u>                 |
|          | <u>K1R1B0</u>             | <u>+1<math>\sigma</math></u> | <u>+0.5<math>\sigma</math></u> | <u>ref</u>                      | <u>0.04</u>                 | <u>-9.49</u>                 | <u>-8.02</u>                | <u>39.05</u>                |
|          | <u>K2R1B0</u>             | <u>+2<math>\sigma</math></u> | <u>+0.5<math>\sigma</math></u> | <u>ref</u>                      | <u>0.14</u>                 | <u>24.49</u>                 | <u>-5.09</u>                | <u>117.97</u>               |
|          | <u>K0R2B0</u>             | <u>ref</u>                   | <u>-0.5<math>\sigma</math></u> | <u>ref</u>                      | <u>0.1</u>                  | <u>-2.74</u>                 | <u>-7.5</u>                 | <u>63.87</u>                |
|          | <u>K1R2B0</u>             | <u>+1<math>\sigma</math></u> | <u>-0.5<math>\sigma</math></u> | <u>ref</u>                      | <u>0.17</u>                 | <u>21.7</u>                  | <u>-5.92</u>                | <u>120.87</u>               |
|          | <u>K2R2B0</u>             | <u>+2<math>\sigma</math></u> | <u>-0.5<math>\sigma</math></u> | <u>ref</u>                      | <u>0.22</u>                 | <u>115.49</u>                | <u>2.67</u>                 | <u>258.59</u>               |
| <u>B</u> | <u>K0R0B1</u>             | <u>ref</u>                   | <u>ref</u>                     | <u><math>\times 0.1</math></u>  | <u>0.04</u>                 | <u>-11.85</u>                | <u>-8.23</u>                | <u>23.81</u>                |
|          | <u>K1R0B1</u>             | <u>+1<math>\sigma</math></u> | <u>ref</u>                     | <u><math>\times 0.1</math></u>  | <u>0.1</u>                  | <u>0.29</u>                  | <u>-6.71</u>                | <u>66.88</u>                |
|          | <u>K2R0B1</u>             | <u>+2<math>\sigma</math></u> | <u>ref</u>                     | <u><math>\times 0.1</math></u>  | <u>0.19</u>                 | <u>61.27</u>                 | <u>-0.67</u>                | <u>163.61</u>               |
|          | <u>K0R1B1</u>             | <u>ref</u>                   | <u>+0.5<math>\sigma</math></u> | <u><math>\times 0.1</math></u>  | <u>0.03</u>                 | <u>-12.56</u>                | <u>-8.3</u>                 | <u>18.61</u>                |
|          | <u>K1R1B1</u>             | <u>+1<math>\sigma</math></u> | <u>+0.5<math>\sigma</math></u> | <u><math>\times 0.1</math></u>  | <u>0.08</u>                 | <u>-4.64</u>                 | <u>-7.32</u>                | <u>54.08</u>                |
|          | <u>K2R1B1</u>             | <u>+2<math>\sigma</math></u> | <u>+0.5<math>\sigma</math></u> | <u><math>\times 0.1</math></u>  | <u>0.17</u>                 | <u>43.19</u>                 | <u>-2.72</u>                | <u>139.33</u>               |
|          | <u>K0R2B1</u>             | <u>ref</u>                   | <u>-0.5<math>\sigma</math></u> | <u><math>\times 0.1</math></u>  | <u>0.09</u>                 | <u>-3.09</u>                 | <u>-7.44</u>                | <u>62.45</u>                |
|          | <u>K1R2B1</u>             | <u>+1<math>\sigma</math></u> | <u>-0.5<math>\sigma</math></u> | <u><math>\times 0.1</math></u>  | <u>0.17</u>                 | <u>24.42</u>                 | <u>-5.18</u>                | <u>122.84</u>               |
|          | <u>K2R2B1</u>             | <u>+2<math>\sigma</math></u> | <u>-0.5<math>\sigma</math></u> | <u><math>\times 0.1</math></u>  | <u>0.22</u>                 | <u>106.1</u>                 | <u>13.76</u>                | <u>228.28</u>               |
| <u>C</u> | <u>K0R0B2</u>             | <u>ref</u>                   | <u>ref</u>                     | <u><math>\times 0.01</math></u> | <u>0.04</u>                 | <u>-11.66</u>                | <u>-8.13</u>                | <u>24.44</u>                |
|          | <u>K1R0B2<sup>†</sup></u> | <u>+1<math>\sigma</math></u> | <u>ref</u>                     | <u><math>\times 0.01</math></u> | <u>0.11</u>                 | <u>3.29</u>                  | <u>-6.1</u>                 | <u>71.59</u>                |
|          | <u>K2R0B2</u>             | <u>+2<math>\sigma</math></u> | <u>ref</u>                     | <u><math>\times 0.01</math></u> | <u>0.18</u>                 | <u>60.8</u>                  | <u>2.6</u>                  | <u>160.45</u>               |
|          | <u>K0R1B2</u>             | <u>ref</u>                   | <u>+0.5<math>\sigma</math></u> | <u><math>\times 0.01</math></u> | <u>0.03</u>                 | <u>-12.41</u>                | <u>-8.23</u>                | <u>19.21</u>                |
|          | <u>K1R1B2</u>             | <u>+1<math>\sigma</math></u> | <u>+0.5<math>\sigma</math></u> | <u><math>\times 0.01</math></u> | <u>0.09</u>                 | <u>-1.28</u>                 | <u>-6.64</u>                | <u>60.57</u>                |
|          | <u>K2R1B2</u>             | <u>+2<math>\sigma</math></u> | <u>+0.5<math>\sigma</math></u> | <u><math>\times 0.01</math></u> | <u>0.18</u>                 | <u>49.2</u>                  | <u>-1.01</u>                | <u>144.24</u>               |
|          | <u>K0R2B2</u>             | <u>ref</u>                   | <u>-0.5<math>\sigma</math></u> | <u><math>\times 0.01</math></u> | <u>0.09</u>                 | <u>-3.83</u>                 | <u>-7.41</u>                | <u>59.18</u>                |
|          | <u>K1R2B2</u>             | <u>+1<math>\sigma</math></u> | <u>-0.5<math>\sigma</math></u> | <u><math>\times 0.01</math></u> | <u>0.16</u>                 | <u>20.49</u>                 | <u>-4.93</u>                | <u>110.98</u>               |
|          | <u>K2R2B2</u>             | <u>+2<math>\sigma</math></u> | <u>-0.5<math>\sigma</math></u> | <u><math>\times 0.01</math></u> | <u>0.19</u>                 | <u>79.78</u>                 | <u>10.57</u>                | <u>186.63</u>               |

405



410 **Figure 6.** Similar to Figure 5 but for WTD.

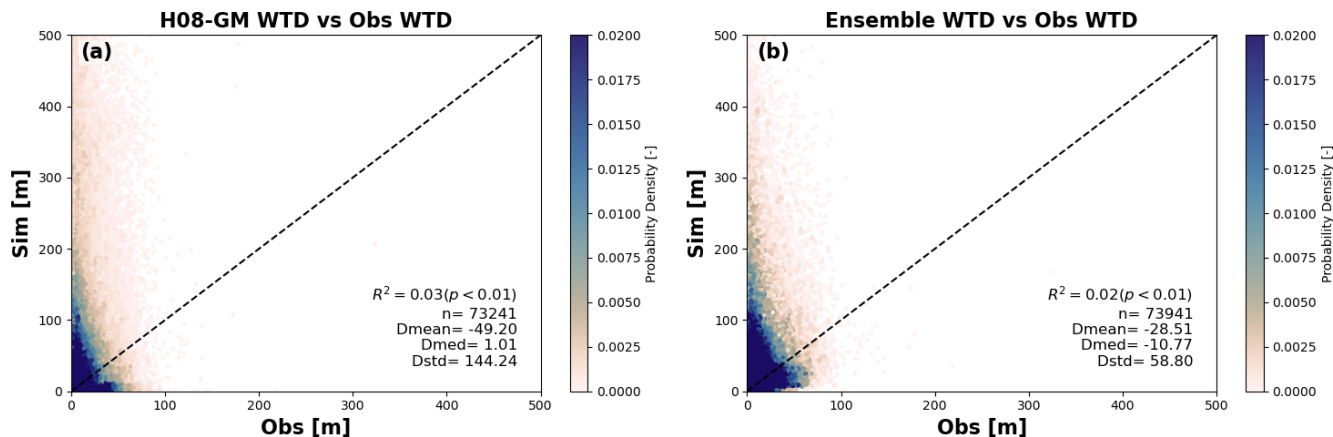
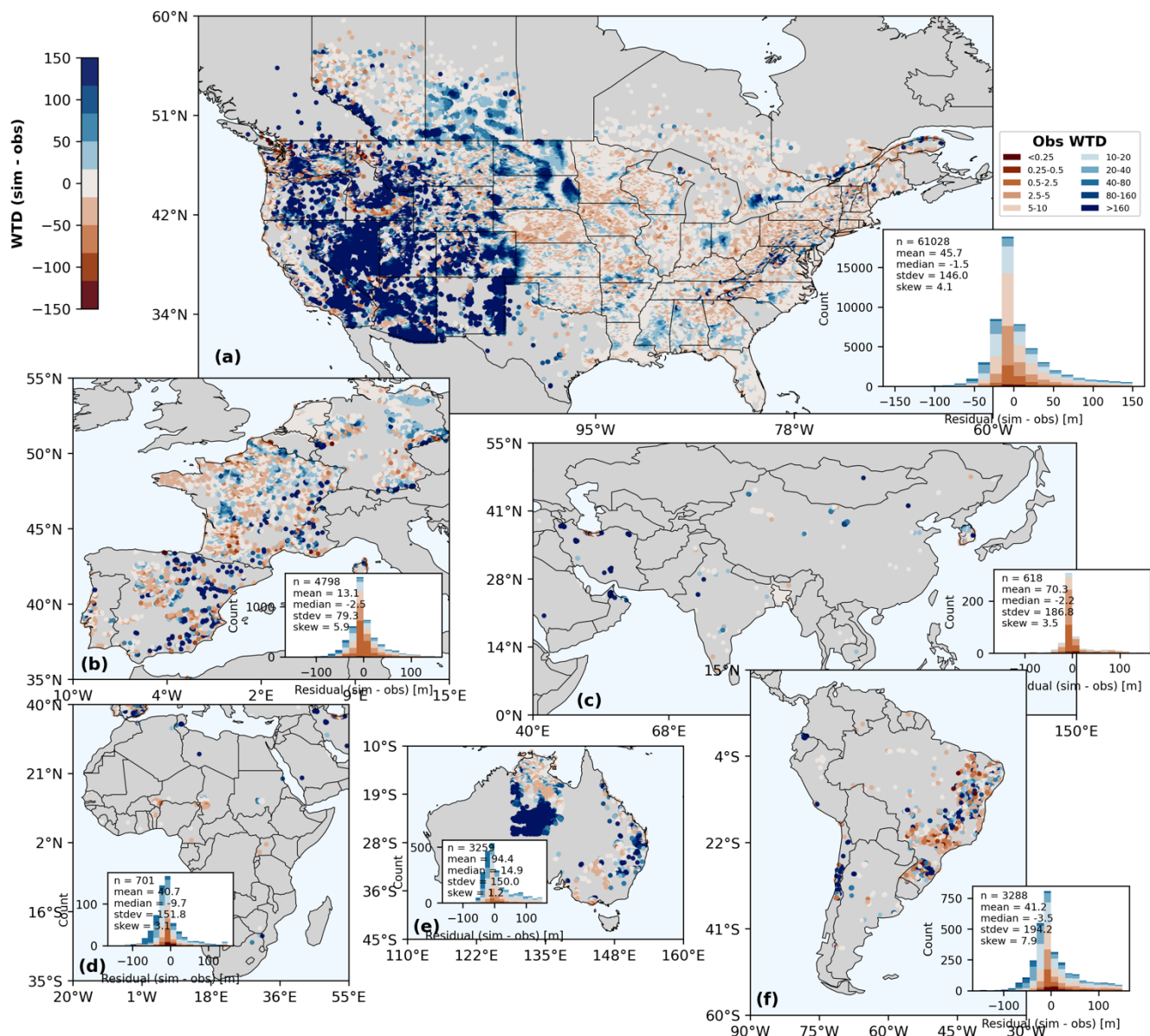


Figure 7 Scatterplots of the simulated WTD against observations. WTD simulation in (a) is from H08-GM (experiment K2R1B2); WTD simulation in (b) is from ensemble mean in Reinecke et al. (2024).  $R^2$ ,  $n$ ,  $Dmean$ ,  $Dmed$ , and  $Dstd$  refers to coefficient of determination, sample size, mean, median and standard deviation of the simulation-observation difference.

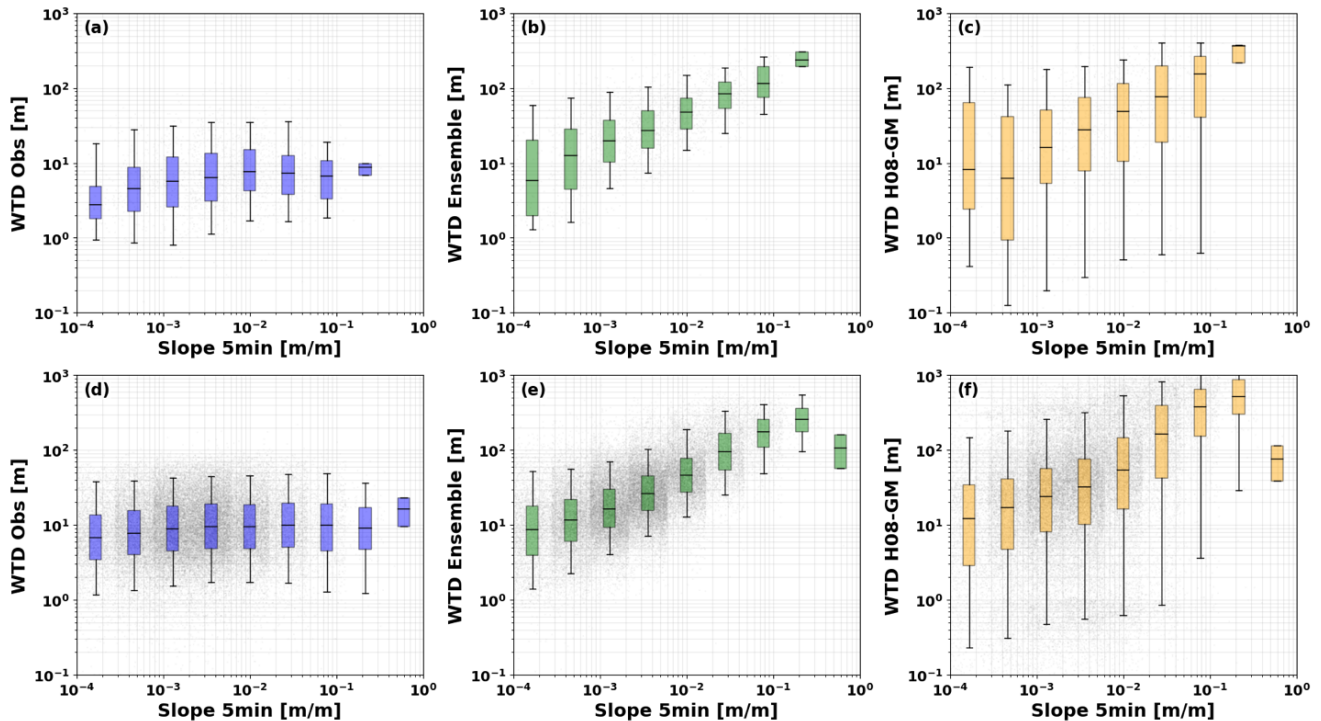
To investigate where the large WTD biases are presented, in Figure 8 we show the spatial maps as well as statistics of the model-observation biases of WTD from the best performance run over each continent. For North America where the highest observational density is presented, the model biases show a slightly left-skewed normal distribution. Approximately 3.9% of the analysed grid cells show biases within  $\pm 1$  m, 44.0% within  $\pm 10$  m, and 78.4% within  $\pm 50$  m. These grids are mostly located in the plain-dominated central and south-eastern U.S. The grid cells with large model-observation biases are distributed mostly over the mountainous areas but in a bimodal way. In the western U.S., the model tends to underestimate the groundwater head, whereas in the East the model tends to overestimate it. This can possibly be attributed to the uncertainty in aquifer properties, as well as the model's limitation in dealing with sharp groundwater head changes in mountainous areas. The topography in the western United States is comparatively higher, and the aquifer thickness is quite shallow (Figure 3(a)). The western mountainous areas mainly serve as the divergence region once it receives water from surface recharge. That is, the water will quickly move to adjacent lowlands due to the steep groundwater head gradient. The East, although also elevated, in fact serves as the convergence region due to the deeper aquifer thickness (Figure 3(a)). Over these areas of steep topographic gradient, the model simulation could become quite sensitive to the aquifer hydraulic conductivity setting. A large  $K$  scenario could possibly cause accelerated flow rate (therefore more water loss) in the West. On the contrary, a small  $K$  scenario would result in an overestimation of groundwater head in the West, as shown in Figure C5, where the bias is shown for the experiments glb\_K1R1B2, respectively. The polarity of biases is rather robust to  $K$  scenarios over other areas. Similar bias distribution is observed for other continents as well. For mountainous regions in the Alps and Brazilian Highlands, the model biases are quite pronounced; whereas for flatter areas such as the Netherlands and Northern Germany in Europe, Northern China Plain and Bangladesh in Asia, Amazon in South America, the model biases are minimal. Nonetheless, we note that the observations in Fan et al. (2013) inevitably embed the influence of human activity, whereas our model simulation is purely a natural run. The simulated groundwater level should be deeper than the current natural run if human water withdrawal were taken into account. This could lead to model-observation gap be skewed: Where the model head is higher than the observations (shallower WTD), the model-observation gap is exaggerated; where the model head is lower than the observations (deeper WTD), the gap is underestimated. The readers should bear this limitation in mind when interpreting the validation results.



**Figure 8.** Validation of simulated WTD against observations over each continent: (a) North America; (b) Europe; (c) Asia; (d) Africa; (e) Australia; and (f) South America. Grid cells are masked when either variable is marked as missing value. The missing values mainly concentrate in western Australia (e), which results in a sharp edge in the centre of this region. The inset panels are histograms of the model–observation head residuals ( $h - h_o$ ) over each continent, with bar heights showing the count of sample pairs; the overlaid text annotations indicate the statistics of that residual distribution (mean, median, standard deviation, skewness).

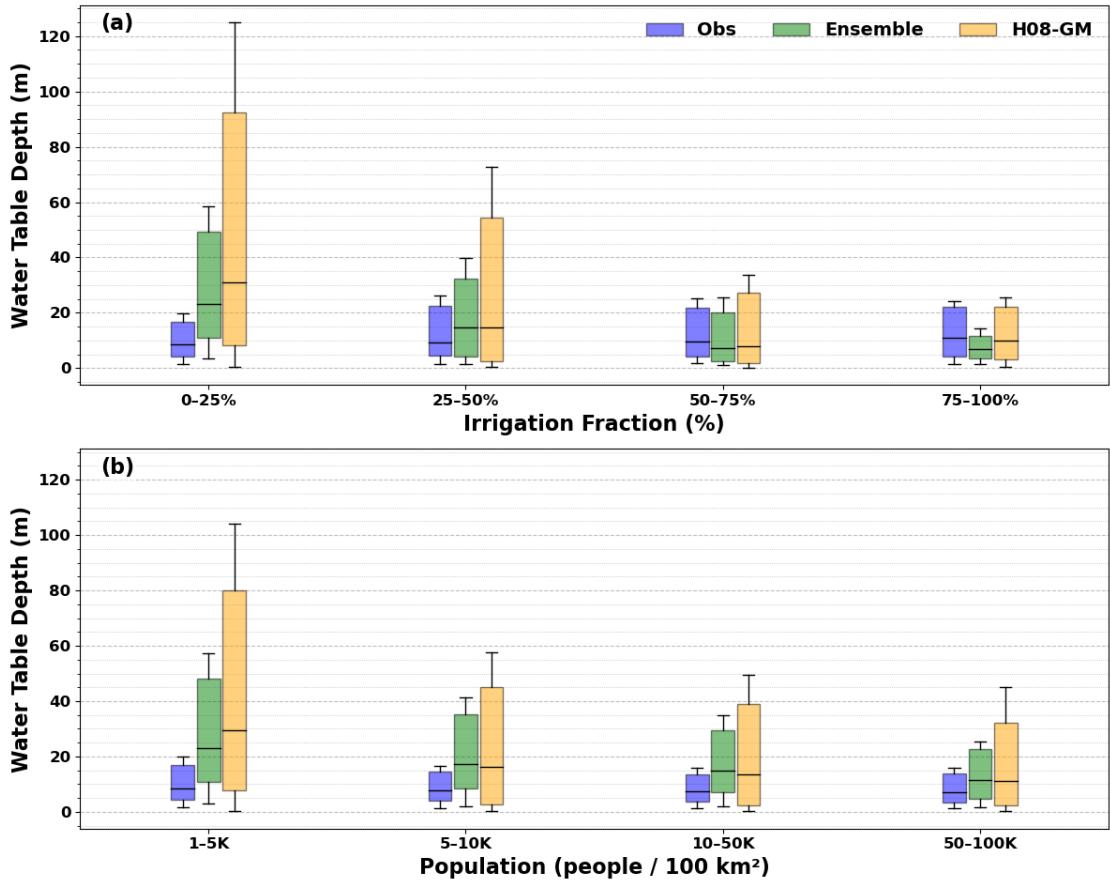
To further investigate the climate and topography effects on WTD, we also show the WTD-slope relationship under water-limited and energy-limited regimes respectively (Figure 9). Consistent to our previous finding, in areas with smaller slope (e.g., below  $10^{-3} \text{ m m}^{-1}$ ), the H08-GM simulated WTD (Figure 9, c and f) compares more closely to the observations (Figure 9, a and b). As the slope becomes steeper, the model-observation gap increases. The ensemble mean of Reinecke et al. (2024) shows a similar pattern but a narrower spread within slope bins, likely reflecting two ensemble members that simulate systematically shallower WTD. The observed WTD is slightly deeper in water-limited regions than in energy-limited regions. The model captures this contrast, though the model-observation discrepancy is also modestly larger.

Since the flatter regions are often located with large cities and extensive human water use activities such as agriculture. We also evaluated the model performance of WTD in terms of cultivation and population density. Figure 10 shows that the simulated WTD compares reasonably well to observations in highly cultivated and populated areas. In regions with irrigation area fraction higher than 50% and population higher than 10,000/100km<sup>2</sup>, both H08-GM and the ensemble-mean from Reinecke et al. (2024) compare closely to observations in terms of median and the 25th–75th percentiles. The ensemble-mean shows shallower WTD in regions with irrigation area fraction higher than 75%, while both H08-GM and ensemble-mean tend to overestimate WTD in highly populated areas. The global and category-specific validations indicate that H08-GM, as well as other global groundwater models, is most suitable for applications in densely populated, irrigation-intensive regions, which is important for investigating human - water interactions in global water cycle.



475

Figure 9. WTD versus grid-scale slope binned on a logarithmic x-axis. Panels (a–c) show energy-limited regions; panels (d–f) show water-limited regions. Columns: (a,d) observations (blue), (b,e) ensemble products (green), and (c,f) H08-GM (orange). For each slope bin, boxplots summarize the WTD distribution (line = median; box = 25<sup>th</sup> and 75<sup>th</sup> interquartile range; whiskers indicate spread; gray dots, where shown, are individual samples). See Figure C3 for the spatial map of water-limited and energy-limited regions.



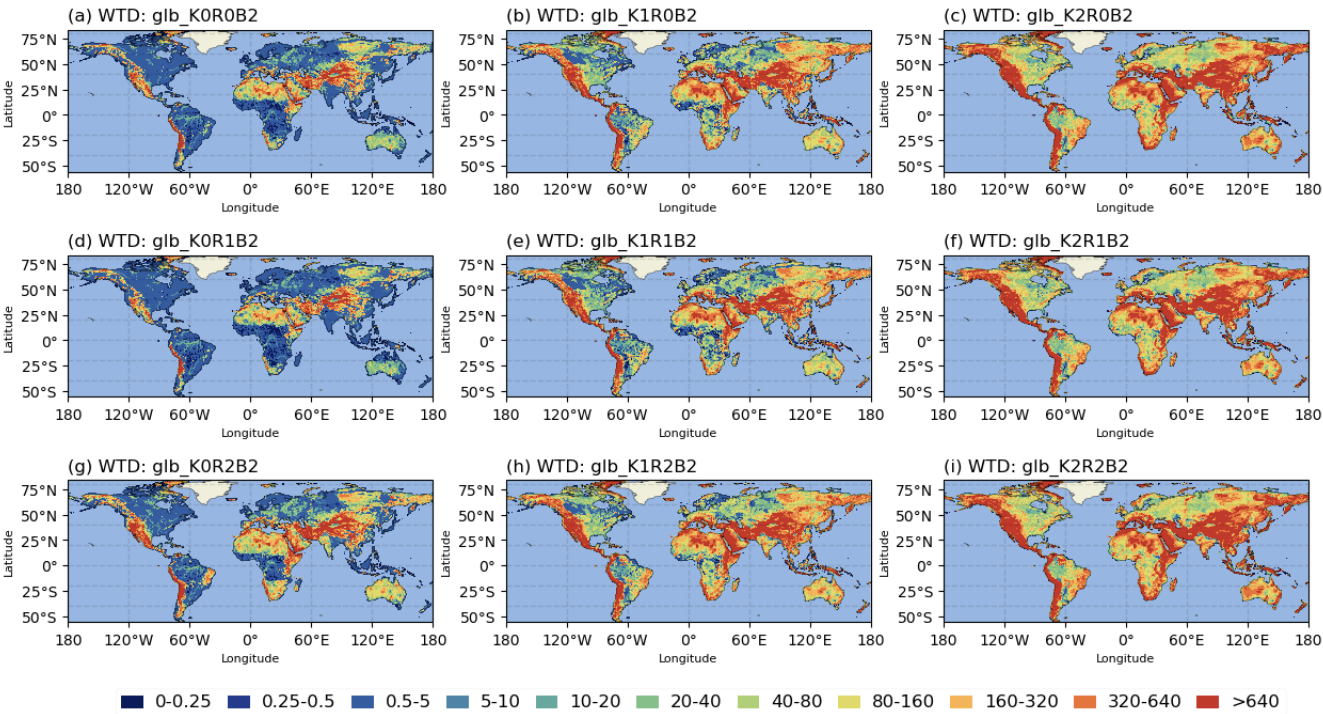
480

Figure 10. WTD classified by irrigation area fraction and population density. (a) Bins of irrigated-area fraction: 0–25%, 25–50%, 50–75%, 75–100%. (b) Bins of population density (people per 100 km<sup>2</sup>): 1–5K, 5–10K, 10–50K, 50–100K. Colors: observations from Fan et al. (2013) (blue), ensemble mean from Reinecke et al. (2024) (green), H08-GM (orange). For each bin, boxplots show the median (line) and 25<sup>th</sup> and 75<sup>th</sup> interquartile range (box); whiskers indicate spread.

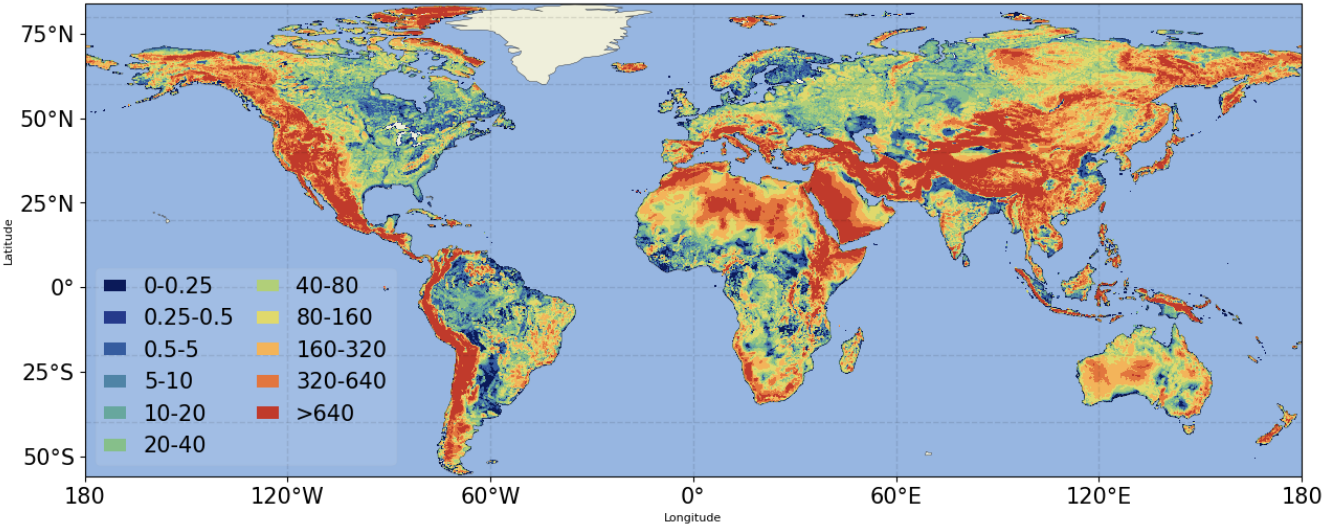
### 3.3 Global Steady-state Groundwater WTD Maps

To investigate the spatial pattern of the simulated WTD from H08-GM, we illustrate the global WTD maps from all experiment runs in Figure 11 and Figure C6 – C7. Consistent to what has been observed in Section 3.2, the simulated WTD is more sensitive to hydrologic conductivity than the other two parameters,  $Rch$  and  $r_{rb}$ , e.g., the colour contrast from left to right of each row is much clearer than that from top to bottom of each column (Figure 12). The sensitivity seems to be higher in humid and flat regions, but this may be a visualization artifact influenced by the color-scale choice.

In Figure 12 we also present the global steady-state map of WTD from the best-run experiment from H08-GM (chosen as K2R0B2 by considering model-observation statistics of both groundwater head and WTD). The global WTD distribution shows a clear spatial gradient: the groundwater levels are considerably deep over the mountainous and arid regions whereas they remain shallow in flat and humid areas. The result corresponds well with previous studies as in Fan et al. (2013), de Graaf et al. (2015), and Reinecke et al. (2019a) and can be explained in the way that the mountains often serve as the divergence place for water to flow out due to their steep topography, and in arid regions the groundwater recharge from the surface is quite limited (vice versa). However, our result corresponds closer to the earlier works of de Graaf et al. (2015) and Reinecke et al. (2019a) than that of Fan et al. (2013) which is derived primarily from the observations in which the groundwater depth is up to 100m. Although partly applied the parameterization scheme of aquifer thickness (i.e., the  $e$ -folding factor) in Fan et al. (2013), the model framework in Reinecke et al. (2019a) largely follows MODFLOW. As such, the large gaps between the numerical and data-driven models here indicate careful comparison in model framework and parameterization schemes is needed to achieve cohesion in the two types of large-scale groundwater modelling studies.



**Figure 11.** Spatial maps of the simulated WTD to under different parameter settings (Experiment group C).



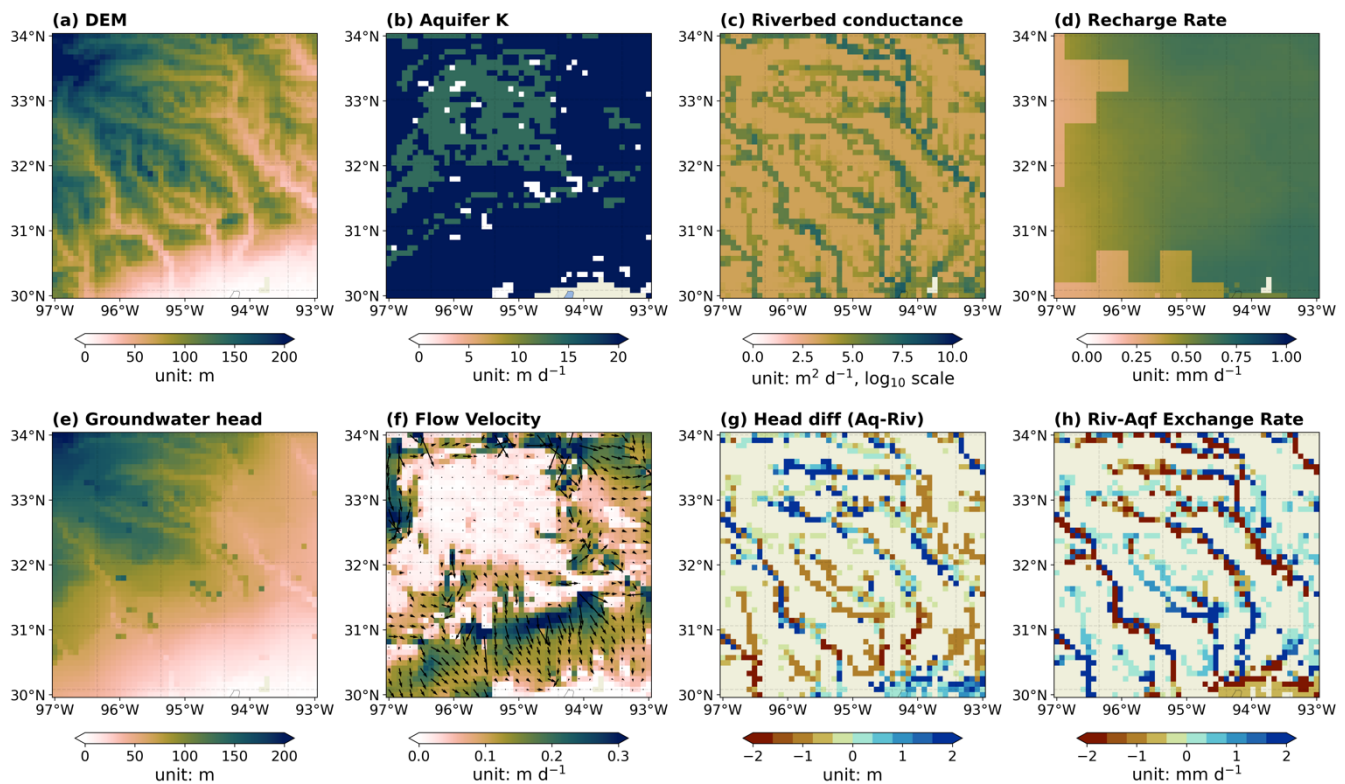
**Figure 12.** Global best-run steady-state Water Table Depth (WTD, meters below land surface).

### 3.4 Mechanisms Controlling Groundwater Distribution and Flow Dynamics

To help further understand the groundwater flow dynamics, in Figure 13 we present an analysis of the lower Mississippi River basin to showcase the complex interplays between groundwater flow and topography, aquifer and river hydrogeologic properties, and surface recharge. The high similarity between the spatial pattern of groundwater head and DEM (Figure 13, a and e), as well as the flow direction and velocity map (Figure 13, f), confirms the general principle that groundwater closely follows topography. However, the local characteristics in the north-western part of this region, where steep topography exists but limited groundwater flow present (shown as the low groundwater flow velocity and much deeper groundwater head compared to DEM), suggest aquifer properties that control the hydraulic gradient also play important roles in determining the water movement. The aquifer's  $K$  in these areas is much lower than in the other regions (Figure 13, b), which confirms this finding.

The role of surface recharge is only marginal in this case due to the strong heterogeneity of topography, but is evident in arid climate zones such as in Yellow River basin in Figure C8. The groundwater head distribution is jointly determined by both topography and recharge – in the northwest part of this region, although the topographic gradient is also sharp (Figure C9(a)), the recharge is quite limited (below  $0.1 \text{ mm d}^{-1}$ ) compared to the southeast high area. Consequently, the groundwater head over the low recharge area is consistently low and shows less spatial heterogeneity, regardless of the topographic gradient which plays an important role in the more humid climate regions.

River properties also play important roles in shaping the local characteristics of the groundwater head distribution through river-aquifer water exchanges. Although the groundwater head in Figure 13 appears much smoother than the topography map, we still observe the traces of major river channels, highlighting the significant role of river-aquifer exchange in determining the spatial distribution of the groundwater head. The topography pattern in Figure 13(a) aligns well with the river-aquifer water exchange rate pattern in Figure 13(h): Where there exists substantial water from groundwater to river (red colour), the groundwater head is lower than that in adjacent cells; Whereas where river supplies additional water to the aquifer (blue colour), the groundwater head is higher than the neighbour grid cells. The river-aquifer exchange rate is further determined by riverbed conductance and head difference between groundwater and river water channels. Most grid cells with higher water exchange rate (either positive or negative) tend to have higher riverbed conductance and larger river-groundwater head difference, which corresponds well to the governing equation in Eq. (1). Such river-aquifer exchange pattern is more evident in the Amazon River basins (Figure C9).



**Figure 13.** Spatial distribution of key parameters controlling groundwater flow and the resulting surface-groundwater interactions. The study region is in lower Mississippi River Basin. Panels (a–d) show model input variables, including the digital elevation model (DEM) (a), aquifer hydraulic conductivity (K) (b), riverbed conductance (c), and groundwater recharge rate (d). Panels (e–h) present simulated outputs, including groundwater head (e), lateral flow velocity with flow directions (f), head difference between aquifer and river (g), and river–aquifer exchange rate (h), where positive values indicate losing rivers (water from rivers to aquifers) and negative values indicate gaining rivers (water from aquifers to rivers). Rectangular in white colour does not indicate missing values but extremely small values.

### 3.5 Global Net Groundwater Lateral Flows Estimated from H08-GM

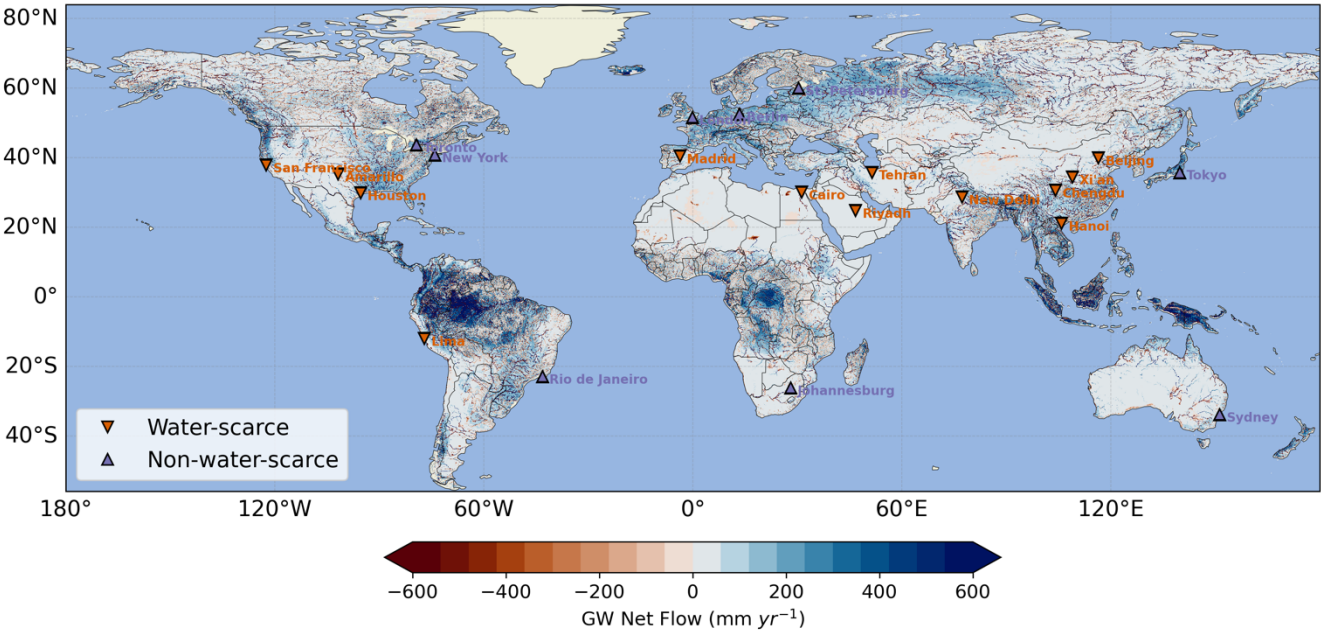
As one motivation for developing the H08-GM model is to evaluate the compensating effect of groundwater lateral flow on urban water availability, in Figure 14 we also show the 41-year mean steady-state annual net lateral flow flux map. The net lateral flow flux here is calculated directly as flux convergence at each grid cell, and represents the net water fluxes a certain grid cell can gain or lose from the groundwater movement. The positive values indicate net inflow or groundwater “importers” (de Graaf and Stahl, 2022). Conversely, the negative values of the sum indicate net outflow or groundwater “exporters”. The global pattern of groundwater lateral flow from the best-run simulation corresponds reasonably well with previous studies (Akhter et al., 2025; de Graaf and Stahl, 2022; Krakauer et al., 2014; Miguez-Macho and Fan, 2025). The highest net lateral flow distributed in Amazon, highlighting its critical role in sustaining the ecosystem in its neighbourhood. Moderately high

flows are observed in the eastern United States, Central Africa, north-western Eurasia, and the tropical islands. Amazon serves as the world's largest groundwater exporters.

560 In terms of magnitude, our results compare more closely with those of (de Graaf and Stahl, 2022), reaching over 600 mm yr<sup>-1</sup> in high flow regions. However, this is considerably higher than the 100 mm yr<sup>-1</sup> reported by (Krakauer et al., 2014), while much lower than the 1000 mm yr<sup>-1</sup> maximum estimated in (Miguez-Macho and Fan, 2025). Two possible reasons may explain this discrepancy. The first is the scale-dependence of lateral flow flux. Previous studies have shown that simulated groundwater lateral flow flux tends to increase as the spatial resolution of a model becomes finer (Akhter et al., 2025; Krakauer et al., 2014).

565 The results of (Miguez-Macho and Fan, 2025), estimated at a 1 km resolution, therefore represent a finer-scale simulation that naturally yields higher flow magnitudes. Second, the estimated flow flux is strongly influenced by the model's parameter settings, especially the hydraulic conductivity. When relatively small hydraulic conductivity values are used, the flux magnitude decreases significantly (Figure C10, left column). However, even under the lowest hydraulic conductivity scenario, the ratio of net lateral flow flux to groundwater recharge can still be high, suggesting the lateral groundwater flow plays a

570 nonnegligible role in the grid cell's water budget.



**Figure 14.** Global distribution of simulated net lateral groundwater flow (mm yr<sup>-1</sup>) derived from the coupled H08-MODFLOW model. Overlaid on the map are major global cities categorized into water-scarce (orange inverted triangles) and non-water-scarce (black upward triangles) groups (Mekonnen and Hoekstra, 2016). Positive values indicate net groundwater flow “exporters” and negative values indicate “importers”.

The net lateral flow results highlight the important role of the compensating effects of groundwater flows in sustaining regional water budgets, which should be considered but have long been downplayed in GWMs. In Figure 14 and Figure 15 we also overlaid several megacities in the world, classified as water-scarce and non-water-scarce categories based on Mekonnen and Hoekstra (2016). It is clearly observed that the groundwater lateral flow effect, whether it be importers or exporters, is quite considerable in some water-scarce cities, e.g., Beijing, Houston, etc., with net groundwater flow higher than 100 mm yr<sup>-1</sup>. For other non-water-scarce cities as Tokyo, Berlin, New York, etc., the net groundwater flow is even higher, approaching 200 mm yr<sup>-1</sup>. The large amount of net groundwater flow must be explicitly incorporated into current water resource management models: Neglecting “exporters” effect may underestimate the city’s water stress while neglecting “importers” effect may tend to overestimate it. However, we note that this analysis is only an exploratory illustration to show that our model has potential for the representation of megacities in GWMs. The operational city-scale groundwater lateral inflow/outflow assessments require more robust analyses to address the model’s spatial resolution, the uncertainties in aquifer hydraulic conductivity, riverbed conductance, and other boundary conditions.

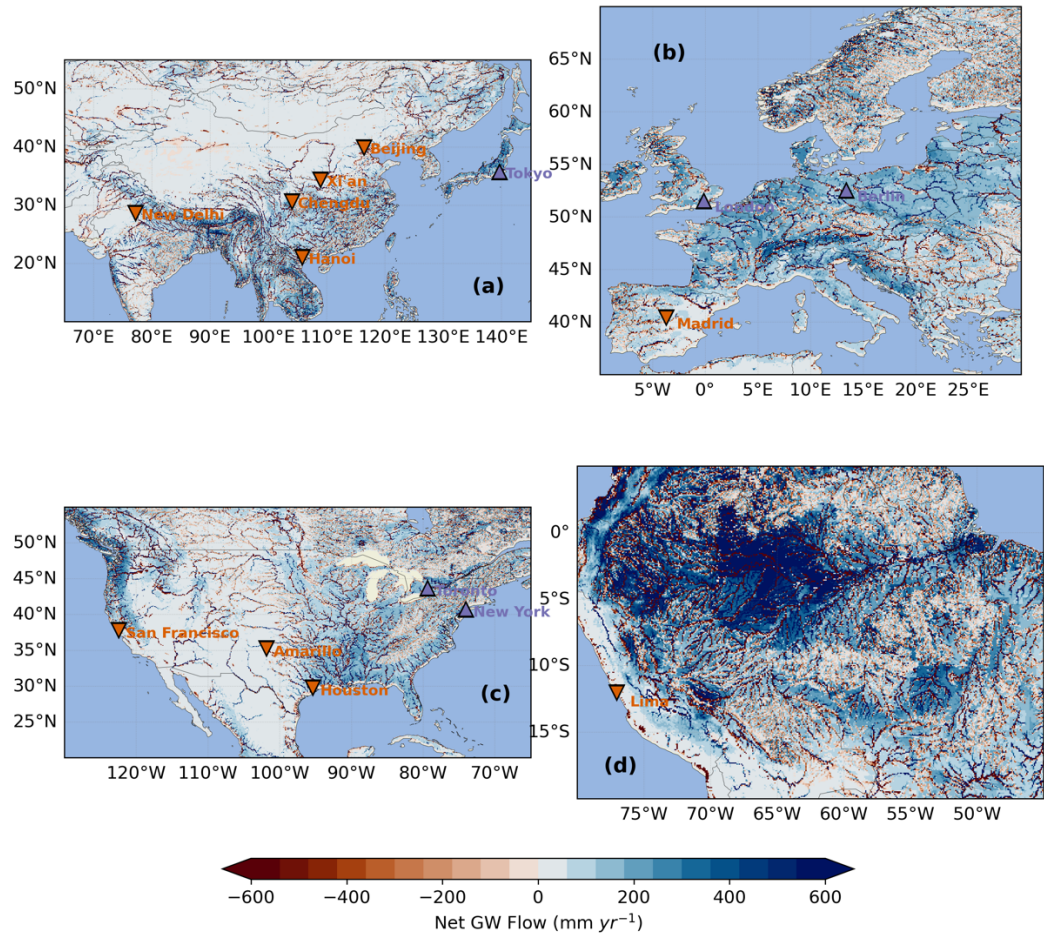


Figure 15. Same as Figure 14, but zoomed in for different regions.

## 4 Conclusions

This study has presented a high-resolution global groundwater model H08-GM by incorporating various global hydrogeological datasets. Sensitivity analyses have been conducted on several key model parameters in order to produce the best model performance in simulating the steady-state groundwater levels. Validated against approximately 1.6 million in-situ observations, the results show that the model with optimal parameter settings performs well at the global scale with  $R$  of 0.93. The model performs particularly well over plain areas where large cities and extensive human activities are located, with groundwater head biases within  $\pm 25\text{m}$ , but the model tends to show larger biases over mountainous regions, possibly due to the uncertainty in aquifer properties as well as model's limitation in dealing with sharp groundwater head changes. Our results demonstrate that the coupled H08-GM modelling framework can effectively reproduce realistic spatial gradients of groundwater heads, with deeper groundwater tables in mountainous areas from shallower groundwater in plains. Such a pattern primarily results from the topographically driven groundwater flow dynamics, with aquifer and river hydrogeological properties contributing significantly to the local heterogeneity. Using the model, we identify the regions that function as net groundwater "importers" or "exporters" at the global scale and show that the annual net groundwater lateral flow amount can be quite considerable, in the magnitude nonnegligible to annual surface groundwater recharge. This highlights the important role of the groundwater lateral flow in maintaining regional water budget and has to be considered in water resources models, particularly for megacities.

Several limitations should be noted for potential model users. First, our model only applies a single unconfined aquifer layer, and thus omits vertical head gradients, aquitard leakage, and coastal effects that are central to deep confined basins (e.g., Northern China Plain, Central Valley, etc.). Consequently, the simulated groundwater head over the areas with deep confined aquifer system can be underestimated. This simpler model conceptualization was chosen due to the limited availability of global confined aquifer hydrogeological parameters and the evidence that the shallow groundwater (mainly unconfined) contributes largely to sustain anthropogenic and ecological groundwater use purposes (Gao et al., 2018). Second, the current simulation is still one-way (H08  $\rightarrow$  MODFLOW) with no feedback from groundwater to land-surface processes. As a result, the excessive groundwater is simply removed from the aquifer system, rather than enters to the surface water to strengthen their recharge to the aquifer. H08 evapotranspiration and allocation do not respond to the simulated groundwater heads or capillary rise; river water level is not updated by modeled baseflow. This could cause underestimation (deeper) of the simulated groundwater head than it should be if the two-way simulation were enabled. Furthermore, there still exist uncertainties in the model's key hydrogeological parameters. Compared to the previous research in de Graaf et al. (2015), which includes approximately 1000 Monte Carlo sensitivity experiments, the limited sensitivity analyses in our study may be subject to the degraded confidence of the selected optimal parameter settings. However, the fact that the simulated groundwater heads compare reasonably well to the in-situ observations globally confirms the feasibility of our model, although more comprehensive parameter tunings are suggested in the future.

Our model contributes as one of the three major GHWMs that explicitly considers groundwater lateral flow at the global scale. Additionally, the capability of H08-GM to directly output groundwater levels, calculate lateral flow rate, and connect rivers and aquifers, provides a powerful tool to investigate the groundwater decline trend over the pumping hotspots in the world, to identify river basins as importers or exporters, and to examine the losing and gaining regimes of streamflow. It will essentially help improve the accuracy of the water resource availability estimated based on the original H08 model. The steady-state simulation result in this paper has demonstrated the 40-year mean natural groundwater level distribution without human disturbance. We will show the temporal groundwater level variability and the human water withdrawal effect over the past 40 years in a following paper, which will help further advance our understanding of the important role of groundwater in supporting human water consumption, and the fundamental mechanisms behind the human-groundwater interactions.

### Appendix A: Algorithms to calculate river channel depth and river width

In the latest version of CaMaFlood, the river channel depth ( $D_{chn}$ ) is calculated based on the power-law empirical equation, as:

$$D_{chn} = \max (H_{min}, H_c * Q_{chn}^{H_p} + H_0) \quad (A1)$$

Where,  $H_{min} = 1.0$  is the prescribed minimum channel depth (unit: m);  $H_c = 0.1$  and  $H_p = 0.50$  are the coefficients,  $H_0 = 0.00$  is the prescribed offset number for river channels;  $Q_{chn}$  is the river discharge (unit:  $m^3 s^{-1}$ ).

The river width ( $RIV_{wth}$ ) is obtained based on both satellite observation and power-law estimation. The satellite-derived river width is first read in as the baseline variable ( $RIV_{gwldr}$ ). The river width based on power-law ( $RIV_{wth}$ ) is then calculated separately, as:

$$RIV_{wth} = \max (W_{min}, W_c * Q_{chn}^{W_p} + W_0) \quad (A2)$$

Where,  $W_{min} = 5.0$  is the prescribed minimum river channel width (unit: m),  $W_c = 2.50$  and  $W_p = 0.60$  are the coefficients, and  $W_0 = 0.00$  is the prescribed offset number;  $Q_{chn}$  is the river discharge (unit:  $m^3/s$ ).

Afterwards,  $RIV_{wth}$  is used to constrain the underestimation of  $RIV_{gwldr}$  for small rivers and overestimation for large rivers, as:

$$RIV_{gwldr} = \begin{cases} \max(RIV_{gwldr}, RIV_{wth}), & \text{if } RIV_{gwldr} < 50 \\ RIV_{wth} * 0.5, & \text{if } RIV_{gwldr} < RIV_{wth} * 0.5 \\ RIV_{wth} * 5.0, & \text{if } RIV_{gwldr} > RIV_{wth} * 5.0 \\ 10000, & \text{if } RIV_{gwldr} > 10000 \end{cases} \quad (A3)$$

**Appendix B. Look-up table for lithology-based aquifer conductivity (log-transformed, m<sup>2</sup>).**

The 16 lithology categories are PY (Pycroclastics), VB (Basic Volcanic Rocks), PA (Acid Plutonic Rocks), MT (Metamorphic Rocks), SU (Unconsolidated Sediments), SS (Siliciclastic Sedimentary Rocks), ND (No Data), PB (Basic Plutonic Rocks), SM (Mixed Sedimentary Rocks), WB (Water Bodies), VI (Intermediate Volcanic Rocks), SC (Carbonate Sedimentary Rocks), VA (Acid Volcanic Rocks), EV (Evaporites), PI (Intermediate Plutonic Rocks), IG (Ice and Glaciers). For each lithological categories there are maximum 4 subcategories (SbC). The mean ( $\mu$ ), sample size, and standard deviation ( $\sigma$ ) for each subcategory are listed. The category-averaged mean ( $\overline{\mu_{logK}}$ ) and standard deviation ( $\overline{\sigma_{logK}}$ ) are then calculated and given in the last two columns.

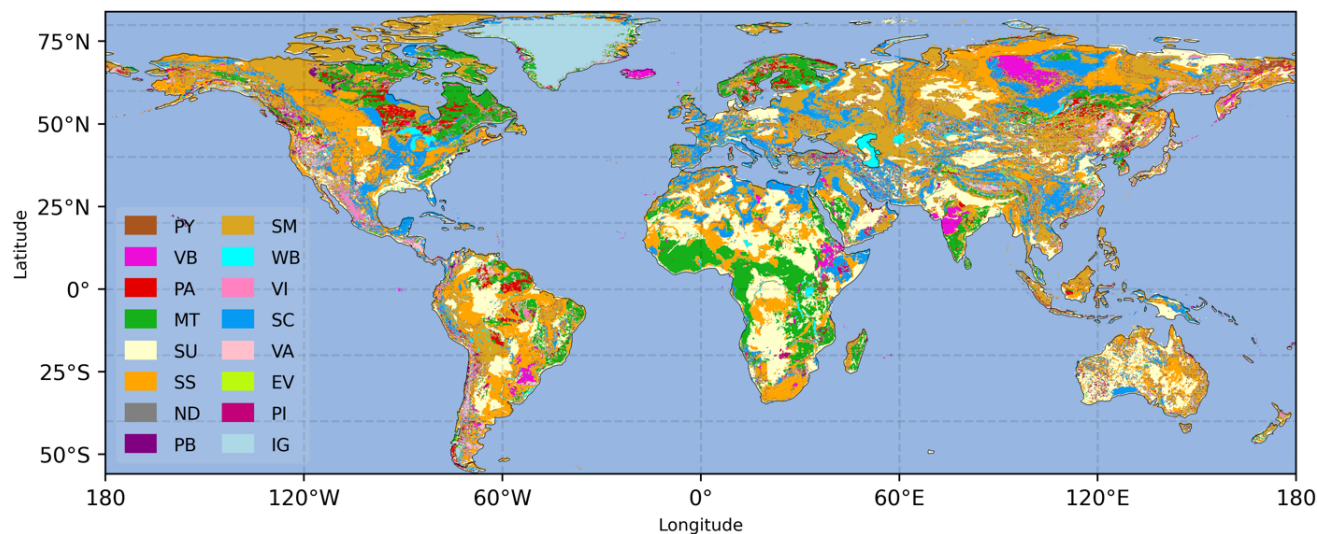
| Cat | $\mu_{logK}$ (m <sup>2</sup> ) |       |       |       | Sample size (-) |      |      |      | $\sigma_{logK}$ (m <sup>2</sup> ) |      |      |      | $\overline{\mu_{logK}}$ (m <sup>2</sup> ) | $\overline{\sigma_{logK}}$ (m <sup>2</sup> ) |
|-----|--------------------------------|-------|-------|-------|-----------------|------|------|------|-----------------------------------|------|------|------|-------------------------------------------|----------------------------------------------|
|     | SbC1                           | SbC2  | SbC3  | SbC4  | SbC1            | SbC2 | SbC3 | SbC4 | SbC1                              | SbC2 | SbC3 | SbC4 |                                           |                                              |
| PY  | -13.0                          | -15.2 | -12.5 | 0.0   | 113             | 20   | 33   | 0    | 2.0                               | 2.5  | 1.8  | 0.0  | -13.2                                     | 2.0                                          |
| VB  | -12.5                          | -12.5 | 0.0   | 0.0   | 33              | 33   | 0    | 0    | 1.8                               | 1.8  | 0.0  | 0.0  | -12.5                                     | 1.8                                          |
| PA  | -14.1                          | -14.1 | 0.0   | 0.0   | 17              | 17   | 0    | 0    | 1.5                               | 1.5  | 0.0  | 0.0  | -14.1                                     | 1.5                                          |
| MT  | -14.1                          | -14.1 | 0.0   | 0.0   | 17              | 17   | 0    | 0    | 1.5                               | 1.5  | 0.0  | 0.0  | -14.1                                     | 1.5                                          |
| SU  | -13.0                          | -10.9 | -14.0 | -13.0 | 113             | 82   | 31   | 113  | 2.0                               | 1.2  | 1.8  | 2.0  | -12.6                                     | 1.8                                          |
| SS  | -15.2                          | -12.5 | -16.5 | -15.2 | 20              | 9    | 11   | 20   | 2.5                               | 0.9  | 1.7  | 2.5  | -15.0                                     | 2.1                                          |
| ND  | N/A                            | N/A   | N/A   | N/A   | N/A             | N/A  | N/A  | N/A  | N/A                               | N/A  | N/A  | N/A  | -20.0                                     | 0.0                                          |
| PB  | -14.1                          | -14.1 | 0.0   | 0.0   | 17              | 17   | 0    | 0    | 1.5                               | 1.5  | 0.0  | 0.0  | -14.1                                     | 1.5                                          |
| SM  | -15.2                          | -12.5 | -16.5 | -15.2 | 20              | 9    | 11   | 20   | 2.5                               | 0.9  | 1.7  | 2.5  | -15.0                                     | 2.1                                          |
| WB  | N/A                            | N/A   | N/A   | N/A   | N/A             | N/A  | N/A  | N/A  | N/A                               | N/A  | N/A  | N/A  | -20.0                                     | 0.0                                          |
| VI  | -12.5                          | 0.0   | 0.0   | 0.0   | 33              | 0    | 0    | 0    | 1.8                               | 0.0  | 0.0  | 0.0  | -12.5                                     | 1.8                                          |

(continued)

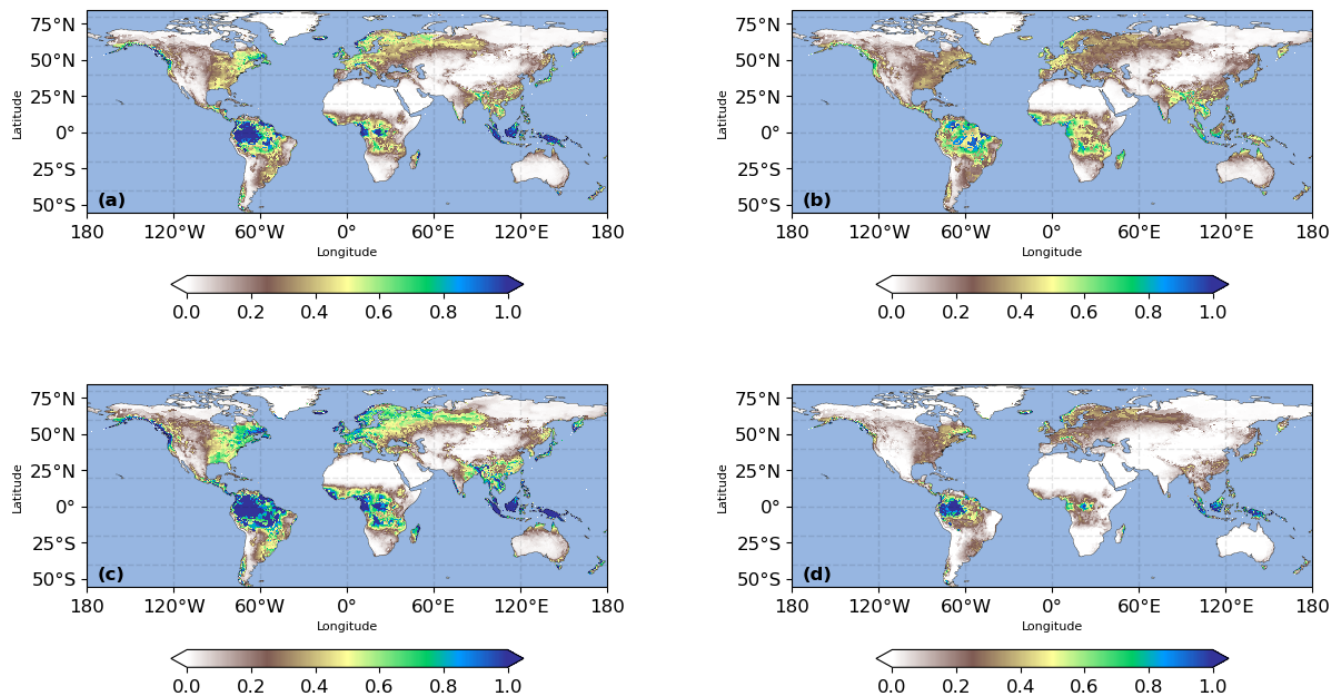
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|    |       |       |     |     |     |     |     |     |     |     |     |     |       |     |
|----|-------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|-----|
| SC | -11.8 | -11.8 | 0.0 | 0.0 | 47  | 47  | 0   | 0   | 1.5 | 1.5 | 0.0 | 0.0 | -11.8 | 1.5 |
| VA | -12.5 | -12.5 | 0.0 | 0.0 | 33  | 33  | 0   | 0   | 1.8 | 1.8 | 0.0 | 0.0 | -12.5 | 1.8 |
| EV | N/A   | N/A   | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | -20.0 | 0.0 |
| PI | -14.1 | 0.0   | 0.0 | 0.0 | 17  | 0   | 0   | 0   | 1.5 | 0.0 | 0.0 | 0.0 | -14.1 | 1.5 |
| IG | N/A   | N/A   | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | -20.0 | 0.0 |

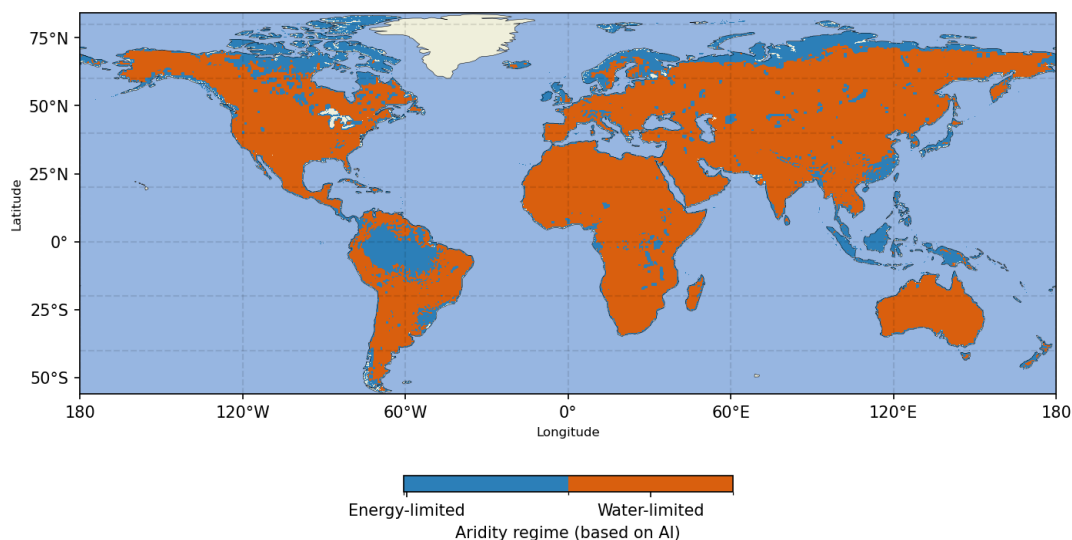
Appendix C: Supplementary figures



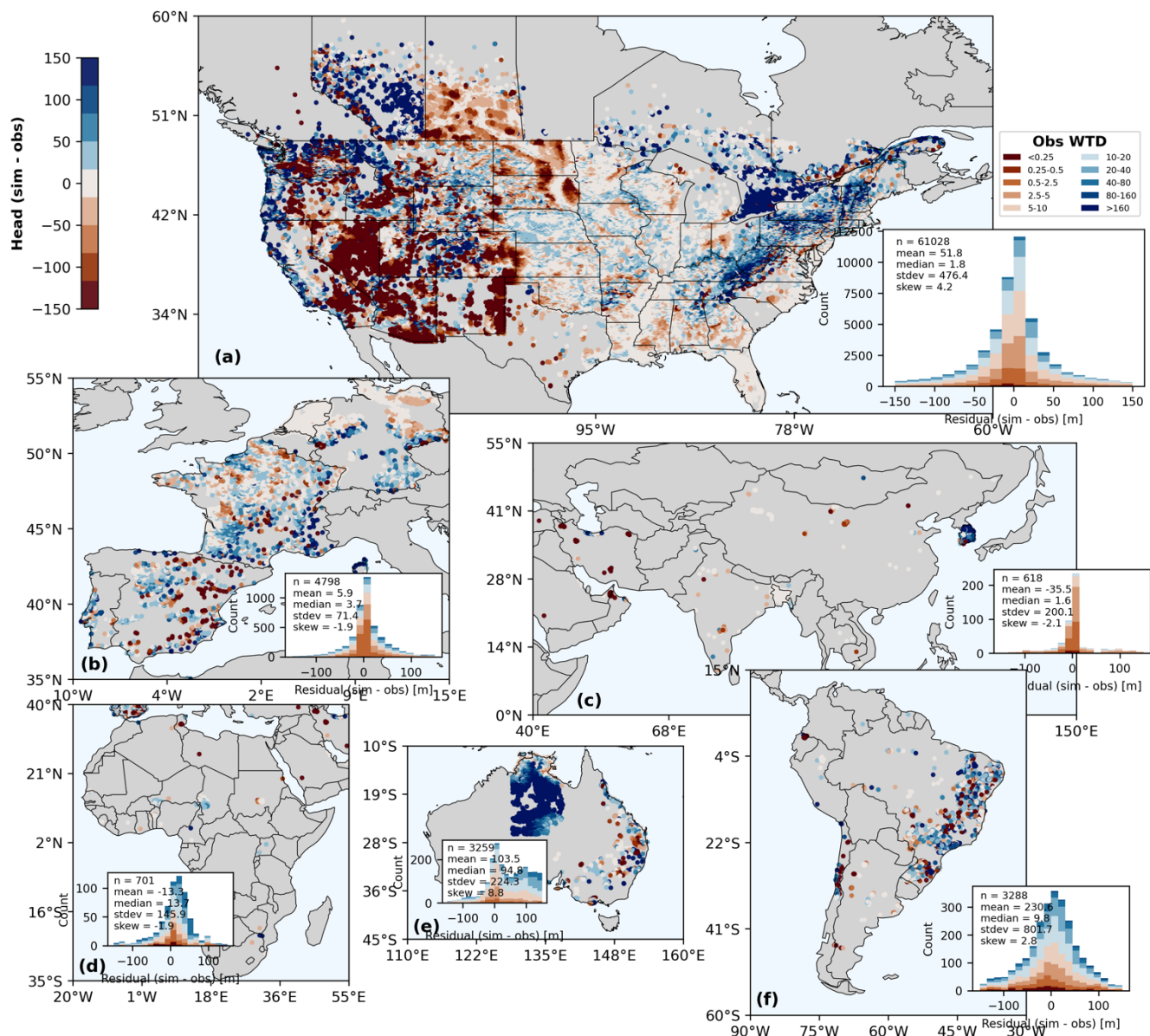
**Figure C1.** Global distribution of lithology category. The 16 lithology categories are PY (Picroclastics), VB (Basic Volcanic Rocks), PA (Acid Plutonic Rocks), MT (Metamorphic Rocks), SU (Unconsolidated Sediments), SS (Siliciclastic Sedimentary Rocks), ND (No Data), PB (Basic Plutonic Rocks), SM (Mixed Sedimentary Rocks), WB (Water Bodies), VI (Intermediate Volcanic Rocks), SC (Carbonate Sedimentary Rocks), VA (Acid Vocanic Rocks), EV (Evaporites), PI (Intermediate Plutonic Rocks), IG (Ice and Glaciers).



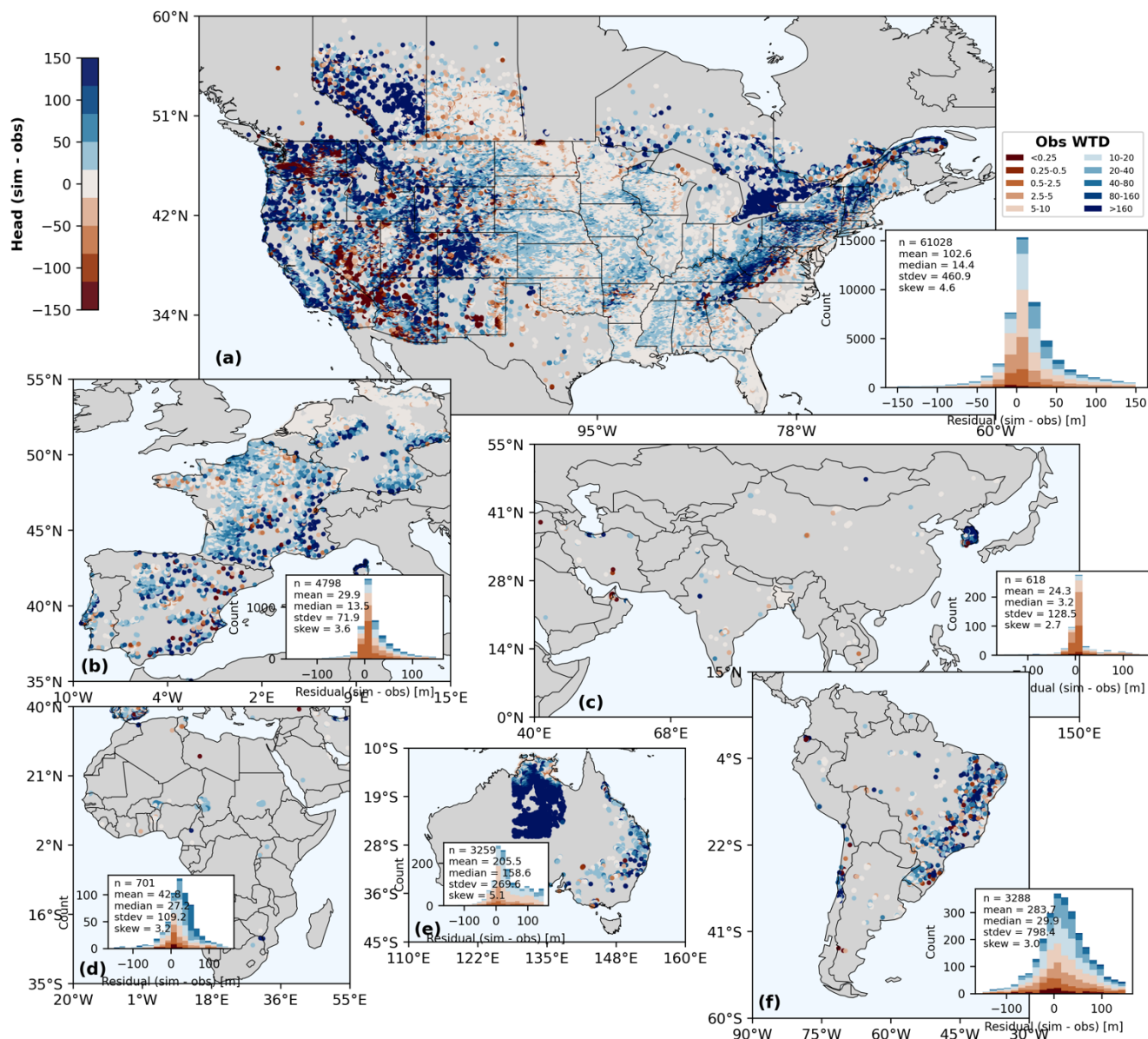
**Figure C2** Global distribution of groundwater recharge statistics for sensitivity analyses. (a) Same as Figure 2(a) in the main context: 41-year average groundwater recharge rate ( $\text{mm d}^{-1}$ ); (b) Standard deviation of groundwater recharge rate ( $\text{mm d}^{-1}$ ); (c) Groundwater recharge of 41-year mean plus 0.5 standard deviation ( $\text{mm d}^{-1}$ ); and (d) Groundwater recharge of 40-year mean minus 0.5 standard deviation ( $\text{mm d}^{-1}$ ).



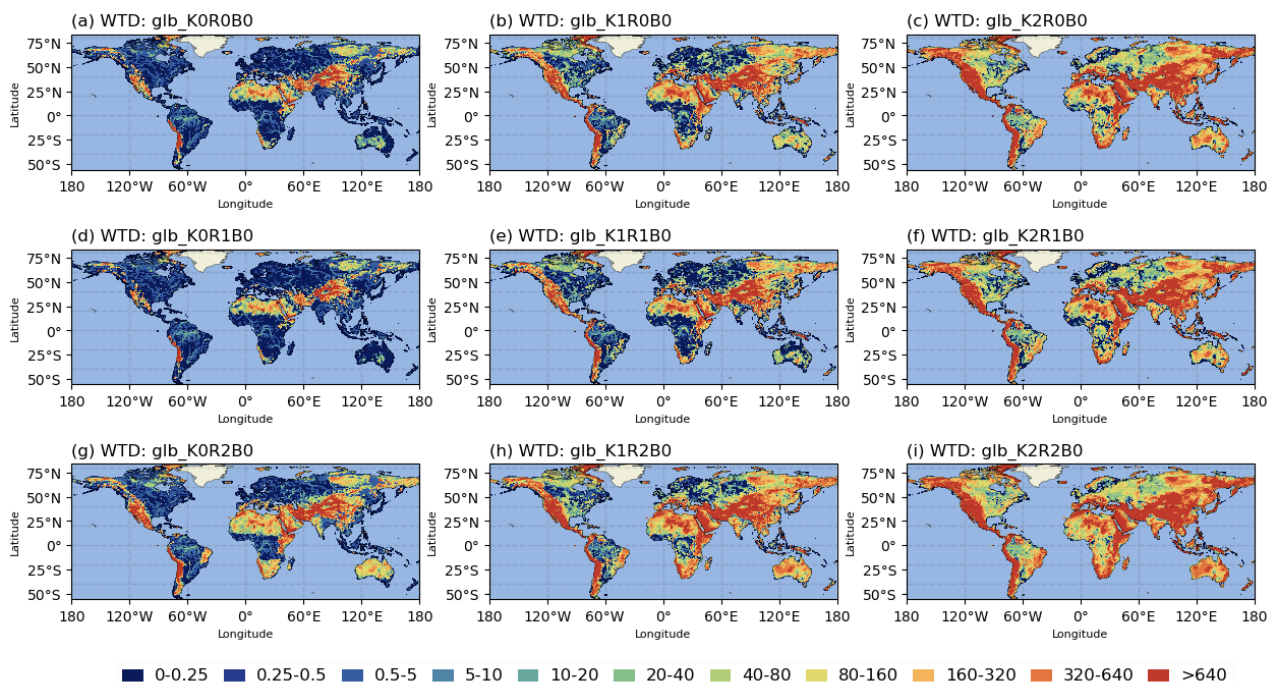
**Figure C3** Global distribution of water-limited and energy-limited regions.



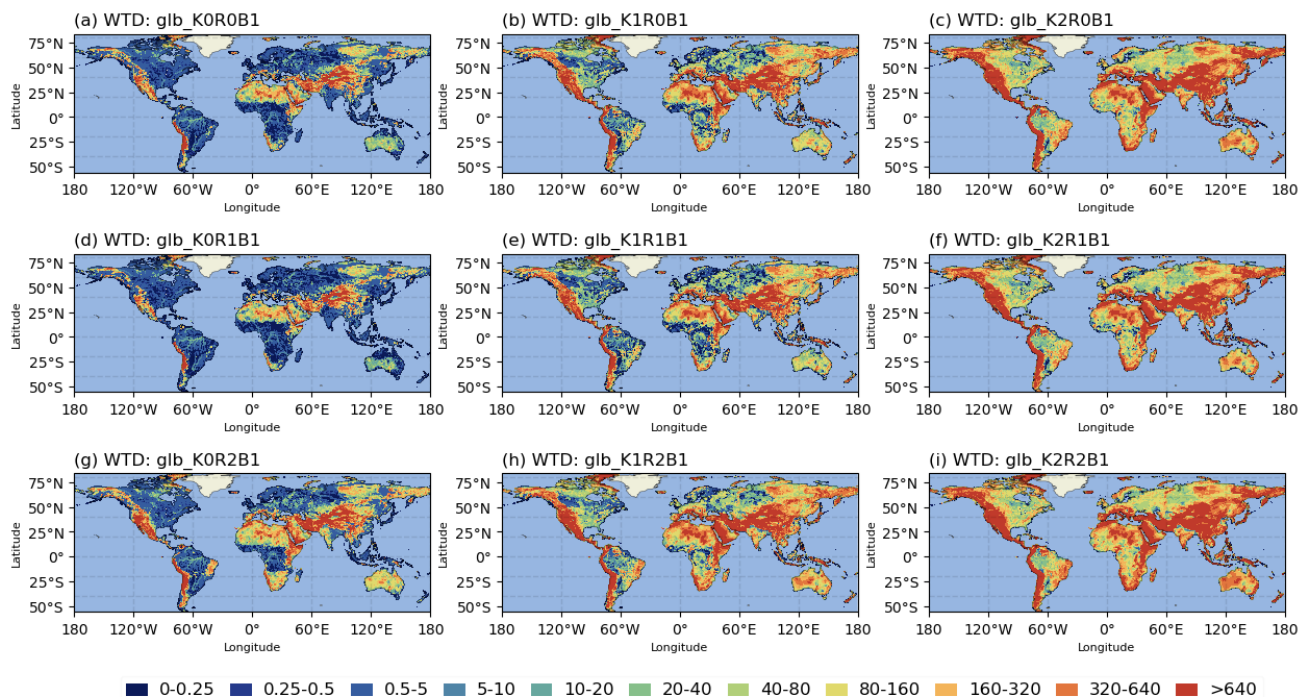
**Figure C4 Validation of simulated groundwater head against observations over each continent: (a) North America; (b) Europe; (c) Asia; (d) Africa; (e) Australia; and (f) South America. The observed groundwater head is obtained as surface elevation minus WTD, both of which are directly from the report in Fan et al. (2013). Grid cells are masked when either variable is marked as missing value. The missing values mainly concentrate in western Australia (e), which results in a sharp edge in the centre of this region. The inset panels are histograms of the model–observation head residuals ( $h - h_o$ ) over each continent, with bar heights showing the count of sample pairs; the overlaid text annotations indicate the statistics of that residual distribution (mean, median, standard deviation, skewness).**



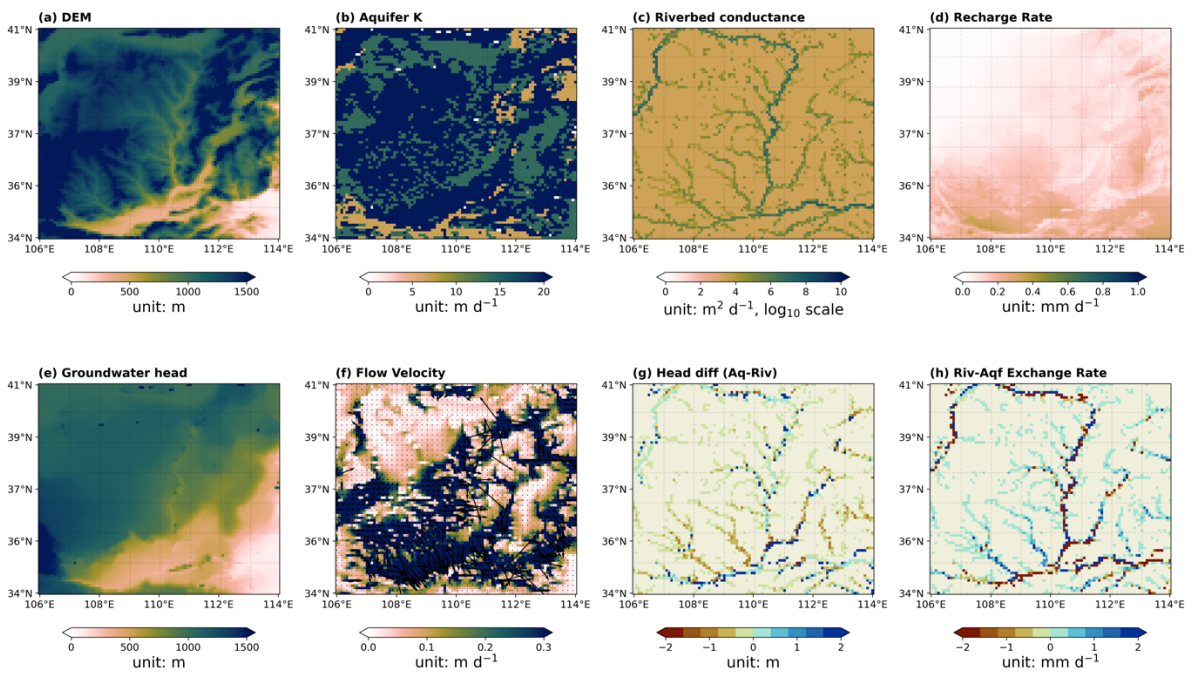
**Figure C5** Simulated groundwater head bias from experiment glb\_K1R1B2



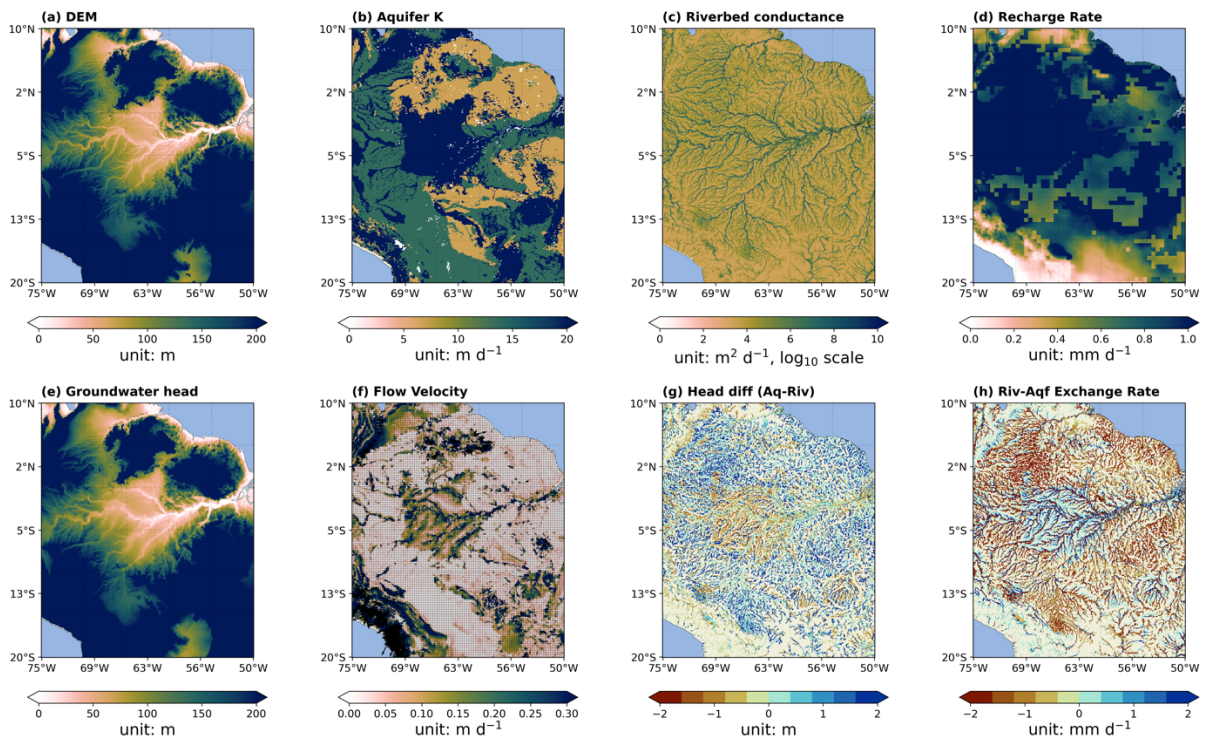
**Figure C6.** Global WTD distribution from sensitivity experiments Group A



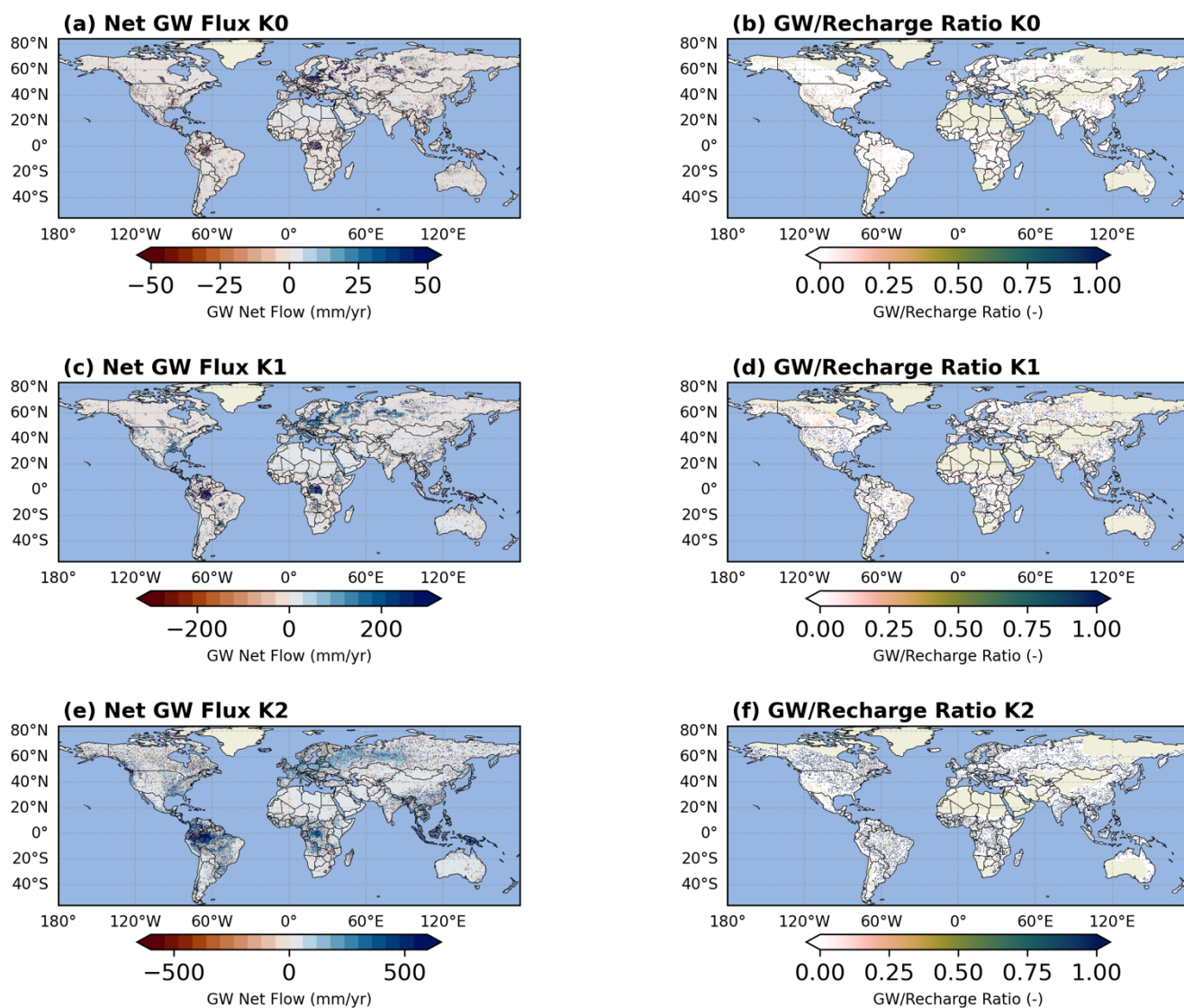
**Figure C7** Global WTD distribution from sensitivity experiments Group B



**Figure C8** Groundwater flow dynamics for Yellow River basin



695 **Figure C9** Groundwater flow dynamics in Amazon River basin



**Figure C10** Net lateral flow flux (left column) and ratio of net lateral flow flux to annual groundwater recharge (right column) under different hydraulic conductivity scenarios. K0, K1, and K2 indicates the original hydraulic conductivity, hydraulic conductivity adjusted by one standard deviation, and hydraulic conductivity adjusted by two standard deviations, respectively. Note the colorbar range in the left column is different.

**Code and Data Availability**

H08-GM v1.0 is open source and distributed under the terms of Creative Commons Attribution 4.0 International License. The development model tools and all data input of H08-GM are available in a Zenodo repository (doi: 10.5281/zenodo.15709184). The development and maintenance of H08-GM are conducted at the Department of Civil Engineering, The University of Tokyo. We welcome researchers from external institutes to contribute.

He, Q., Hanasaki, N., Matsumura, A., Sutanudjaja, E., & Oki, T. (2025). Release of H08-GM(v1.0) code (steady-state). Zenodo. <https://doi.org/10.5281/zenodo.15709184>

**Supplement.**

All supplementary materials can be found in Appendix attached in this manuscript.

**Author Contributions**

QH and NH conceptualized this work. QH performed methodology, implementation for all workflows, pre-processing of hydrogeological data, the simulation of MODFLOW 6, and analyses of the simulation results. AM prepared the global H08 model output. EHS helped with preparation of the aquifer thickness data and several technical issues of MODFLOW simulation. NH and TO supervised this research. QH prepared the manuscript, with contributions from all authors.

**Competing Interests.**

The contact author has declared that none of the authors has any competing interests.

**Disclaimer.**

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## Review Statement

## References

- Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P.-P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P., and Nelkin, E.: The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present), *J. Hydrometeor.*, 4, 1147–1167, [https://doi.org/10.1175/1525-7541\(2003\)004<1147:TVGPCP>2.0.CO;2](https://doi.org/10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2), 2003.
- Akhter, T., Pokhrel, Y., Felfelani, F., Ducharne, A., Lo, M., and Reinecke, R.: Implications of Lateral Groundwater Flow Across Varying Spatial Resolutions in Global Land Surface Modeling, *Water Resources Research*, 61, e2024WR038523, <https://doi.org/10.1029/2024WR038523>, 2025.
- Bakker, M., Post, V., Langevin, C. D., Hughes, J. D., White, J. T., Starn, J. J., and Fienen, M. N.: Scripting MODFLOW Model Development Using Python and FLOPY, *Groundwater*, 54, 733–739, <https://doi.org/10.1111/gwat.12413>, 2016.
- van Beek, L. P. H., Wada, Y., and Bierkens, M. F. P.: Global monthly water stress: 1. Water balance and water availability: GLOBAL MONTHLY WATER STRESS, 1, *Water Resour. Res.*, 47, <https://doi.org/10.1029/2010WR009791>, 2011.
- Bierkens, M. F. P. and Van Den Hurk, B. J. J. M.: Groundwater convergence as a possible mechanism for multi-year persistence in rainfall, *Geophys. Res. Lett.*, 34, L02402, <https://doi.org/10.1029/2006GL028396>, 2007.
- Braune, E. and Xu, Y.: The Role of Ground Water in Sub-Saharan Africa, *Groundwater*, 48, 229–238, <https://doi.org/10.1111/j.1745-6584.2009.00557.x>, 2010.
- 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.
- Calow, R. C., MacDonald, A. M., Nicol, A. L., and Robins, N. S.: Ground Water Security and Drought in Africa: Linking Availability, Access, and Demand, *Groundwater*, 48, 246–256, <https://doi.org/10.1111/j.1745-6584.2009.00558.x>, 2010.
- Cao, G., Zheng, C., Scanlon, B. R., Liu, J., and Li, W.: Use of flow modeling to assess sustainability of groundwater resources in the North China Plain, *Water Resources Research*, 49, 159–175, <https://doi.org/10.1029/2012WR011899>, 2013.

- 765 Condon, L. E. and Maxwell, R. M.: Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion, *Sci. Adv.*, 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. 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.
- 770 Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., Hersbach, H., and Buontempo, C.: WFDE5: bias-adjusted ERA5 reanalysis data for impact studies, *Earth Syst. Sci. Data*, 12, 2097–2120, <https://doi.org/10.5194/essd-12-2097-2020>, 2020.
- Dai, Y., Zeng, X., Dickinson, R. E., Baker, I., Bonan, G. B., Bosilovich, M. G., Denning, A. S., Dirmeyer, P. A., Houser, P. R., Niu, G., Oleson, K. W., Schlosser, C. A., and Yang, Z.-L.: The Common Land Model, *Bulletin of the American Meteorological Society*, 84, 1013–1024, <https://doi.org/10.1175/BAMS-84-8-1013>, 2003.
- 775 Döll, P., Kaspar, F., and Lehner, B.: A global hydrological model for deriving water availability indicators: model tuning and validation, *Journal of Hydrology*, 270, 105–134, [https://doi.org/10.1016/S0022-1694\(02\)00283-4](https://doi.org/10.1016/S0022-1694(02)00283-4), 2003.
- Fan, Y., Li, H., and Miguez-Macho, G.: Global Patterns of Groundwater Table Depth, *Science*, 339, 940–943, <https://doi.org/10.1126/science.1229881>, 2013.
- 780 Gao, X., Huo, Z., Xu, X., Qu, Z., Huang, G., Tang, P., and Bai, Y.: Shallow groundwater plays an important role in enhancing irrigation water productivity in an arid area: The perspective from a regional agricultural hydrology simulation, *Agricultural Water Management*, 208, 43–58, <https://doi.org/10.1016/j.agwat.2018.06.009>, 2018.
- Gee, G. W. and Hillel, D.: Groundwater recharge in arid regions: Review and critique of estimation methods, *Hydrological Processes*, 2, 255–266, <https://doi.org/10.1002/hyp.3360020306>, 1988.
- 785 Gleeson, T., Smith, L., Moosdorf, N., Hartmann, J., Dürr, H. H., Manning, A. H., Van Beek, L. P. H., and Jellinek, A. M.: Mapping permeability over the surface of the Earth: MAPPING GLOBAL PERMEABILITY, *Geophys. Res. Lett.*, 38, n/a–n/a, <https://doi.org/10.1029/2010GL045565>, 2011.
- Gleeson, T., Wada, Y., Bierkens, M. F. P., and Van Beek, L. P. H.: Water balance of global aquifers revealed by groundwater footprint, *Nature*, 488, 197–200, <https://doi.org/10.1038/nature11295>, 2012.
- 790 Gleeson, T., Moosdorf, N., Hartmann, J., and Van Beek, L. P. H.: A glimpse beneath earth’s surface: GLobal HYdrogeology MaPS (GLHYMPS) of permeability and porosity, *Geophys. Res. Lett.*, 41, 3891–3898, <https://doi.org/10.1002/2014GL059856>, 2014.
- 795 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., de Graaf, I., 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.
- 800 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. N., Burek, P., Bierkens, M. F. P., and Wagener, T.: Functional relationships reveal differences in the water cycle representation of global water models, *Nat Water*, 1, 1079–1090, <https://doi.org/10.1038/s44221-023-00160-y>, 2023.

- de Graaf, I. E. M. and Stahl, K.: A model comparison assessing the importance of lateral groundwater flows at the global scale, *Environ. Res. Lett.*, 17, 044020, <https://doi.org/10.1088/1748-9326/ac50d2>, 2022.
- 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>, 2015.
- 805 de Graaf, I. E. M., van Beek, R. L. P. H., Gleeson, T., Moosdorf, N., Schmitz, O., Sutanudjaja, E. H., and Bierkens, M. F. P.: 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.
- Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, *The Cryosphere*, 6, 221–233, <https://doi.org/10.5194/tc-6-221-2012>, 2012.
- 810 Guillaumot, L., Smilovic, M., Burek, P., de Bruijn, J., 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.
- Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing, *Hydrol. Earth Syst. Sci.*, 12, 1007–1025, <https://doi.org/10.5194/hess-12-1007-2008>, 2008a.
- 815 Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 2: Applications and assessments, *Hydrol. Earth Syst. Sci.*, 12, 1027–1037, <https://doi.org/10.5194/hess-12-1027-2008>, 2008b.
- Hanasaki, N., Yoshikawa, S., Pokhrel, Y., and Kanae, S.: A global hydrological simulation to specify the sources of water used by humans, *Hydrol. Earth Syst. Sci.*, 22, 789–817, <https://doi.org/10.5194/hess-22-789-2018>, 2018.
- 820 Harbaugh, A. W.: MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process, U.S. Geological Survey, 2005.
- Harbaugh, A. W., Banta, E. R., Hill, M. C., and McDonald, M. G.: MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process, U.S. Geological Survey, 2000.
- 825 Harbaugh, A. W., Banta, E. R., Hill, M. C., and McDonald, M. G.: MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process, U.S. Geological Survey, 2000.
- Hartmann, J. and Moosdorf, N.: The new global lithological map database GLiM: A representation of rock properties at the Earth surface: TECHNICAL BRIEF, *Geochem. Geophys. Geosyst.*, 13, <https://doi.org/10.1029/2012GC004370>, 2012.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.: The ERA5 global reanalysis, *Q.J.R. Meteorol. Soc.*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- 830 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.: The ERA5 global reanalysis, *Q.J.R. Meteorol. Soc.*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- Huggins, X., Gleeson, T., Serrano, D., Zipper, S., Jehn, F., Rohde, M. M., Abell, R., Vigerstol, K., and Hartmann, A.: Overlooked risks and opportunities in groundwatersheds of the world’s protected areas, *Nat Sustain*, 6, 855–864, <https://doi.org/10.1038/s41893-023-01086-9>, 2023.
- 835 Huggins, X., Gleeson, T., Serrano, D., Zipper, S., Jehn, F., Rohde, M. M., Abell, R., Vigerstol, K., and Hartmann, A.: Overlooked risks and opportunities in groundwatersheds of the world’s protected areas, *Nat Sustain*, 6, 855–864, <https://doi.org/10.1038/s41893-023-01086-9>, 2023.

- Huscroft, J., Gleeson, T., Hartmann, J., and Börker, J.: Compiling and Mapping Global Permeability of the Unconsolidated and Consolidated Earth: GLObal HYdrogeology MaPS 2.0 (GLHYMPS 2.0), *Geophysical Research Letters*, 45, 1897–1904, <https://doi.org/10.1002/2017GL075860>, 2018.
- 840 IGRAC: International Groundwater Resources Assessment Centre (IGRAC) database., 2004.
- Jasechko, S., Seybold, H., Perrone, D., Fan, Y., and Kirchner, J. W.: Widespread potential loss of streamflow into underlying aquifers across the USA, *Nature*, 591, 391–395, <https://doi.org/10.1038/s41586-021-03311-x>, 2021.
- Keune, J., Gasper, F., Goergen, K., Hense, A., Shrestha, P., Sulis, M., and Kollet, S.: Studying the influence of groundwater representations on land surface-atmosphere feedbacks during the European heat wave in 2003, *JGR Atmospheres*, 121, 845 <https://doi.org/10.1002/2016JD025426>, 2016.
- Koirala, S., Yeh, P. J. -F., Hirabayashi, Y., Kanae, S., and Oki, T.: Global-scale land surface hydrologic modeling with the representation of water table dynamics, *JGR Atmospheres*, 119, 75–89, <https://doi.org/10.1002/2013JD020398>, 2014.
- Kollet, S. J. and Maxwell, R. M.: Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model: INFLUENCE OF GROUNDWATER DYNAMICS ON LAND, *Water Resour. Res.*, 850 44, <https://doi.org/10.1029/2007WR006004>, 2008.
- Krakauer, N. Y., Li, H., and Fan, Y.: Groundwater flow across spatial scales: importance for climate modeling, *Environ. Res. Lett.*, 9, 034003, <https://doi.org/10.1088/1748-9326/9/3/034003>, 2014.
- Kuang, X., Liu, J., Scanlon, B. R., Jiao, J. J., Jasechko, S., Lancia, M., Biskaborn, B. K., Wada, Y., Li, H., Zeng, Z., Guo, Z., Yao, Y., Gleeson, T., Nicot, J.-P., Luo, X., Zou, Y., and Zheng, C.: The changing nature of groundwater in the global water 855 cycle, *Science*, 383, eadf0630, <https://doi.org/10.1126/science.adf0630>, 2024.
- Lange, S., Menz, C., Gleixner, S., Cucchi, M., Weedon, G. P., Amici, A., Bellouin, N., Müller Schmied, H., Hersbach, H., Buontempo, C., and Cagnazzo, C.: WFDE5 over land merged with ERA5 over the ocean (W5E5 v2.0) (2.0), <https://doi.org/10.48364/ISIMIP.342217>, 2021.
- 860 Langevin, C., Hughes, J. D., Banta, E. R., Niswonger, R., Panday, S., and Provost, A.: Documentation for the MODFLOW 6 Groundwater Flow Model, 2017.
- Lehner, B., Verdin, K., and Jarvis, A.: New Global Hydrography Derived From Spaceborne Elevation Data, *EoS Transactions*, 89, 93–94, <https://doi.org/10.1029/2008EO100001>, 2008.
- Margat, J. and Gun, J. V. D.: *Groundwater around the World*, 0 ed., CRC Press, <https://doi.org/10.1201/b13977>, 2013.
- 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.
- 865 Maxwell, R. M., Chow, F. K., and Kollet, S. J.: The groundwater–land-surface–atmosphere connection: Soil moisture effects on the atmospheric boundary layer in fully-coupled simulations, *Advances in Water Resources*, 30, 2447–2466, <https://doi.org/10.1016/j.advwatres.2007.05.018>, 2007.
- 870 Maxwell, R. M., Condon, L. E., and Kollet, S. J.: A high-resolution simulation of groundwater and surface water over most of the continental US with the integrated hydrologic model ParFlow v3, *Geosci. Model Dev.*, 8, 923–937, <https://doi.org/10.5194/gmd-8-923-2015>, 2015.

- McDonald, M. G. and Harbaugh, A. W.: A modular three-dimensional finite-difference ground-water flow model, <https://doi.org/10.3133/twri06A1>, 1988.
- Medici, G., Munn, J. D., and Parker, B. L.: Delineating aquitard characteristics within a Silurian dolostone aquifer using high-density hydraulic head and fracture datasets, *Hydrogeol J*, 32, 1663–1691, <https://doi.org/10.1007/s10040-024-02824-9>, 2024.
- Mekonnen, M. M. and Hoekstra, A. Y.: Four billion people facing severe water scarcity, *Sci. Adv.*, 2, e1500323, <https://doi.org/10.1126/sciadv.1500323>, 2016.
- Miguez-Macho, G. and Fan, Y.: A global humidity index with lateral hydrologic flows, *Nature*, 644, 413–419, <https://doi.org/10.1038/s41586-025-09359-3>, 2025.
- 880 Mu, M., Pitman, A. J., De Kauwe, M. G., Ukkola, A. M., and Ge, J.: How do groundwater dynamics influence heatwaves in southeast Australia?, *Weather and Climate Extremes*, 37, 100479, <https://doi.org/10.1016/j.wace.2022.100479>, 2022.
- Mukate, S. V., Panaskar, D. B., Wagh, V. M., and Baker, S. J.: Understanding the influence of industrial and agricultural land uses on groundwater quality in semiarid region of Solapur, India, *Environ Dev Sustain*, 22, 3207–3238, <https://doi.org/10.1007/s10668-019-00342-3>, 2020.
- 885 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.
- Ok, T. and Sud, Y. C.: Design of Total Runoff Integrating Pathways (TRIP)—A Global River Channel Network, *Earth Interact.*, 2, 1–37, [https://doi.org/10.1175/1087-3562\(1998\)002<0001:DOTRIP>2.3.CO;2](https://doi.org/10.1175/1087-3562(1998)002<0001:DOTRIP>2.3.CO;2), 1998.
- 890 Otoo, N. G., Sutanudjaja, E. H., Van Vliet, M. T. H., Schipper, A. M., and Bierkens, M. F. P.: Mapping groundwater-dependent ecosystems using a high-resolution global groundwater model, *Hydrol. Earth Syst. Sci.*, 29, 2153–2165, <https://doi.org/10.5194/hess-29-2153-2025>, 2025.
- Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., and Wagener, T.: Sensitivity analysis of environmental models: A systematic review with practical workflow, *Environmental Modelling & Software*, 79, 214–232, <https://doi.org/10.1016/j.envsoft.2016.02.008>, 2016.
- Reinecke, R., Foglia, L., Mehl, S., Trautmann, T., Cáceres, D., and Döll, P.: Challenges in developing a global gradient-based groundwater model (G<sup>3</sup> M 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>, 2019a.
- 900 Reinecke, R., Foglia, L., Mehl, S., Herman, J. D., Wachholz, A., Trautmann, T., and Döll, P.: Spatially distributed sensitivity of simulated global groundwater heads and flows to hydraulic conductivity, groundwater recharge, and surface water body parameterization, *Hydrol. Earth Syst. Sci.*, 23, 4561–4582, <https://doi.org/10.5194/hess-23-4561-2019>, 2019b.
- 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>, 2021.
- 905

- Reinecke, R., Gnann, S., Stein, L., Bierkens, M., De Graaf, I., Gleeson, T., Essink, G. O., Sutanudjaja, E. H., Ruz Vargas, C., Verkaik, J., and Wagener, T.: Uncertainty in model estimates of global groundwater depth, *Environ. Res. Lett.*, 19, 114066, <https://doi.org/10.1088/1748-9326/ad8587>, 2024.
- 910 Reinecke, R., Stein, L., Gnann, S., Andersson, J. C. M., Arheimer, B., Bierkens, M., Bonetti, S., Güntner, A., Kollet, S., Mishra, S., Moosdorf, N., Nazari, S., Pokhrel, Y., Prudhomme, C., Schewe, J., Shen, C., and Wagener, T.: Uncertainties as a Guide for Global Water Model Advancement, *WIREs Water*, 12, e70025, <https://doi.org/10.1002/wat2.70025>, 2025.
- Rodell, M., Beaudoin, H. K., and NASA/GSFC/HSL: GLDAS Noah Land Surface Model L4 3 hourly 0.25 x 0.25 degree Subsetted, Version 1, <https://doi.org/10.5067/F4KOLPJZHKOT>, 2007.
- 915 Rohde, M. M., Stella, J. C., Singer, M. B., Roberts, D. A., Caylor, K. K., and Albano, C. M.: Establishing ecological thresholds and targets for groundwater management, *Nat Water*, 2, 312–323, <https://doi.org/10.1038/s44221-024-00221-w>, 2024a.
- Rohde, M. M., Albano, C. M., Huggins, X., Klausmeyer, K. R., Morton, C., Sharman, A., Zaveri, E., Saito, L., Freed, Z., Howard, J. K., Job, N., Richter, H., Toderich, K., Rodella, A.-S., Gleeson, T., Huntington, J., Chandanpurkar, H. A., Purdy, A. J., Famiglietti, J. S., Singer, M. B., Roberts, D. A., Caylor, K., and Stella, J. C.: Groundwater-dependent ecosystem map  
920 exposes global dryland protection needs, *Nature*, 632, 101–107, <https://doi.org/10.1038/s41586-024-07702-8>, 2024b.
- Saccò, M., Mammola, S., Altermatt, F., Alther, R., Bolpagni, R., Brancelj, A., Brankovits, D., Fišer, C., Gerovasileiou, V., Griebler, C., Guareschi, S., Hose, G. C., Korb, K., Lictevout, E., Malard, F., Martínez, A., Niemiller, M. L., Robertson, A., Tanalgo, K. C., Bichuette, M. E., Borko, Š., Brad, T., Campbell, M. A., Cardoso, P., Celico, F., Cooper, S. J. B., Culver, D., Di Lorenzo, T., Galassi, D. M. P., Guzik, M. T., Hartland, A., Humphreys, W. F., Ferreira, R. L., Lunghi, E., Nizzoli, D.,  
925 Perina, G., Raghavan, R., Richards, Z., Reboleira, A. S. P. S., Rohde, M. M., Fernández, D. S., Schmidt, S. I., Van Der Heyde, M., Weaver, L., White, N. E., Zgmajster, M., Hogg, I., Ruhi, A., Gagnon, M. M., Allentoft, M. E., and Reinecke, R.: Groundwater is a hidden global keystone ecosystem, *Global Change Biology*, 30, e17066, <https://doi.org/10.1111/gcb.17066>, 2024.
- Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L., and McMahon, P. B.:  
930 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley, *Proc. Natl. Acad. Sci. U.S.A.*, 109, 9320–9325, <https://doi.org/10.1073/pnas.1200311109>, 2012.
- Scanlon, B. R., Fakhreddine, S., Rateb, A., De Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Long, D., 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  
935 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, D04103, <https://doi.org/10.1029/2008JD010636>, 2009.
- Siebert, S., Kumm, M., Porkka, M., Döll, P., Ramankutty, N., and Scanlon, B. R.: A global data set of the extent of irrigated  
940 land from 1900 to 2005, *Hydrol. Earth Syst. Sci.*, 19, 1521–1545, <https://doi.org/10.5194/hess-19-1521-2015>, 2015.
- Sutanudjaja, E. H., Van Beek, L. P. H., De Jong, S. M., Van Geer, F. C., and Bierkens, M. F. P.: Large-scale groundwater modeling using global datasets: a test case for the Rhine-Meuse basin, *Hydrol. Earth Syst. Sci.*, 15, 2913–2935, <https://doi.org/10.5194/hess-15-2913-2011>, 2011.
- 945 Sutanudjaja, E. H., Van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H. C., Drost, N., Van Der Ent, R. J., De Graaf, I. E. M., Hoch, J. M., De Jong, K., Karssen, D., López López, P., Peßenteiner, S., Schmitz, O., Straatsma, M. W., Vannamettee,

- E., Wisser, D., and Bierkens, M. F. P.: PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model, *Geosci. Model Dev.*, 11, 2429–2453, <https://doi.org/10.5194/gmd-11-2429-2018>, 2018.
- Verkaik, J., Sutanudjaja, E. H., Oude Essink, G. H. P., Lin, H. X., and Bierkens, M. F. P.: GLOBGM v1.0: a parallel implementation of a 30 arcsec PCR-GLOBWB-MODFLOW global-scale groundwater model, *Geosci. Model Dev.*, 17, 275–300, <https://doi.org/10.5194/gmd-17-275-2024>, 2024.
- Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., and Bierkens, M. F. P.: Global depletion of groundwater resources: GLOBAL GROUNDWATER DEPLETION, *Geophys. Res. Lett.*, 37, n/a-n/a, <https://doi.org/10.1029/2010GL044571>, 2010.
- Wada, Y., Wisser, D., and Bierkens, M. F. P.: Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, *Earth Syst. Dynam.*, 5, 15–40, <https://doi.org/10.5194/esd-5-15-2014>, 2014.
- Wagener, T., Reinecke, R., and Pianosi, F.: On the evaluation of climate change impact models, *WIREs Climate Change*, 13, e772, <https://doi.org/10.1002/wcc.772>, 2022.
- Watanabe, K. and Flury, M.: Capillary bundle model of hydraulic conductivity for frozen soil, *Water Resources Research*, 44, 2008WR007012, <https://doi.org/10.1029/2008WR007012>, 2008.
- Watanabe, K. and Osada, Y.: Comparison of Hydraulic Conductivity in Frozen Saturated and Unfrozen Unsaturated Soils, *Vadose Zone Journal*, 15, 1–7, <https://doi.org/10.2136/vzj2015.11.0154>, 2016.
- Weedon, G. P., Balsamo, G., Bellouin, N., Gomes, S., Best, M. J., and Viterbo, P.: The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data, *Water Resources Research*, 50, 7505–7514, <https://doi.org/10.1002/2014WR015638>, 2014.
- Yamazaki, D., Oki, T., and Kanae, S.: Deriving a global river network map and its sub-grid topographic characteristics from a fine-resolution flow direction map, *Hydrol. Earth Syst. Sci.*, 13, 2241–2251, <https://doi.org/10.5194/hess-13-2241-2009>, 2009.
- Yamazaki, D., Kanae, S., Kim, H., and Oki, T.: A physically based description of floodplain inundation dynamics in a global river routing model, *Water Resources Research*, 47, 2010WR009726, <https://doi.org/10.1029/2010WR009726>, 2011.
- Yamazaki, D., O’Loughlin, F., Trigg, M. A., Miller, Z. F., Pavelsky, T. M., and Bates, P. D.: Development of the Global Width Database for Large Rivers, *Water Resources Research*, 50, 3467–3480, <https://doi.org/10.1002/2013WR014664>, 2014.
- Yang, W., Long, D., Scanlon, B. R., Burek, P., Zhang, C., Han, Z., Butler, J. J., Pan, Y., Lei, X., and Wada, Y.: Human Intervention Will Stabilize Groundwater Storage Across the North China Plain, *Water Resources Research*, 58, e2021WR030884, <https://doi.org/10.1029/2021WR030884>, 2022.