Reply to Reviewer #2 Comments

We have categorized the reviewers comments and provided responses. Author responses are in **bold** and *italic.*

Title: DECIPHeR-GW v1: A coupled hydrological model with improved representation of surface-groundwater interactions

Summary

This study presents a coupled hydrological modeling framework integrating the DECIPHeR land surface hydrological model with a 2D groundwater model. Applied to 669 watersheds across England and Wales, the coupled model (DECIPHeR-GW) demonstrates improved streamflow simulations, particularly in areas with strong groundwater-surface water interactions.

DECIPHeR-GW features an HRU-based structure that feeds a gridded groundwater model, allowing for dynamic water exchange based on water table and root zone elevations. The model incorporates six key parameters for stochastic calibration (including soil and aquifer properties) and enables simulations across large domains.

Evaluation against observations shows enhanced temporal variability and streamflow magnitude compared to the uncoupled model. While generally successful, the study acknowledges challenges in watersheds significantly impacted by human activities.

Positive Aspects

- The manuscript shows great clarity and organization, making it highly readable and accessible. The manuscript effectively guide the reader through the study's objectives, methodology, results, and discussion.
- The presentation of results is good, with a clear and concise narrative that effectively conveys the key findings. The authors interpret the results, providing insightful discussions on their implications and limitations.
- The figures and tables are well-designed and informative, effectively illustrating the key findings and supporting the conclusions.
- The supplementary information is also valuable and well-presented, providing important details and supporting data that helps in the overall understanding of the study.

Thank you very much for your comments. We appreciate your positive feedback on our manuscript.

General Comments:

- The manuscript presents a coupled land-surface and groundwater model. While the importance of incorporating groundwater is recognized, a more focused research question is needed. The authors should clearly articulate how their approach differs from existing coupling methods, highlighting the novelty of their model. Additionally, a discussion on the positioning of their model within the spectrum of simplified to physics-based groundwater representations is needed.

Thanks for your comment.

In our coupled model, the coupling method, including the mapping and transformation of variables between HRU-scale surface components and gridded groundwater systems, is adapted from existing approaches used in coupling SWAT and MODFLOW. However, the key novelty of our coupled method lies in the introduction of three dynamic coupling scenarios to simulate the surface water and groundwater interactions. These scenarios dynamically determine interactions and recharge fluxes based on the saturation state of the root zone and the position of groundwater heads, offering a more flexible and precise method to modelling these processes. We will highlight this in the revised manuscript.

It is also important to clarify that the primary objective of this study is not to propose a novel coupling methodology but to develop and describe a new coupled model. Currently, there are limited types of coupling models between HRU-scale surface components and grid-based groundwater models, with the SWAT and MODFLOW coupling model being the one widely used representative example. In contrast, our work represents the first attempt to couple DECIPHeR HRU-scale model with a new two-dimensional gridded groundwater model. Through this model description paper, we aim to comprehensively present the structure and implementation of this novel coupled model, addressing both research and practical application needs. We will better clarify where the model sits in the current spectrum of simplified to physics-based groundwater representations in the discussion.

- The manuscript emphasizes the model's scalability. However, a more detailed discussion on the potential scale mismatch between the regional land surface model and the large-scale groundwater model is required. Specifically, the authors should clarify what type of groundwater flow represented at the 1 km grid scale, considering the local-scale flows discharging into streams. The manuscript should address how these different scales are reconciled within the model.

The surface component of our coupled model, the DECIPHeR model, is a HRU-scale hydrological model rather than a regional-scale land surface model. In our coupled model, the average size of an HRU is 0.31 km^2, approximately one-third the size of a 1 km groundwater grid. The surface water and groundwater components are of similar scales and are comparable, thus scale mismatch is not a significant concern in our study. To transfer and convert the variables and fluxes across the HRU scale and grid scale, we apply the existing mapping methods from coupling SWAT and MODFLOW.

In this revision, we will provide some statistical information about HRU sizes to help understand the scale matching between the HRU scale and 1km groundwater grid scale. Also, we will include a figure depicting the map of HRUs and groundwater grids, offering a clear representation of their spatial distributions.

- The manuscript highlights computational efficiency as a key advantage of DECIPHeR-GW. A more thorough discussion on the model assumptions that contribute to this efficiency is needed. The authors should explicitly state which processes are simplified or neglected in both the land surface and groundwater components. A comparison of the model's assumptions to those of other computationally expensive models, particularly those that incorporate fine-resolution environmental data and capture land surface heterogeneity, would provide valuable context.

Thanks. We will add more thorough discussion on the model assumptions, the processes that are simplified and neglected in this revision. We will also add a comparison of the model's assumptions to those of other computationally expensive models.

Specific Comments

- **Abstract:**

[19] A more specific description of the catchment characteristics would help the understanding of the study area.

We will provide more characteristics of our study area catchments in the revision.

[20] Please specify the variable being analyzed in this context.

The variable being analyzed here in Line 20 is streamflow. We will clarify this in the revised version.

[23-24] The abstract currently does not explicitly establish a strong connection between computational efficiency and large-domain simulations as a significant challenge in traditional land surface modeling. Consider incorporating some of the performance measurements described in the Discussion.

- Consider including a brief statement in the abstract regarding the spatial resolution of both the land surface and groundwater components of the coupled modeling framework to provide further context for the reader.

Thank you for your comments. We will add a brief statement of the spatial resolution of surface and groundwater components of the coupled model. Also we will present quantitative metrics that demonstrate the high computational efficiency of our model in the abstract.

- **Introduction:**

[46-49] It would be beneficial for the authors to explicitly articulate the specific aspects of groundwater representation in existing models that are challenging or form the basis of their research hypothesis.

The challenging aspects of groundwater representation are outlined later in the introduction (Lines 63-79). However, we will add a short summary here in the revision.

[80-86] A dedicated section discussing the novelty of the proposed approach would add more to the relevance of the study. This section should clearly differentiate the current methodology from previously mentioned modeling approaches, highlighting the unique contributions and advancements of the presented work.

- The inclusion of a dedicated paragraph discussing the scales of the modeling framework is recommended. This paragraph should address potential scale mismatches between the land surface and groundwater components, and how these differences are addressed within the model.

Please see response to the first and second general comments.

- **The DECIPHeR-GW model**

[93-101] To enhance clarity, it would be beneficial to include a more detailed description of the HRU construction process. This would clarify how the domain is discretized and how this discretization may influence the representation of key hydrological processes.

When referring to "previous studies" in line 97, please specify whether this refers specifically to the DECIPHeR model or to land surface models in general.

In line 101, it would be helpful to elaborate on the specific requirements for large-scale simulations, as defined by the authors.

We will add more details about the HRU construction process in this revision. In Line 97, the 'previous studies' refers to the DECIPHeR model. We will clarify this and re-write the line 101 to make it clear.

[106-113] While other large-scale coupled models can be computationally expensive due to the inclusion of detailed processes (such as vertical water movement), it is unclear how DECIPHeR-GW balances computational efficiency with process representation.

If computational demands and input data requirements are reduced, it is essential to clearly describe which hydrological processes are simplified or omitted, and how these simplifications are compensated for through the calibration process.

Thank you for this comment. The groundwater component of our coupled model did not consider the vertical water movement and does not include the river channel representation. We will add more details about the simplified/omitted hydrological processes in the revision.

[120] Given that the variable Qex in Figure 1 may represent recharge rates exceeding infiltration capacity, it is important to discuss whether the model considers the potential for saturated overland flow.

Our model does not account for infiltration capacity but does consider saturated overland flow, which occurs when the root zone reaches its maximum storage capacity. We will clarify this in the revised manuscript.

[147] Does the hydrological model allow for two-way interactions between river routing and the HRUs, enabling water from the river to contribute to aquifer recharge?

Both the DECIPHeR and coupled DECIPHeR-GW model do not allow for the two-way interactions between the river routing and the HRUs. The saturated flow from HRUs will be added to the nearest river channel for river routing, but the river flow in the river channel will not affect the HRUs. Due to the simplified and computational-efficient nature of our groundwater model, it does not have a specific representation of river channels, it only simulates the groundwater movements between the grids. Therefore, it is currently unable to simulate river water contributing to aquifer recharge. We will clarify this in the revision.

[154] Please provide further details on how the parameterization of the groundwater grid is connected to the characteristics of the overlying HRUs. Does each HRU has a set of soil parameters and those are weighted average to parametrize the groundwater grid?

The parameterization of the groundwater grid is not connected to the characteristics of the overlying HRUs. The model parameters for the surface water and groundwater components are at different scales, and each is prepared independently without the need for conversion.

In our coupled model, the groundwater model is primarily controlled by two parameters, i.e., transmissivity (T) and specific yield (Sy), both of which are mainly related to geological conditions and lithology types. Using a lithology base map at a 1 km grid resolution (same with groundwater grids resolution), transmissivity and specific yield values are estimated at the same scale for model calibration. The same set of transmissivity and specific yield values is assigned to the groundwater grids with the same lithology type.

Therefore, the parameterization of the groundwater grid relies on lithology types, and soil texture information or parameters are not required for these grids.

Soil texture parameters are key factors in determining the parameterization of HRUs. Other surface component model parameters, such as maximum root zone storage (SRmax), saturated hydraulic conductivity (Ks), and pore size distribution index (B), are also defined at the HRU scale based on soil texture. We will clarify this in the revision.

[187] How are the HRUs over the buffering zone updated within the model if they belong to a different catchment?

According to our current model set up, the HRUs do not exist on the buffer zone. Our coupled model currently operates at the river basin scale. After delineating the river basin boundaries, the model defines the final groundwater simulation domain by including groundwater grids that encompass the entire river basin area along with an additional buffer zone. Consequently, the groundwater simulation domain (especially the buffer zone) extends beyond the river basin boundaries.

Each river basin is treated as an independent study area during model construction, without accounting for connections between neighbouring river basins. The groundwater grids and buffer zones outside the river basin boundaries do not incorporate or consider HRUs, which are exclusively confined within the river basin boundaries. The variables of HRUs, i.e., recharge and precipitation, occur solely within these boundaries. We have mentioned this limitation in the discussion section (Lines 552-563). We will make this clear in the revision.

[191] How are the systems of watersheds connected, considering that each watershed has its own groundwater model?

Is the connection solely through river routing, or do the buffering zones of adjacent watersheds also interact or overlap?

Our coupled model currently runs at river basin scale. Same with other widely-used hydrological models, such as SWAT model, the digital terrain analysis (DTA) of our surface water component DECIPHeR model will delineate catchments using the most downstream gauge and clip the

groundwater grid for the simulation domain. Each river basin is configured individually, rather than modelling the entire continent or nation.

Within each river basin, all the HRUs and sub-catchments are connected as well as river channels in the surface components. As for the subsurface components, all the groundwater grids beneath the river basin and also the buffer zone is connected. The hydrological fluxes and variables, including recharge, groundwater discharge, groundwater head are transferred between these two components.

As mentioned in the limitation (Lines 552-563), our coupled model is set up at the river basin scale and does not account for the exchange of hydrological variables, such as groundwater flow, between neighbouring river basins. Therefore, the river basins are not connected to each other at the moment. The buffer zones of adjacent river basins may overlap geographically, but they do not interact with each other. We have noted in the discussion that this could be a potential area for improvement in future work. We will make this clearer in the revision.

- **Model implementation and evaluation across England and Wales**

[202-205] To enhance clarity and reproducibility, a detailed description of the meteorological, soil properties and elevation data used in the study would be beneficial. This should include information on the temporal and spatial resolution of the data, as well as a list of the variables used to parameterize the model.

Thank you for your suggestion. We will add a table in the revision to provide more detailed information of the meteorological, soil properties and elevation data used in the study.

[244] The manuscript would benefit from a more detailed description of the spatial resolution and configuration of the HRUs. The inclusion of a figure illustrating the HRU distribution within the study area would significantly help.

In this revision, we will add a figure illustrating the HRU distributions within one of our study catchments.

- **Results**

[358] To further strengthen the analysis, it would be valuable to quantify the correlation between human activity and the model's performance. If these specific catchments are not being monitored, it is important to discuss the potential implications for the calibration process, particularly with regard to the representation of human-induced water abstractions.

We will add a further analysis between human activity and the model's performance in this revision. We will add a discussion about the potential implications of the calibration process for the water abstraction impacted catchments.

Figure S8 of the supplementary information appears to be missing units for surface water abstractions, groundwater abstractions, and wastewater discharges.

Thank you for pointing out this issue. We will add the units labels in the revised version of the Figure S8.

[370] The inclusion of a figure showing the temporal mean water table elevation for the study area would provide insights into the spatial and temporal variability. This would allow for a visual assessment of the water table's consistency with the expected topographic trends.

Thank you for your suggestions. Since our model operates at the river basin scale, the groundwater grids do not cover the entire UK at the national-scale. Moreover, there is no groundwater interactions between different river basins in our current model setup, making it less meaningful to present the temporal mean water table elevation for all study catchments.

However, in this revision, we will include a groundwater table simulation result map for the Thames Basin, a groundwater-dominated region that serves as a representative basin to present the simulations of our coupled model.

Reference:

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Coxon, G., Freer, J., Lane, R., Dunne, T., Knoben, W. J., Howden, N. J., Quinn, N., Wagener, T., and Woods, R.: DECIPHeR v1: dynamic fluxEs and connectivity for predictions of HydRology, Geoscientific Model Development, 12, 2285-2306, 2019.
Lane, R. A., Freer, J. E., Coxon, G., and Wagener, T.: Incorporating uncertainty into multiscale parameter regionalization to evaluate the performance of nationally consistent parameter fields for a hydrological model, Water Resources Research, 57, e2020WR028393, 2021.
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Samaniego, L., Kumar, R., and Attinger, S.: Multiscale parameter regionalization of a grid-based hydrologic model at the mesoscale, Water Resources Research, 46, https://doi.org/10.1029/2008WR007327, 2010.