Response to reviewers' comments

Manuscript number (HESS-2023-25)

Note: Below, the reviewers' comments are in red, our responses are in black; line numbers refer to the revised manuscript unless otherwise indicated; new text in the revised manuscript (marked version) is underlined.

Review

The article titled "Economic valuation of subsurface water contributions to watershed ecosystem services using a fully integrated groundwater-surface water model" presents an advanced approach to quantifying and valuing the ecosystem services provided by water, particularly focusing on subsurface water contributions. Using the HydroGeoSphere (HGS), a fully integrated hydrological model, the research effectively simulates water fluxes and assesses the economic value of subsurface water contributions over an 18-year period in the South Nation Watershed (SNW), located in eastern Ontario, Canada.

The article shows improvement from its previous versions, but there are still a few corrections and suggestions that can enhance the clarity, depth, and accessibility of the work. Below are the suggestions organized by sections:

Introduction:
Clarification of Technical Terms:

Lines 33 and 42: Terms like "critical zone" and "vadose zone" may not be familiar to a broader scientific audience. Since these are technical terms, it would be helpful to briefly define or explain them within the text. This will make the article accessible to readers from diverse backgrounds, especially those not specialized in hydrology.

We appreciate the reviewer's perspective on our use of terminology and have changed the text to be more descriptive.

Line 33 now reads "The role of subsurface water (including groundwater and soil moisture) in socio-economic…"

Line 40 now reads "To date, most ecosystem services research has focused on aboveground factors and processes (e.g., land use change), and very little focus has been given to subsurface water and its influence…"

Lines 80-81: The transition from the previous paragraph about the model to the sentence in Line 81 is abrupt. Introducing the concept of evapotranspiration with a starting sentence in this paragraph would smoothen the flow and provide better continuity in the narrative. Clarification on the importance of the study.

We thank the reviewer for identifying this abrupt change in topic. We have added a new introductory sentence to this paragraph to build up the connection between evapotranspiration and the previous paragraph (Line 81-82). It now reads " In humid climates, evapotranspiration is often the most significant

component of the hydrologic cycle after precipitation, and must be carefully considered when modelling near surface hydrologic processes. Evapotranspiration is the fraction of rainfall…"

Lines 108-111: The sentences in this section need to be rewritten to emphasize how the findings of this study will contribute to the scientific community and policymakers. Instead of merely presenting the novelty of the method, it is important to convey the practical and scientific implications, highlighting the potential for better watershed management and policy decisions informed by subsurface water valuation.

Thank you to the reviewer for pointing out the need to address the broader scientific and policymaker communities. We have added the following sentence to the end of this paragraph (Lines 114-116).

"Results from this study are also directly relevant to the broader scientific and policymaking communities who are seeking insights into the role of subsurface water in supporting societal endpoints under a wide range of different climatological conditions in humid continental climates."

Materials and Methods:

Methodological Assumptions:

Lines 243-244: The study utilizes methods such as the benefit transfer approach and market price replacement cost method, both of which are based on certain assumptions. It would be helpful for the authors to include these assumptions within the text to ensure transparency. Explaining assumptions will also help readers understand the limitations or conditions under which the results hold validity.

Thank you for the comment; In response, we have incorporated the following clarification into the manuscript (Lines 243-249):

"The benefit transfer method, widely used for the economic valuation of ecosystem services, leverages existing valuation studies to estimate the value of the services in different geographical contexts. The method relies on two key assumptions. First, it assumes that the value of any ecosystem service (or bundle) under valuation is comparable across different regions, which may not always hold true due to variations in ecological and socio-economic conditions. Additionally, the methods used in the primary studies (e.g., market price, replacement cost methods) assume that market prices or the costs of replacing ecosystem services accurately reflect their true value (Aziz et al, 2023). These assumptions inherently limit the precision of the results, meaning the estimated values should be interpreted as approximate rather than definitive. Nevertheless, these estimates provide useful insights, especially for regions like the South Nation Watershed, where primary valuation studies are lacking and can guide initial policy development and resource management decisions."

Results:

Sensitivity Analysis:

While the benefit transfer approach is standard practice for economic valuation, the article could benefit from a sensitivity analysis that examines how variations in input values influence the final estimates. Adding a sensitivity analysis will strengthen the robustness and credibility of the economic conclusions. This would allow the study to show the potential range of outcomes and better reflect economic uncertainties.

Thank you for the insightful comment regarding the addition of a sensitivity analysis. We agree that this would enhance the robustness of the economic valuation and better account for uncertainties. In response, we have added the following to the text to address the potential variation in the benefit transfer estimates (Lines 261-264):

"The benefit transfer method provides an approximation of ecosystem service values with potential transfer errors ranging from 62% to 86% based on domestic studies (Aziz, 2021). In our study context, we transfer the values from the region immediately adjacent to our study region, an approach that constrains the error."

Lines 336-337: The authors should elaborate on why they examined correlations between certain variables. Providing a clear rationale for choosing these specific correlations will help justify the analysis and clarify the relationships being studied.

To highlight why we chose to correlate green water value with precipitation, we have added a sentence (354-357), so the section now reads as: "In the SNW, precipitation is the main driver of the terrestrial hydrologic cycle and low precipitation is the primary indicator of climatological drought. In general, there is a strong inverse correlation between total annual precipitation and green water value, with an R^2 of 0.45 ($p < 0.0001$). "

Discussion:

Organization and Structure:

The discussion section is too lengthy and can be difficult to follow in its current form. Dividing it into subsections—such as Model Predictions, Ecosystem Services Valuation, Limitations, and Model Uncertainty—would improve the clarity and readability of the discussion. This restructuring would help readers navigate through the key findings, limitations, and implications more easily.

Thank you to the reviewer for pointing this out and we agree. In the revised manuscript we have added the following subheadings within the discussion section.

L361: Drought Year Hydrologic Behavior

L409: Hydrologic Influences on Ecosystem Services and Economic Valuation

L431: Strengths and Limitations of Fully-Integrated GW-SW Models

L464: Extension to Other Regions

Generalization of Findings:

The article acknowledges that the results are specific to the South Nation Watershed, but it lacks sufficient discussion on how these findings can be generalized to other regions. Discussing how the study's methodology could be adapted or applied to different watersheds with varied hydrogeological conditions would increase the relevance of the study and appeal to a broader audience. Additionally, a discussion on how water contributes to other ecosystem services—such as water purification and biodiversity support—could provide a more holistic understanding of subsurface water's role.

Thank you to the reviewer for this suggestion. Having now broken down the discussion section into subsections, we feel that the last paragraph of the current discussion section addresses the topic of extensibility to other regions with adequate detail. We have highlighted the primary considerations for future work that extends our methodology to other regions and we feel any further description would become very hypothetical and scenario specific.

Regarding the reviewer's suggestion to include further discussion on how water, and groundwater, support ecosystem services other than those which we considered, we would like to defer our introduction section. Specifically, we point reader to the review paper of Griebler and Avramov (2015) where this topic is discussed in great detail. We feel that any further discussion of the broader implications of water and groundwaters role in ecosystem services would be cursory in comparison to the review paper, and would be tangent to our work.

Griebler, C. and Avramov, M.: Groundwater ecosystem services: A review, Freshw. Sci., 34, 355–367, https://doi.org/10.1086/679903, 2015.

Conclusion:

The conclusion would benefit from concrete policy recommendations. Adding recommendations based on the study's findings would make the results more actionable for policymakers, particularly in the context of drought management, sustainable agricultural practices, and watershed conservation. Also, adding a few lines about limitations would give readers a clearer understanding of how much confidence to place in the results and under what conditions the study's findings might apply to other regions.

Thank you to the reviewer for this valuable suggestion. We have added the following text to the conclusions section to provide actionable information for policy management (Lines 489-496)

"Surface water ecosystem services are frequently valued in the literature, whereas the valuation of subsurface water reserves and flows receives considerably less attention. Valuing groundwater resources can provide watershed stewards incentives they can use to support land use management practices that influence flood damages, drought impacts, drinking water quality/quantity, and ecological functions in surface water systems, for instance. The valuation approach provided herein, using integrated numerical hydrogeological models, provides a rigorous standardized means to provision value to ecosystem services associated with all components of the hydrological cycle. This approach offers a template for standardizing water valuation in ecosystem service markets and could guide the integration of water ecosystem service payments across diverse jurisdictions."

Regarding the inclusion of limitations within the Conclusion section, we have provided a detailed discussion of the study's limitations in the Discussion section, and we feel that reiterating these points in the Conclusion may lead to redundancy. We hope this approach maintains clarity and conciseness in the manuscript.

Finally, we thank the reviewer(s) again for their constructive feedback/comments, which have helped us to improve/strengthen the manuscript.