RESPONSE LETTER

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Title: Managed Aquifer Recharge in Confined Multi-Layer Aquifers: A Scalable Framework for Drought Resilience in Central Europe

Corresponding Author: Abdelrahman Ahmed Ali Abdelrahman
All Authors: Abdelrahman Ahmed Ali Abdelrahman, Hagen Koch, Mobarok Hossain, Ronjon Heim, Clara Hauke, and Irina Engelhardt

Response to the Reviewer #3:

1- The manuscript presents an integrated framework combining drought indices, MCDA, and environmental flow analysis. While the integration itself is useful, it remains unclear which component constitutes the principal scientific innovation relative to existing MAR suitability assessment frameworks.

Authors' response:

We have added a statement in the Introduction (Lines 65-75) highlighting that the principal scientific innovation of this framework is its shift from static, unconfined-aquifer screening to a dynamic, spatiotemporal assessment specifically designed for confined multi-layer aquifers. This is achieved by integrating time-series drought indices for operational timing and ecological flow thresholds for source-water sustainability.

Changes made in the manuscript:

Introduction Section (Lines 65-75)

Unlike conventional MAR suitability frameworks that primarily focus on static hydrogeological criteria in unconfined aquifers, the principal scientific innovation of this study lies in its dynamic, multi-component integration specifically designed for confined multi-layer aquifers. By coupling GIS-MCDA with time-series drought indices (SPEI/SGI) to trigger recharge operations, and ecological flow thresholds to safeguard source water, the framework transitions from a purely spatial screening tool to a spatiotemporal, climate-resilient operational blueprint for ASTR.

2-The suitability assessment represents one of the core outputs of the study, yet no uncertainty analysis appears to be conducted.

Authors' response:

We agree that addressing uncertainty is critical. We have added a paragraph in Section 4.3 detailing our uncertainty approach. We used the sensitivity analysis on criterion weighting (Table S3) to demonstrate the robustness of the suitability map across different scenarios. Additionally, we clarified that the strict application of absolute constraint masks (e.g., Well Protection Zones) significantly mitigates spatial uncertainty and prevents false-positive site selections.

Changes made in the manuscript:

Section 4.3 (After Line 395)

To address uncertainty in the MCDA suitability assessment, we conducted a sensitivity analysis on criterion weighting (Table S3), which demonstrated that the spatial distribution of highly suitable zones remains robust across different weighting scenarios (S1, S2, S3). Furthermore, while uncertainties exist in the 3D hydrogeological model inputs (e.g., K and storativity), the application of strict absolute constraint masks (e.g., Well Protection Zones 1-2, water bodies) significantly reduces the risk of false-positive site selection, ensuring a conservative and reliable final suitability map.

Section 3.4 (Lines 262-265)

We combined all criteria using a weighted overlay approach. To address potential subjectivity in criterion weighting, we conducted a sensitivity analysis comparing three scenarios: S1 (equal weighting), S2 (hydrogeology-focused, prioritizing storativity and conductivity), and S3 (distance-focused, prioritizing proximity to source water and wells). This analysis demonstrates the framework's robustness and transferability without relying on single-factor prioritization (Table S3 in the Supplementary Material).

Supplementary Material (Table S3)

Table S3: MCDA weighting scenarios for sensitivity analysis

Scenarios	Storativity	Hydraulic conductivity	Depth	Land Use	Distance to source	Distance to wells
S1 (equal weight)	0.167	0.167	0.167	0.167	0.167	0.167
S2 (hydro-heavy)	0.25	0.25	0.20	0.10	0.10	0.10
S3 (distance-heavy)	0.10	0.10	0.10	0.15	0.275	0.275

Section 4.3 (revised text)

We developed an ASTR suitability map using GIS-MCDA (Fig. 6). The analysis integrated six criteria (Fig. 4a), classified into five classes: very low (0-20), low (21-40), moderate (41-60), suitable (61-80), and highly suitable (81-100).

Sensitivity Analysis Results: We tested three weighting scenarios (Table 2). Results demonstrate high robustness (Fig. 6; Table 3). The "Very Low" suitability class remained stable at ~29% across all scenarios (variation <0.3%), indicating physical constraints consistently define unsuitable areas. The "Suitable" class showed moderate variation (36.7-43.3%; $\Delta = 6.6\%$), while "Highly Suitable" areas varied between 17.2% (S3) and 27.7% (S2) ($\Delta = 10.5\%$).

Despite percentage variations, the spatial distribution of high-suitability zones remained geographically consistent across all scenarios (Fig. 6a-c), confirming that site suitability is primarily controlled by underlying physical characteristics rather than subjective weight assignment (Hani et al., 2023; Vandala and Mahed, 2025).

Baseline Scenario (S1) Results: Under the equal-weight baseline scenario (S1), 19.5% of the area (670 km^2) was highly suitable, and 43.3% (1,484 km^2) suitable. Combined, 62.8% of the catchment (2,154 km^2) is viable for ASTR. Highly suitable zones concentrate where Aquifer 2 has higher storativity ($>5\times10^{-3}$) and K (>30 m/d), optimal distances to rivers (500–800 m) and wells (<10 years travel time), and minimal land-use conflicts.

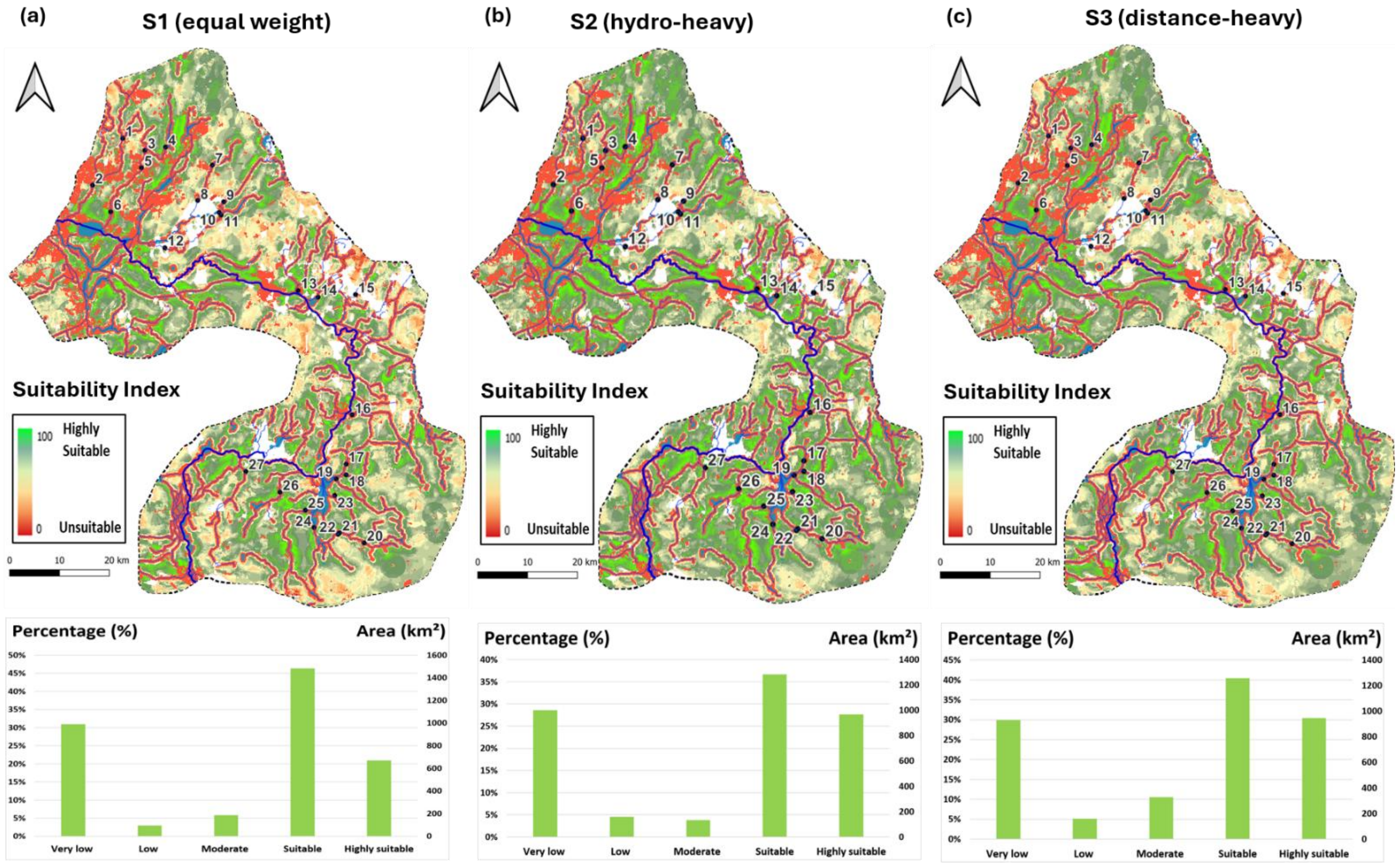

Figure 6. Sensitivity analysis of ASTR site suitability under three MCDA weighting scenarios: (a) S1 (equal weight), (b) S2 (hydro-heavy), and (c) S3 (distance-heavy). Bar charts show the percentage (%) and area (km²) per suitability class. The consistent spatial distribution of high-suitability zones across scenarios demonstrates the robustness of the MCDA results to criterion weighting. See Tables 2–3 for detailed weights and distributions.

Table 3: Suitability class distribution across weighting scenarios

Suitability class	S1 (%)	S2 (%)	S3 (%)	S1- S2	S1- S3
Very low	28.92	28.63	28.84	0.29	0.08
Low	2.82	3.21	2.92	-0.39	-0.1
Moderate	5.4	3.78	10.56	1.62	-5.16
Suitable	43.31	36.72	40.46	6.59	2.85
Highly suitable	19.56	27.66	17.22	-8.1	2.34

3-The manuscript should better explain how key hydrogeological controls on ASTR performance are represented. Factors such as aquifer heterogeneity, vertical hydraulic conductivity, leakage through confining units, storage properties, groundwater age, and geochemical compatibility can significantly influence recharge efficiency and recovery rates. The current framework appears to evaluate site suitability largely from a screening perspective and may therefore overestimate practical feasibility. The authors should discuss these limitations more explicitly.

Authors' response:

We thank the reviewer for this crucial point. We added a paragraph in the Discussion explicitly acknowledging that as a regional screening tool, the framework may overestimate practical feasibility. We listed the key local hydrogeological controls that must be evaluated in future site-specific pilot studies.

Changes made in the manuscript:

Discussion (After L 525)

As a first-tier regional screening tool, our framework may overestimate practical feasibility if applied directly to operational design. Critical local controls, such as vertical hydraulic conductivity, leakage through confining units, groundwater age, and geochemical compatibility, are not explicitly resolved at this scale and must be evaluated in subsequent site-specific pilot studies.

4-The manuscript would benefit from independent validation of the suitability results. For example, the identified high-potential zones could be compared with existing MAR facilities, groundwater management schemes, hydrogeological investigations, or known recharge-favorable areas. Without external validation, it remains difficult to evaluate whether the suitability map reflects actual field conditions or methodological artefacts.

Authors' response:

We thank the reviewer for this valuable comment. We have added a clarification in the Discussion regarding validation. Although direct validation is limited by the absence of operational ASTR schemes in the region, the identified high-potential zones show agreement with known favorable hydrogeological areas, providing indirect validation. Future work will apply transient groundwater flow modeling (e.g., MODFLOW) to further evaluate storage efficiency and recovery performance.

Changes made in the manuscript:

Discussion (After L 525)

While this framework identifies potentially suitable recharge volumes at the regional scale, it does not simulate local hydraulic consequences. Future site-specific validation using transient groundwater flow modeling (e.g., MODFLOW) will be required to assess hydraulic responses, storage efficiency, recovery performance, and potential impacts on neighboring users, thereby bridging the gap between regional screening and operational implementation.

5-ASTR systems are generally most valuable during prolonged drought periods, which are precisely the periods when surface-water availability becomes most constrained. Consequently, mean annual recharge volumes may not accurately reflect operational feasibility. The authors should evaluate recharge availability during critical low-flow years and discuss how climate variability and drought persistence affect the reliability of source-water supplies.

Authors' response:

We thank the reviewer for this crucial point. We have added an analysis of the severe drought year 2018 (new Table S3), which demonstrates MAR volume reductions of 40–100% compared to long-term means (Results show that under Approach 1, MAR volumes dropped by 6–100% (mean 41%), and under Approach 2 by 20–100% (mean 77%) compared to long-term means (see new Table S3)). We clarified in Section 4.4, the Abstract, and the Conclusion that mean annual figures may overestimate drought-period reliability. Furthermore, we explicitly emphasized that the primary operational value of ASTR lies in capturing surplus wet-period flows for later recovery, rather than relying on constrained surface-water availability during droughts.

Changes made in the manuscript:

Section 4.4 (end of section)

While mean annual MAR volumes provide a useful baseline, analysis of the severe drought year 2018 reveals substantial reductions (40–100% depending on site and threshold, Table S3). This confirms that mean annual figures can overestimate operational reliability during prolonged dry periods. However, the core operational value of ASTR lies precisely in capturing surplus flood flows during wet periods for storage and subsequent recovery during droughts, rather than relying on constrained surface-water availability during the drought itself.

Abstract

Under mean annual conditions, site-specific recharge volumes range from 1.6–4.3 Mm^3, though these volumes drop substantially (40–100%) during severe drought years (e.g., 2018), emphasizing the necessity of capturing wet-period surpluses.

Conclusion

While mean annual estimates indicate significant potential, drought-year constraints highlight the importance of capturing wet-period surplus—the fundamental rationale for ASTR implementation.

Table S3

Table S3. MAR-eligible volumes (Mm³) during drought year 2018 vs. mean annual values.

Site	Approach 1 (2018/Mean)	Approach 2 (2018/Mean)
1	0.3 / 0.6 (50%)	0.0 / 0.4 (0%)
2	1.5 / 1.6 (94%)	1.2 / 2.0 (60%)
4	0.6 / 1.3 (46%)	0.0 / 0.9 (0%)
12	3.2 / 4.4 (73%)	0.0 / 3.0 (0%)
13	0.0 / 1.1 (0%)	0.0 / 0.9 (0%)
15	0.9 / 1.0 (90%)	0.4 / 0.5 (80%)

6-The framework identifies potentially available recharge volumes but does not evaluate their hydraulic consequences within the receiving aquifer system. Groundwater flow modelling could provide valuable information regarding water-level recovery, storage efficiency, recovery ratios, residence times, and potential impacts on neighbouring users. The absence of such analysis limits the ability to translate suitability results into operational recommendations.

Authors' response:

We thank the reviewer for this valuable comment. We agree that groundwater flow modeling represents an important next step for translating regional suitability results into site-specific operational recommendations. We have clarified in the Discussion that the current framework provides a regional screening assessment, while transient groundwater flow modeling will be applied in future work to evaluate hydraulic responses, storage efficiency, recovery performance, and potential impacts on neighboring users.

Changes made in the manuscript:

Discussion (After L 525)

While this framework identifies potentially suitable recharge volumes at the regional scale, future site-specific validation using transient groundwater flow modeling will assess hydraulic responses, storage efficiency, recovery performance, and potential impacts on neighboring users, bridging the gap between regional screening and operational implementation.

7-The economic evaluation appears to rely on generalized literature-derived unit costs. However, ASTR economics are strongly site-specific and influenced by infrastructure requirements, treatment processes, monitoring obligations, energy costs, regulatory constraints, and long-term maintenance expenditures. The authors should provide a more detailed discussion of the uncertainties associated with the estimated savings and assess the sensitivity of the results to variations in cost assumptions.

Authors' response:

We thank the reviewer for highlighting this critical issue. We have already addressed this concern in our response to Reviewer 1 (Comment 6) by: (1) adding Table 4 summarizing European cost benchmarks with explicit uncertainty notes; (2) inserting a dedicated paragraph in Section 3.6 detailing ±30% site-specific cost variability; (3) scaling back all savings claims to "order-of-magnitude estimates" in the Abstract and Discussion; and (4) removing specific monetary figures (€23–111M) to avoid false precision. These revisions comprehensively address the uncertainties in literature-derived costs and emphasize that detailed techno-economic assessments are required before investment decisions.

8-Since the proposed framework is intended to enhance drought resilience, its application under future climate conditions should be explored. Incorporating climate projections or at least discussing the potential impacts of changing precipitation patterns, evapotranspiration rates, and streamflow regimes would considerably strengthen the long-term relevance of the study.

Authors' response:

We thank the reviewer for this valuable point. We have added a discussion paragraph addressing the application of our framework under future conditions. We clarified that while our demand projections incorporate future socio-economic pathways (SSP1 and SSP2), the supply-side assessment relies on historical flow regimes. We explicitly noted that projected increases in evapotranspiration and precipitation variability will likely make future surface-water availability more intermittent, reinforcing the necessity of our restrictive Approach 2 to ensure operational viability and ecological safety.

Changes made in the manuscript:

Discussion (After line 515)

While our demand projections explicitly incorporate future socio-economic pathways (SSP1 and SSP2), the supply-side assessment of surface-water availability in this study relies on historical flow regimes. Given projected increases in evapotranspiration and precipitation variability in Central Europe, future surface-water availability for ASTR will likely become more intermittent and constrained. This anticipated shift reinforces the necessity of the restrictive Approach 2, which prioritizes the capture of extreme flood peaks, ensuring that ASTR operations remain ecologically safe and operationally viable even as baseline flows decline under future climate conditions.

9-The future water-demand and climate assessment is based on RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. However, the manuscript does not justify the use of the RCP framework instead of the more recent SSP-RCP scenario framework adopted in CMIP6 and the IPCC AR6. Given that socioeconomic development constitutes a central component of future water demand, the use of standalone RCPs may not adequately represent the interactions between climate forcing and socioeconomic pathways. The authors should clarify:

(i) whether the climate projections originate from CMIP5 or CMIP6 datasets;

(ii) why SSP-based scenarios (e.g., SSP1-2.6, SSP2-4.5, SSP5-8.5) were not considered;

(iii) how socioeconomic assumptions were incorporated into the demand projections; and

(iv) whether the projected climate variables were bias-corrected prior to their use in the hydrological assessment.

Authors' response:

We thank the reviewer for this crucial correction. We have updated the manuscript to explicitly use the combined SSP-RCP framework (SSP1-2.6 and SSP2-4.5), aligning with IPCC AR6, as this was the framework applied by our project partners for assessing socio-economic dimensions. To address the specific points raised: (i) The climate projections are based on regionalized datasets (UBA) aligned with established CMIP ensembles. (ii) The SSP-RCP framework was used to properly capture the interactions between climate forcing and socio-economic pathways. (iii) Socioeconomic assumptions were incorporated using detailed, sector-specific water demand projections from local stakeholders (BWB, Adelphi Research, ZALF) mapped to SSP narratives. (iv) Yes, the projected climate variables were bias-corrected and rigorously calibrated against observed historical records (DWD, LfU) within the hydrological model.

(Note: SSP5-8.5 was excluded per recent scientific consensus on its unrealistic trajectory).

Changes made in the manuscript:

Section 3.3 (Lines 222-230)

Projections were developed using the combined SSP-RCP scenario framework (specifically SSP1-2.6 and SSP2-4.5), aligning with the IPCC AR6 and recent German Environment Agency (UBA) regional climate projections (Kreienkamp et al., 2022). This framework explicitly integrates climate forcing with socioeconomic pathways, providing a more robust representation of future water demand interactions. SSP1-2.6 represents a sustainability-oriented pathway, while SSP2-4.5 represents a middle-of-the-road pathway. (Note: The high-emission SSP5-8.5 scenario was excluded, as recent scientific consensus considers it an unrealistic trajectory). Socioeconomic assumptions for water demand were incorporated via detailed, sector-specific projections from local utilities and research institutes (e.g., BWB, Adelphi Research, ZALF). Furthermore, the projected climate variables were bias-corrected and calibrated against observed historical meteorological and hydrological records within the SWIM hydrological model to ensure the reliability of the water-balance estimates.

10- Since hydrological simulations are highly sensitive to biases in precipitation and temperature, the absence of information regarding bias correction raises concerns about the reliability of the projected water-balance estimates. A detailed description of the downscaling and bias-correction procedures is therefore necessary.

Authors' response:

We thank the reviewer for highlighting this important methodological detail. We clarify that no standalone RCP climate scenarios were used in this study; the previous RCP terminology was incorrect and has been replaced with the SSP framework throughout the manuscript. Climate inputs were derived from bias-adjusted and spatially downscaled datasets (W5E5v2.0 and ISIMIP Phase 3). Furthermore, the reliability of these bias-corrected inputs was verified by comparing simulated historical streamflows against observed discharge records, ensuring robust water-balance estimates.

Changes made in the manuscript:

Section 3.3 (After line 215)

To ensure the reliability of the water-balance estimates, we derived climate inputs from bias-adjusted and spatially downscaled datasets. Historical model calibration and validation were performed using the W5E5v2.0 dataset, which is bias-adjusted against observational records (Lange, 2019). The reliability of these inputs was further evaluated by comparing simulated historical streamflows with observed discharge records, ensuring a robust representation of the regional water balance.

References

Lange, S., & Büchner, M. 2021. ISIMIP3b bias-adjusted atmospheric climate input data. ISIMIP Repository. https://doi.org/10.48364/ISIMIP.842396.1