

Reply to anonymous referee 5

We would like to thank the anonymous referee 5 for his comments on the manuscript and we are glad he finds this work presents an interest for the hydrogeological community. We provide a response to each comment hereafter.

Major Comments:

1. *The manuscript currently spends considerable space to describe the comprehensive modeling systems, but the relationships among the different components are not clear. The context includes extensive jargon and acronyms, making it difficult to identify which model components are central to the study. For example, in Section 2.2.2, Aquifer is described as using two groundwater models, EauDyssée and MODCOU. However, their conceptual and structural differences are not clearly articulated. It also remains unclear why two groundwater models are required for different aquifers rather than a unified modeling framework. I fully understand this is a community effort and credit should be fully acknowledged, but to make the manuscript's message clear and scientifically meaningful, I suggest the authors to pick up the most relevant components for description.*

- Reply: the referee is right in saying that many acronyms are used, that blur the description of the modelling chain, particularly the Aquifer platform. As the referee pointed out, the platform was developed through a collaborative effort with the aim of utilising existing models (modelling software packages running on specific areas) and leveraging the expertise of each contributor who developed the model (Vergnes et al., 2020). In this paper, we consider two hydrogeological modelling software packages: EauDyssée and MARTHE. Both are dedicated to simulate specific aquifers in particular regions, in order to address the needs of local stakeholders. Therefore, their performances are deemed optimal in the areas simulated, which is consistent with Aquifer's philosophy, and respects its operational use, as mentioned in lines 139-140. We agree that this point may be unclear and we propose adding the following sentence at the line 136:

“The philosophy of the platform is to regroup existing models, one model is defined as a pair of catchments and the hydrogeological modelling software used. Each model is developed and configured for a specific region to meet the needs of stakeholders. The platform was assessed over a sixty-year period [...]”

Regarding the differences inherent to MARTHE and EauDyssée, the descriptions of the two modelling software packages were shortened to address the request of referee 1 in the first review cycle, and we proposed referring the reader to Vergnes et al. (2020) for further details. As referee 1 eventually accepted the paper, we propose not adding any further elements, but reducing the use of acronyms as much as possible to improve clarity. Furthermore, we propose emphasising the relationships between the different elements of the modelling chain more clearly.

2. *An important element is missing from the current study: the model simulation during the historical period should be validated against observations. Such validation is essential to demonstrate confidence in the models' ability to represent groundwater dynamics before applying it to future climate projections.*

- Reply: the referee is right; this kind of evaluation is necessary, particularly when analysing future changes in relation to a reference historical simulation. As mentioned in lines 135–139 of the previous version of the manuscript, Vergnes et al. (2020) evaluated

the performance of Aquifer platform simulations over a sixty-year period by comparing them with piezometric heads from the ADES ("Accès aux Données sur les Eaux Souterraines") database (<http://www.adeseaufrance.fr/>, last access the 29th November 2024, Chery and Cattani (2003)). The Aquifer platform demonstrated good performance. To avoid duplicating information in this paper, we propose not adding any further analysis on this topic and instead directing the reader to Vergnes et al. (2020).

3. In the result part, the manuscript mainly presents groundwater level projections without sufficiently analyzing the processes driving those changes. The forcings that drive groundwater variability, such as precipitation, evapotranspiration, recharge, and river-aquifer interaction regimes, and topographic and hydrogeologic factors that shape groundwater heterogeneity, are not systematically presented or discussed. Without such process-based analysis, it is difficult to assess whether differences arise from climate forcing, hydrological parameterization, or structural model differences. I strongly encourage the authors to include analyses on the components below in their result presentation:

- Changes in precipitation and recharge across scenarios;
 - Changes in river discharge or surface water interactions where relevant;
 - A structured discussion linking climate forcing --> recharge --> groundwater level response.
- Reply: on his first comment, the referee 4 from the last review cycle made a similar remark. In response, we provided additional information on the water balance, including precipitation, real evapotranspiration, and aquifer recharge, as represented by the drainage and runoff variables simulated by the SURFEX land surface model. For the three RCPs, we focused the analysis on the long-term horizon by representing the quantiles Q10, Q50 and Q90 of the future relative change for the four variables. To avoid including too much information in the paper, a concern raised by the first three referees who asked us to reduce its size and to focus the results on the important results (here, groundwater levels), we proposed adding this analysis to the supplementary material. This analysis is provided in appendix D of the current version, and we use its results for the discussion in:
- section 4.1.1 to discuss the origin of the uncertainty observed on the SPLI (lines 376-389);
 - section 4.2 to discuss how future groundwater will evolve.

We propose to not add the evolution of the water balance into the results section, because it would imply to change the entire shape of the paper which was already accepted as it stands by one referee, and we think that the topic of the present paper deals with groundwater levels and it is important to let the reader focused on it. Moreover, bringing new information would increase its length which contradicts the requirements raised by the three referees. However, to answer to answering the referee 5's comment, we propose to rephrase the paragraph at lines 456-461:

"In section 4.1.1, we demonstrated that this contrast is already visible in earlier stages of the modelling chain, in particular on the drainage and runoff variables simulated by SURFEX and which constitute the main drivers of the aquifers recharges (see Appendix D). For RCP8.5 (see Figure D4), the North-South divide is already visible for precipitation and real evapotranspiration but the contrast remains moderate. Conversely, the contrast is much clearer for the groundwater recharge term across the three quantiles, particularly for drainage, with northern France becoming wetter and southern regions drier. Note that the Q90 quantile still highlights a decrease in drainage in regions close to the

Pyrenean mountains. All these elements are consistent with joint research from the EXPLORE2 project on groundwater recharge (Lanini et al., 2024) and surface hydrology (Jaouen et al., 2025; Trambly et al., 2025; Sauquet et al., 2026).”

4. Potentially related to the previous point, the study employs six GCMs to generate climate forcing. However, there is little discussion of how these GCMs differ in terms of their physical representations (e.g., precipitation bias structure, evapotranspiration sensitivity, circulation patterns), which directly influence recharge and groundwater dynamics. Including a concise description of key structural differences among the selected GCMs would help readers interpret why groundwater responses differ under different climate forcings. At minimum, a short summary of known characteristics (e.g., wetter/drier bias tendencies, seasonal precipitation shifts, etc.) would strengthen the interpretation of ensemble spread.

- Reply: the referee is right in saying that the inherent characteristics of each GCM will influence recharge and, consequently, groundwater. However, focusing solely on GCMs would not be rigorous, as Evin et al. (2025) highlighted that RCMs contribute the most to the uncertainty between members regarding precipitation, which is the main factor influencing groundwater dynamics. Therefore, to be accurate, we should investigate the patterns related to the 17 GCM/RCM couples regrouped in the Explore2 ensemble. Such an analysis has already been carried out by Marson et al., (2026), and including it in the present paper would be redundant and would require excessive space in an already lengthy paper, as stated by three previous referees. Furthermore, we believe that it would exceed the scope of the present paper, which aims to assess the future of groundwater in a probabilistic way using all available climate projections, and considering each storyline individually, in line with the recommendations of the Explore2 project. Additionally, the use of storylines already slightly highlights the inherent bias of the four corresponding GCM/RCM couples and their impact on groundwater for the purposes of this paper. However, we propose rephrasing paragraph at lines 123–126 in order to explain this divergence and refer the reader to Marson et al. (2026) for further details:

“The large number of GCM/RCM couples in the EXPLORE2 ensemble is one of the project's main strengths, which allows to better account for uncertainty when extracting future trends using a probabilistic approach. Evin et al. (2025) identified climate components as being the primary source of uncertainty in particular for precipitation, which is the main factor influencing recharge and, consequently, groundwater. Indeed, the climate models can produce different results for the same future scenario, depending on the formulation and parametrisation of physical and thermodynamic processes, which can vary considerably from one model to another, as well as on the spatial resolution. Further details on the biases induced by each specific GCM and RCM can be found in Marson et al. (2026).

In light of this divergence, which limits the extraction of future trends using a probabilistic approach, a second approach is adopted. This approach involves selecting four contrasting storylines (i.e., CPs based on contrasted trends) from the available GCM/RCM couples using the RCP8.5. This allows us to focus on four contrasting possible futures (Shepherd et al., 2018; Shepherd, 2019). Unlike the probabilistic approach, the aim here is to consider each narrative individually to maintain its physical consistency without mixing it with the other narratives in the set. The selected storylines are [...]”

Minor Comments:

1. Line 4: “CMIP5”: Since there are updated results from CMIP6, why not use the latest one but CMIP5? At least the author should explain the reason.

- Reply: The CMIP6 projections were not used here since they have not yet been downscaled or bias-corrected at a regional level. Therefore, they are still unusable for regional studies. However, each climate projection from the EXPLORE2 dataset was compared to the CMIP6 ensemble and found to be compatible with regard to relative changes in precipitation and temperature (Marson et al., 2026). We propose to add this information before the line 140 of the previous submitted version while describing the used climate projections:

“It should be noticed that the latter CMIP6 projections are not used here, since they have not yet been downscaled or bias-corrected at the regional level. However, the EXPLORE2 dataset was compared with projections from CMIP6, and the projections used here are included within the CMIP6 confidence interval (Marson et al., 2026). This lends credibility to the use of these climate projections, particularly given that they have been used in recently published papers (Tramblay et al., 2025; Sauquet et al., 2026).”

2. Line 16: “high and low flow events”: In terms of groundwater, groundwater levels high or low are not necessarily related to high/low groundwater flow. The authors might want to rephrase the wording here.

- Reply: as requested, we rephrased the sentence:

“The increase in the severity of events is a well-known consequence of climate change on surface hydrology, but is less prevalent in groundwater hydrology, which is characterised by a longer residence time.”

3. Line 57: “two distributed hydrogeological modelling ...” Please specify which two

- Reply: the two distributed hydrogeological modelling are described in section 2.2.2. To avoid repetition, we propose to not specify their names at the line 57.

4. Line 111: what is quantile mapping and why it should be quantile-based, not the original value based?

- Reply: for each climate variable, quantile mapping involves comparing the cumulative density function of the variable from a climate projection with the one from a reference meteorological database over a historical period (Potter et al., 2020). The obtained functions are then combined into a mapping function covering the entire spatial grid, on the assumption that the meteorological reference and the climate projection are projected onto the same grid. This mapping function is calculated for each typical month of a hydrological year. Ultimately, the mapping function is applied to future climate values to obtain a bias-corrected time series for each pixel. As quantile mapping is a common bias-correction method in regional-scale climate projection studies, we propose not adding any supplementary information to the already manuscript deemed too long.

5. Line 119: “gaz”, typo, should be “gas”

- Reply: as requested, the word “gaz” has been replaced by “gas”.

6. *Line 159: This is interesting. The authors may need to explain more about why groundwater contribution is this low. Is it because groundwater level is generally deep in France?*

- Reply: the referee's observation is correct: the limited contribution of groundwater to evapotranspiration—which encompasses both plant transpiration and soil evaporation (Vergnes et al., 2014)—is primarily due to the depth of French aquifers. These aquifers typically lie below the root zone, preventing direct transpiration, as plant roots cannot access them. Additionally, the water potential gradient is insufficient to overcome this physical limitation. While upward capillary fluxes in the soil could theoretically facilitate ground evaporation, this phenomenon remains limited in the aquifers included in the AquifR platform. Most of these aquifers are sedimentary in nature (Vergnes et al., 2020), characterized by a soil matrix with low permeability, which restricts the upward movement of water through capillary action. We suggest not including further details on this topic in the manuscript, as previous reviewers emphasised the need for a concise description of AquifR, and such additions would not provide essential insights for the study.

7. *Line 182: “homogeneous format”, what does it mean? What format?*

- Reply: here, we are referring to the format in which the results are provided to the user. The modelling software packages included in AquifR, i.e., MARTHE and EauDyssée, produce results in their own specific format. One advantage of AquifR is that the outputs are post-processed and provided in the same netCDF format, regardless of the model, making them easier for users to work with. The results are projected over an irregular spatial grid with a resolution ranging from 100 m to 2,000 m.

8. *Line 194-195: Why to use different models for different aquifers? The authors need to clearly explain their motivation (pros and cons of each model)*

- Reply: as answered to the referee's first major comment, the platform was developed through a collaborative effort with the aim of utilising existing models. In the case of the Somme catchment, two models were already existing, one using MARTHE and the other using EauDyssée. However, they did not cover exactly the same area and they only partially overlapped. Therefore, the choice was made to include them both into the AquifR platform to optimise the spatial extent covered by the AquifR platform

9. *Line 228, Table2: What's the criteria to determine the thresholds for each category?*

- Reply: the thresholds for each category are commonly used for each normalised indicator, which are designed similarly to the Standardised Precipitation Index (SPI), including the SPLI. The SPI was designed by McKee et al. (1993) to analyse drought events over several time scales, with a particular focus on return periods of 2.5, 5 and 10 years. For a given category, the SPI (here, SPLI) value corresponds to the frequency associated with the return period of this category, as extracted from a frequency curve calculated over a period of at least 30 years.

10. *Line 312, Figure 3: Why there are missing panels? Is it because no GCM data available? The authors need to indicate this in caption.*

- Reply: the referee is right, the missing panels indicate the GCM/RCM couples not included in the EXPLORE2 climate projection dataset. As requested, this element has

been specified in the caption of Figure 3, as well as in the captions of the corresponding figures in supplementary material.

Reply to anonymous referee 6

We would like to thank the anonymous referee 6 for his comments on the manuscript and we are glad he finds this work presents an interest for the hydrogeological community. We propose an answer for each specific comment hereafter.

Comments:

1. *The novelty of the work is still not articulated clearly enough. I encourage the authors to refine the framing of the manuscript and to state more explicitly where the scientific contribution lies. In particular, the contribution appears to lie in the integrated use of a large regional climate-projection ensemble, a physically based multi-aquifer hydrogeological platform, SPLI-based comparison across heterogeneous aquifer systems, and storyline-based interpretation for risk communication. The authors should also better explain the relevance of this framework beyond the French context, especially for regions where groundwater projections are strongly affected by climate-model uncertainty and spatially heterogeneous recharge responses. Clarifying this broader relevance would strengthen the contribution of the manuscript.*

- Reply: the referee is right; we propose to better emphasise the novelty of the work by:
- adding the following sentences after the line 52 to introduce the storyline in the introduction section:

“Given the potential divergence in results derived from climate projection datasets, a second approach has recently emerged: the use of storylines. These are contrasted climate projections, each based on distinct design assumptions (Shepherd et al., 2018). The objective is to emphasis the variability of climate change impacts while maintaining the physical consistency of each projection, avoiding the aggregation of results as in probabilistic approaches.”

- rephrasing the sentence at lines 73-76, where the novelty of the paper is first stated:

“The primary contribution of this paper lies in its utilisation of a large ensemble of climate projections used to better account for climate internal variability—a dimension that has been poorly carried out in the literature, particularly with respect to the evolution of groundwater under climate change. Additionally, this work places specific emphasis on four contrasting projections from the EXPLORE2 dataset. These projections are employed as storylines to illustrate the diverse impacts of climate change on groundwater, an approach that, to the best of our knowledge, has not yet been carried out in the literature. Finally, the use of the Aquifer platform enables the integration of heterogeneous aquifer systems, representing another key strength of this study.”

- rephrasing the sentences at lines 342-347:

“As highlighted in the introduction section, the use of such an extensive range of CPs enables a robust assessment of uncertainties associated with internal climate variability. When combined with the exploration of four distinct storylines to illustrate contrasting future scenarios, this methodological approach remains rare in the existing literature, particularly in studies examining groundwater dynamics under climate change. Furthermore, the Aquifer platform provides a noticeable advantage by accounting for the heterogeneity of aquifers across hexagonal France. This capability is further enhanced by the integration of the SPLI, which facilitates spatially explicit

analyses of future groundwater level trends. Collectively, these elements—the CP ensemble, the storyline-based approach, and the high-resolution aquifer modelling—represent the primary scientific advancements of this paper, with direct implications for groundwater management and climate adaptation strategies.”

- Adding the following sentence after the line 389:

“Note that the uncertainties highlighted in the CP ensemble—and their propagation through the modelling chain—may be transferable to other mid-latitude regions where, as mentioned above, precipitation projections exhibit high variability due to the precipitation inherent chaotic nature (Nuissier et al., 2011; Fereday et al., 2018).”

2. The description of the SURFEX–AquiFR coupling has been improved, but the modelling assumptions regarding boundary conditions remain insufficiently explicit. The authors should clearly state whether future groundwater changes are driven only by climate-induced changes in SURFEX-derived drainage and runoff, or whether other factors such as river boundary conditions, river stages, groundwater abstraction, land use, and direct groundwater evapotranspiration are also modified. A short clarification in the methods section would help readers understand whether the study isolates the climate-change signal or represents combined climate and anthropogenic influences.

- Reply: the point of the study is to isolate the climate-change, following one major requirement of the EXPLORE2 project. This demand is motivated first because it allows a more rigorous analysis without mixing several factors, and second because adding factors such as the evolution of anthropic response to climate change would be too difficult to add to the evaluation. All the elements related to human activities are supposed constant over the 21st century regardless the socio-economical scenario. This includes land use and groundwater abstraction. The latter is simulated using a climatology-based approach involving historical data of groundwater abstraction at a monthly time step. To better emphasize this point, we propose

- to reformulate the sentence at lines 77-81:

“It is important to clarify that this study does not explicitly address the impacts of anthropogenic factors on water resources, as the EXPLORE2 project was designed to disentangle climate change impacts from those of human activities. This separation aims to provide stakeholders with clear, actionable insights for developing targeted adaptation measures. Consequently, all anthropogenic factors, including land use and groundwater abstraction, are held constant throughout the 21st century simulations. Nevertheless, previous work using the AquiFR platform has demonstrated that groundwater abstraction, by inducing declines in groundwater levels, can substantially reduce aquifer-river exchange fluxes, with significant implications for headwater basin dynamics (Guillaumot et al., 2024).”

- to add the following sentence before the line 179:

“Furthermore, groundwater abstraction is simulated at a monthly time step for each model, using a climatology-based approach that relies on historical data. As stated in the introduction section, groundwater abstraction rates are assumed

to remain unchanged in future projections, thereby allowing the isolation of climate change impacts on groundwater dynamics.”

Furthermore, although EauDyssée and MARTHE simulate rivers discharges and groundwater-river exchanges, this study focuses exclusively on groundwater level projections. This decision is based on two key considerations: (1) the emphasis here is on groundwater dynamics, a less documented yet critical aspect of water resource management; (2) future river discharge projections under climate change are already comprehensively addressed in other studies within the EXPLORE2 project (Tramblay et al., 2025; Sauquet et al., 2026). The referee is right, that point is unclear in the paper, and we propose to add the following sentence at the line 179:

“While EauDyssée and MARTHE simulate rivers discharges and groundwater-river exchanges, this study focuses exclusively on groundwater level projections. The choice is motivated to focus the reader attention of groundwater levels and because studies included in the EXPLORE2 project already carry out the future evolution of river discharge under climate change over hexagonal France (Tramblay et al., 2025; Sauquet et al., 2026).”

As for direct groundwater evapotranspiration, we mentioned at the lines 157-159 that the contribution of groundwater to actual evapotranspiration is less than 2% over hexagonal France (Decharme et al., 2019), and therefore deemed negligible. This limited contribution, regrouping both plant transpiration and soil evaporation (Vergnes et al., 2014), is primarily due to the depth of French aquifers. These aquifers typically lie below the root zone, preventing direct transpiration, as plant roots cannot access them. Additionally, the water potential gradient is insufficient to overcome this physical limitation. While upward capillary fluxes in the soil could theoretically facilitate ground evaporation, this phenomenon remains limited in the aquifers included in the AquiFR platform. Most of these aquifers are sedimentary in nature (Vergnes et al., 2020), characterized by a soil matrix with low permeability, which restricts the upward movement of water through capillary action. We propose not including further details on this topic in the manuscript, as earlier reviewers emphasised the need for a concise description of AquiFR, and such additions would not provide essential insights for the study.

3. The use of SPLI is appropriate because it enables comparison of groundwater-level anomalies across heterogeneous aquifer systems. However, the manuscript should avoid overstating the novelty of the index itself, as SPLI is conceptually close to other standardized groundwater-level or groundwater-drought indicators. The authors should emphasize that the main contribution lies in applying SPLI within a large climate-projection ensemble and the AquiFR multi-aquifer modelling framework.

- Reply: The referee is right. As requested by the referee’s comment 1, we rewrote the paragraphs highlighting the novelty of this paper in the introduction and discussion section (see the authors’ response to the referee’s comment 1).

4. The manuscript still contains a number of grammatical, spelling and formatting issues. These are minor issues, but they affect the readability and polish of the manuscript, and I recommend a careful final proofreading.

Line 14, “This accompanied by” should be “This is accompanied by”;

Line 16, “high and low flow events” is not fully appropriate for groundwater and could be replaced by “high and low groundwater-level events”;

Lines 70–74, “an multi-model ensemble approach” should be corrected to “a multi-model ensemble approach” and “The large number of used projections” should be corrected to “The large ensemble of projections used here”;

Line 135, “french rivers” should be revised to “French rivers”;

Line 158, there is an extra opening parenthesis in “2% ((Decharme et al., 2019)”;

Lines 204–214, “groundwater levels is”, “wheareas”, and “Thrid” should be corrected;

Lines 327–328, “more %50 of the time” should be revised to “more than 50% of the time”.

- Reply: as requested, we addressed all the above-listed issues raised by the referee, and we carefully read the paper for proofreading.

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