

Climate change impacts on groundwater simulated using the **AquiFR** modelling platform

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Abstract. In the context of increasing water stress and climate change, the assessment of changes in groundwater resources is a major challenge for water decision-makers. As part of the EXPLORE2 project, the aim of this study is to estimate changes in groundwater levels over France during the 21st century. We used the hydrogeological modelling platform **AquiFR** together with 36 regional climate projections from Eurocordex (CMIP5) from three Representative Concentration Pathways (RCPs),
5 bias-corrected according to a state-of-the-art method: RCP2.6, RCP4.5 and RCP8.5. In order to better reflect the uncertainties, 4 storylines based on the RCP8.5 scenario have been selected to be representative of possible futures that can illustrate the impacts of worst-case scenarios and help decision-makers to adopt sustainable groundwater management policies. The future evolution of groundwater is assessed using the standardized piezometric level index, a normalized indicator that provides return periods based on the distribution value over a reference period, here 1975-2004. We found significant scatters between regional
10 climate models. Overall, a rise in groundwater levels, affecting most of the study area, is the dominant signal, especially in northern France. This result is in contrast to previous studies in this area. Under RCP8.5 (highest greenhouse gas emissions scenario), the evolution of the occurrence of current 10-year return period events shows a significant increase in the risk of high groundwater levels mostly on the northern part of France, confirmed by 3 out of the 4 storylines, together with an increase in the 10-year low groundwater levels mostly observed in South of France, which is shared by the four storylines. This highlights
15 a North-South differentiation. The increase in high and low flow events is quite common in surface hydrology, but is less common for groundwater, which has a longer residence time.

1 Introduction

In France, groundwater supports 70% of drinking water, for both supply of drinking water to households (Maréchal and Rouillard, 2020) and agricultural purposes. The latter accounts for one-third of agricultural withdrawals (Pasquier, 2017). Therefore,
20 understanding and anticipating future groundwater temporal evolution is crucial for stakeholders and decision-makers involved in the sustainable management of water resources, especially because this evolution depends on both human activities and climate (Baulon et al., 2020; Guillaumot et al., 2024). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) states that a large proportion of hydrological systems (e.g., surface rivers, groundwater tables, ...) are already being affected on a global scale and will be further affected in the coming decades by climate change (IPCC, 2014, 2022). Among the projected

25 changes figures intensification of extreme events in terms of floods and droughts, in both frequency and intensity (Kundzewicz et al., 2014; Prudhomme et al., 2014; Garner et al., 2015), potentially affecting groundwater management.

Several projects have provided a first global assessment of the consequences of climate change on French hydrology, e.g., the EXPLORE 2070 project (Chauveau et al., 2013) using climate projections provided by the Coupled-Model Intercomparison Project 3 (CMIP3) global exercise, or more recent projects using climate projections from the CMIP5 global exercise (Taylor et al., 2012) regionalized over France by Dayon et al. (2018), to assess the future of groundwater on specific watersheds (Boé et al., 2018; Habets et al., 2021). These studies projected a widespread drop in groundwater levels induced by a decrease in recharge of between 10 and 25%, with spatial variations (Stollsteiner, 2012; Habets et al., 2013). Two areas were more severely affected: the Loire basin, with a decrease in recharge of between 25 and 30% over half of its surface; and especially South-West France, with decreases of between 30 and 50%. Completed with surface hydrology assessment, the EXPLORE 2070 project

30 allowed to better measure the magnitude of the challenge of defining national adaptation or attenuation strategies, regarding numerous sectors of activity, e.g., energy and agriculture (Carroget et al., 2017).

However, more recent studies suggest that the impacts of climate change on French hydrological systems, including groundwater, are more contrasted, especially in northern France (Costantini et al., 2023; Vergnes et al., 2023), highlighting the need of a new general assessment of climate change impacts over the French hydrology. Following the IPCC recommendations (IPCC, 2022), the EXPLORE2 project (Marson et al., 2024; Sauquet et al., 2024) aims to update the conclusions of the EXPLORE 2070 project for this purpose. Regarding groundwater, this project is an opportunity to integrate larger study areas and more aquifers of interest.

In such a context, the study of climate change on hydrological systems requires the use of a hydroclimatic modelling chain, ranging from updated greenhouse gas emission scenarios to hydrological indicators, and established as best as possible on a

45 multi-model ensemble approach (Sansom et al., 2013). The principle is to use several radiative forcing scenarios, climate models and hydro(geo)logical models to quantify the uncertainty associated with the projections (Knutti et al., 2013; Rajib et al., 2014). Indeed, each climate model differs in elements such as precipitation distribution (Lafaysse et al., 2014; Shepherd, 2019) which necessarily leads to different projections at the end of the modelling chain. Consequently, using multiple models at each step is strongly recommended (Hingray and Saïd, 2014; Vidal et al., 2016; Hingray et al., 2019). Eventually, the challenge

50 for modellers is to assess the uncertainties inherent to the amount of obtained results, for example by identifying converging patterns or, conversely, the absence of a robust trend from all projections. (Kennel et al., 2016).

In order to provide consistent information on groundwater, the use of models providing realistic representations of aquifer systems is required (Vergnes et al., 2020). Therefore, the hydrogeological part of the modelling chain is often composed of spatially distributed hydrogeological regional models built over specific studies areas at the regional scale (Stollsteiner, 2012; Højberg et al., 2013; Maxwell et al., 2015). In this respect, the hydrogeological platform *AquiFR* (Vergnes et al., 2020) is a relevant candidate as the platform integrates four distributed hydrogeological modelling software packages with several regional applications, in order to account for the heterogeneity of French aquifers. However, although the *AquiFR* platform integrates several hydrogeological software packages, it is not based on a multi-model approach, as each package is applied to a specific catchment and almost no simulated areas overlap spatially. Despite that limit, the *AquiFR* system is already operational for

60 historical reanalysis, real-time monitoring and seasonal forecast of groundwater, when coupled with the SURFEX land surface model to provide recharge over its entire domain (Masson et al., 2013; Le Moigne et al., 2020), especially for the assessment of dry events to help decision-makers (Habets et al., 2021).

As part of a study on the impact of climate change on French groundwater, CMIP5 global climate projections has already been used by Habets et al. (2021) to force Aquifer. Since, projections have been updated and a new assessment is required.
65 Furthermore, Vergnes et al. (2023) have also already assessed the impact of climate change on French groundwater resources, but using a single layer aquifer model and a coarser spatial configuration than Aquifer, with a set of 5 climate projections. All these elements underline the interest of the present work. As part of the EXPLORE2 project, the aim of this study is to assess the impact of climate change projected by regional climate models on several French aquifers of interest. For this purpose, the hydrogeological modelling platform Aquifer is used to simulate hydrogeological projections using an multi-model ensemble
70 approach based on 36 climate projections that used three future socio-economic scenarios. These projections are a subset of the Euro-CORDEX project (Jacob et al., 2020) resulting from the CMIP5 exercise (IPCC, 2014), downscaled with a method combining weather typing and quantile mapping approaches, that are made available on a public database (DRIAS, Soubeyroux et al. (2021)).

It should be noted that addressing anthropisation impacts on water resource is not one of the objectives of this paper, as the
75 purpose of the EXPLORE2 project was to identify climate change impacts and anthropisation impacts separately, in order to help users to engage into adaptation measures. However, previous study performed with Aquifer have shown that groundwater abstraction by declining groundwater level reduces the water exchange between aquifer and river, with significant impact on the head water basin (Guillaumot et al., 2024).

80 2 Material and Methods

2.1 Regionalized climate projections from EXPLORE2

The climate projections (CPs) used to force the Aquifer platform mainly come from the DRIAS-2020 database (DRIAS 2021; <http://www.drias-climat.fr/>, last access the 25th of October, 2024) that provides downscaled and unbiased climate projections on the French domain. It is based on a subset of projections from the Euro-CORDEX project (CooRdinated Downscaling EX-
85 periment – European Domain; Jacob et al. (2020)), which is included in CMIP5 (IPCC, 2014). As part of the implementation of the EXPLORE2 database, the original DRIAS-2020 database has been extended to include the latest EURO-CORDEX simulations with evolving aerosol forcing (Robin et al., 2023) leading to the EXPLORE2-Climat 2022 database.

To obtain future climate variables, General Circulations Models (GCMs; Phillips (1956); Randall (2000)) are forced by Radiative Concentration Pathways (RCPs), greenhouse gas emission scenarios following specific socio-economical trajectories
90 through the 21st century. However, GCM outputs have a coarse spatial resolution around 2.5°, i.e., between 100 and 200 km², which is insufficient to adequately represent local meteorological phenomena and extreme events, and thus prevents their direct use as climate forcing in hydrological models for studies at regional or local scales. Thus prior to use a statistical down-

scaling method, a dynamic downscaling is made by using RCMs (Regional Climate Models) to provide detailed estimates of meteorological parameters (e.g., temperature, precipitation, humidity, wind, solar radiation, ...) at an hourly time step for regional applications using a dynamic downscaling approach (Liang et al., 2008; Tapiador et al., 2020), at a spatial resolution from 10 to 20 km².

Then, the ADjustment to MOuNTain regions (ADAMONT; Verfaillie et al. (2017)) was applied to the RCM outputs to both improve spatial resolution and correct bias according to an historical meteorological reference by a two-steps method:

1. Weather regime computation (Michelangeli et al., 2009; Driouech et al., 2010): each day from both the RCMs and the meteorological reference are clustered into four weather regimes, based on the cluster of the geopotential height at 500 hPa of the ERA-40 analysis, per each one of the four seasons: (1) December, January, February (DJF); (2) March, April, May (MAM); (3) June, July, August (JJA); (4) September, October, November (SON). Then, quantile distributions of each climate variables from both the RCMs and the meteorological reference are computed for the 16 weather regimes/seasons couples (Verfaillie et al., 2017);
2. Quantile mapping (Maurer et al., 2010; Navarro-Racines et al., 2020; Potter et al., 2020): for each couple, quantile mapping is applied on the quantile distributions of RCMs climate variables being adjusted according to the meteorological reference.

The historical meteorological reference used is the SAFRAN reanalysis (Le Moigne et al., 2020), providing "pseudo-observed" data, useful for bias correction all over France.

At the end of the procedure, the CPs simulated by the GCM/RCM couples provide downscaled climate variables at hourly time step and on a regular grid of 8 km × 8 km. The total set gathers 6 GCMs coupled with 9 RCMs, and forced by 3 RCPs : (1) RCP2.6, a stringent mitigation scenario assuming an efficient environmental international policy (van Vuuren et al., 2007); (2) RCP4.5, an intermediate stabilization scenario (Thomson et al., 2011); (3) RCP8.5, a very high green house gaz emission scenario without efficient environmental international policy (Riahi et al., 2011). The EXPLORE2 project uses 17 GCM/RCM pairs forced by 1 to 3 RCPs, for a total of 36 simulations (Table A1 in supplementary material, appendix A), all downscaled and bias corrected by ADAMONT.

Following the recommendations of the EXPLORE2 project, the analyses of CPs were done on four time periods regrouping 1 historical period and 3 future horizons for a total period ranging from 1975 to 2099, considering that an hydrological year is set from august 01st to july 31th (Table 1). Furthermore, four storylines, i.e., CPs based on contrasted trends, were se-

Table 1. Temporal splitting of the climate projections from the EXPLORE2 project

Historical period	Short-term horizon	Intermediate horizon	Long-term horizon
1975-2004	2021-2050	2041-2070	2071-2099

lected from the GCM/RCM couple in the EXPLORE2 project using the RCP8.5, in order to focus on four contrasted possible futures(Shepherd et al., 2018; Shepherd, 2019): (Marson et al., 2024):

1. Orange storyline (EC-EARTH/HadREM3-GA7-05 couple): climate affected by a strong warming and very dry in the summer;
2. Green storyline (HadGEM2-ES/ALADIN63 couple): serious warming and increased rainfall;
- 125 3. Purple storyline (HadGEM2-ES/CCLM4-8-17 couple): serious warming in temperature and strong seasonal contrast in precipitation with the winter season having large amount of precipitation, while summer season has low amount of precipitation;
4. Yellow storyline (CNRM-CM5/ALADIN63 couple): future changes remaining relatively low;

2.2 The Aquifer modelling platform

- 130 Aquifer is a hydro-meteorological modelling platform based on a multi-model approach to simulate french rivers and ground-water systems (Habets et al., 2021). The platform was assessed on a sixty-year period (Vergnes et al., 2020), and has demonstrated good performance in simulating groundwater level, compared to observed 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)). Nowadays, the Aquifer platform is used in an operational context for real-time monitoring and seasonal
- 135 forecasting on the main sedimentary basins and aquifers for groundwater decision-makers (Habets et al., 2021).

2.2.1 The SURFEX modelling platform

- A specific feature of Aquifer is that the SURFEX modelling platform ("SURFace EXternalisée" in French; Masson et al. (2013)) is used to solve the water and energy balances at the surface-atmosphere interface, using several land surface schemes,
- 140 dedicated to each land use category. The groundwater recharge and surface runoff simulated by SURFEX is used to force the hydrogeological models implemented in Aquifer.

- More specifically, only the ISBA ("Interactions Sol - Biosphère – Atmosphère" in French; Noilhan and Planton (1989)) land surface scheme, which is included in the SURFEX modelling platform, is used to simulate the continental area. ISBA allows a direct coupling with an atmospheric model, with a spatial resolution adaptable to a wide range of grid sizes, from hundreds of
- 145 kilometers (e.g., when coupled to a global climate model) to a few kilometers for more local studies, for example coupled with the MODCOU model (Le Moigne et al., 2020) or the CTRIP model (CNRM version of the Total Runoff Integrating Pathways model; Decharme et al. (2019); Munier and Decharme (2022)) for hydrological studies.

- The atmospheric forcing used by SURFEX varies depending on the purpose, either the SAFRAN historical reanalysis ("Système d'Analyse Fournissant des Renseignements Adaptés à la Nivologie" in French; Vidal et al. (2010)) for historical reanalysis
- 150 and real-time monitoring or seasonal forecasting (Roehrig et al., 2020).

2.2.2 Hydrogeological modelling software

Two physically-based hydrogeological modelling software packages are integrated into the Aquifer platform: EauDyssée (Saleh et al., 2013) and MARTHE (“Modélisation des Aquifères avec un maillage Rectangulaire, Transport et Hydrodynamique” in French; Thiéry (2015)). These software packages represent sedimentary aquifers, with explicit representation of river-aquifer exchanges and simplified transfer within the unsaturated zone (Philippe et al., 2011).

EauDyssée is an updated version of the MODCOU modelling software (Ledoux, 1980) gathering several modules. Among the most important ones, there is the SAM module (“Simulation des Aquifères Multi-couches” in French; Ledoux et al. (1989)) to simulate multilayer aquifers using a finite difference numerical scheme to solve the groundwater diffusivity equation, with an approach based on 2D horizontal groundwater flows and vertical exchange through aquitards, in order to represent both unconfined and confined aquifers (Vergnes et al., 2020). Then, the RAPID module (Routing Application for Parallel computation of Discharge; David et al. (2011)) for river routing uses matrix-based version of the Muskingum routing scheme to calculate discharge simultaneously through a river network. RAPID is coupled with groundwater models, which allows exchanges with groundwater in both directions.

MARTHE is the hydrogeological modelling software program from the French Geological Survey (BRGM) which simulates coupled groundwater flows and mass transfers and rivers flows using single-layer to multilayer aquifers and hydrographic networks. MARTHE simulates groundwater flows by a 3-dimensional finite volume approach to solve the hydrodynamic equation based on Darcy’s law and mass conservation on a regular rectangular grids, coupled to a kinetic wave approach used to simulate river flows (Vergnes et al., 2020).

More detailed information about hydrogeological modelling software are provided in Habets et al. (2021). In practice, the hydrogeological modelling software packages are simultaneously and synchronously fed by the recharge and drainage simulated by SURFEX and connected via a Python software. The Aquifer results are provided in a homogeneous format defined according to an irregular spatial grid with a resolution ranging from 100 m to 2000 m on a monthly time step (Habets et al., 2021).

2.2.3 Spatial coverage of the Aquifer domain

In this paper, the Aquifer domain is defined as the spatial extent of the 13 models simulated within the Aquifer platform, one model being defined as a pair of catchments and the hydrogeological modelling software used (see Figure 1 and Table A2 in supplementary material, appendix A). These models are mainly located in the large sedimentary basin in the North part of France, including Poitou-Charentes, the Loire and the Parisian basin, up to the Nord Pas-de-Calais region. Two other models are located further out: MARTHE Alsace, which covers an area of around 1,100 km² East of France, and MARTHE Tarn-et-Garonne, of a similar size, which is the only in the southern part of mainland France. The surface areas of the aquifer systems within the models vary from about 7000 to 66000 km². On the Somme and the Basse-Normandie basins, both EauDyssée and MARTHE are used. In these cases, the simulations are carried out separately using the two different hydrogeological software

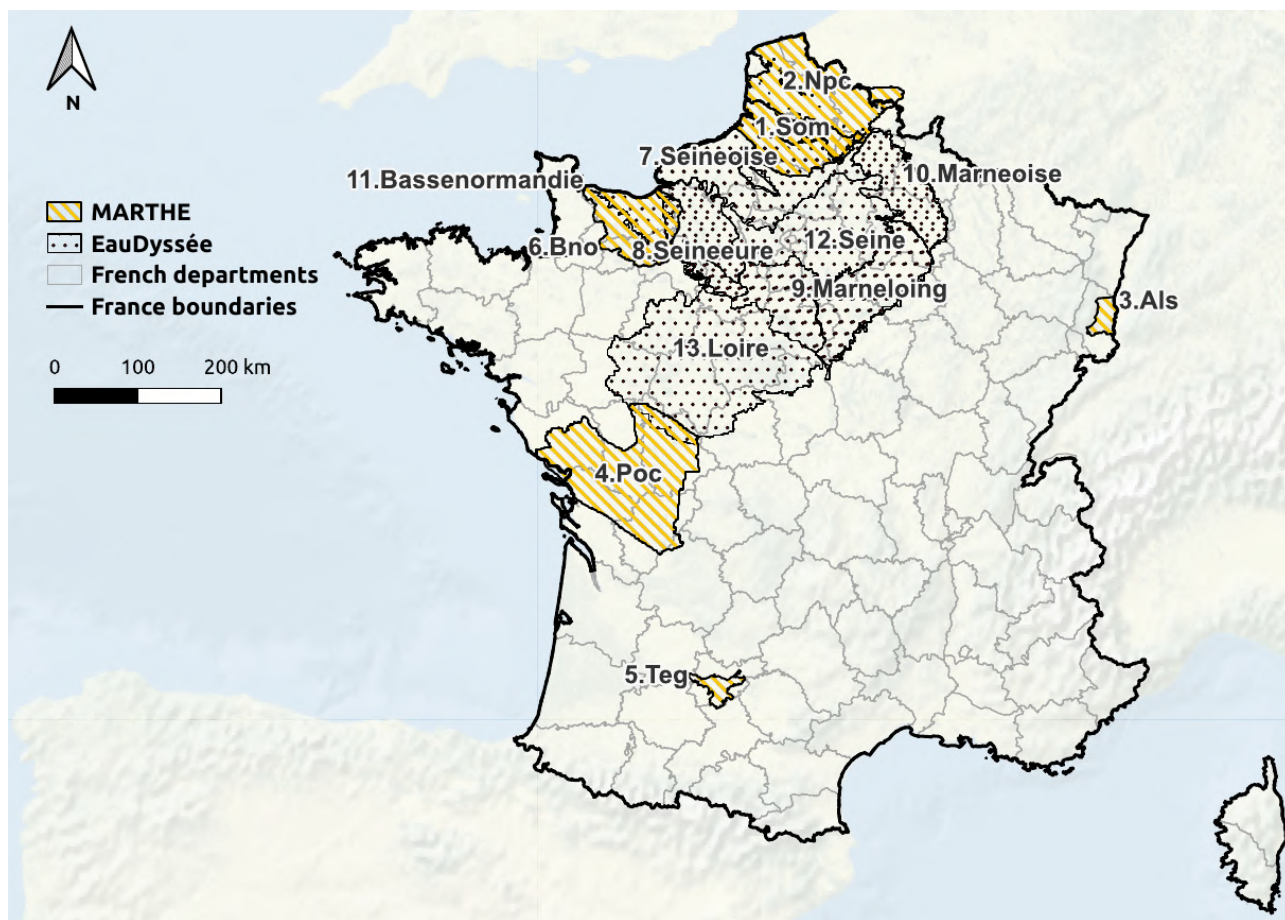


Figure 1. Spatial distribution of the AquiFR models. The numbers refer to the IDs of each model regrouped in supplementary material (see Table A2).

185 packages, and the obtained might models overlap spatially (to account for potential evolution of the groundwater edge). Therefore, priority is given to the most accurate models on top of the maps when plotting, and when performing the corresponding analyses. This order corresponds to the numbering of the IDs presented in Table A2, from the uppermost surface layer to the deepest layer, and is applied to all spatial projection results in this article.

190 2.3 Method used to analyse the climate change projections

2.3.1 Standardized Piezometric Level Index

In the following, the evolution of the groundwater level over the AquiFR domain is analysed using the Standardized Piezometric Level Index (SPLI; Seguin (2015)), a normalized indicator of monthly water table level very useful to evidence the evolution

compared to the distribution on a reference period, regardless the intrinsic hydrogeological heterogeneity of the study area.

195 The advantage of the SPLI is that it makes it easy to interpret the state of the groundwater levels in term of above or below mean state for the given month. The greatest advantage comes with mapping, as map of the groundwater level are linked to the topography, whereas SPLI maps allows to interpret the state of the aquifers compared to the past reference evolution (Seguin, 2015; Vergnes et al., 2023). Therefore, the SPLI is widely used by the French Geological Survey (BRGM), as well as for seasonal forecasts with AquifR over France.

200 The SPLI is based on the same approach than the well-known Standard Precipitation Index (SPI; McKee et al. (1993)). The first step consists in extracting 12 series of monthly groundwater level from the reference historical time series, separately from January to December, from an historical series of N years ($N = 30$). Then, monthly cumulative distribution functions (CDFs) are extracted from the monthly groundwater levels and they are used to fit empirical distribution functions based on standard normal distributions using a non-parametric Kernel Density Estimation (KDE, Figure 2-b) using the scikit-learn

205 Python package (Pedregosa et al., 2011). Eventually, the adjusted CDF from the KDE is projected over a standardized normal distribution using a quantile-quantile projection (Figure 2-c), deducing the SPLI value. In the end, each value of groundwater level from an evaluated period (example with the piezometer 01266X1013_S1 located in the Seine-Oise basin on Figure 2-a)) is converted into a SPLI value (Figure 2-d)), which corresponds to the return period of the equivalent event in the historical reference period.

210 The SPLI values are centered on 0, which corresponds to a simulated groundwater level closed to the median of the groundwater levels in the reference series. A negative value indicates a lower level, i.e., for an event lower (and thus drier) than the median, up to -3 (corresponding to a very low water level), while positive values indicate a higher level, i.e., for a wetter event, up to +3. The range of SPLI values associated with return periods (T) is divided into seven categories (Table 2).

Table 2. Classification of groundwater heads (H) assessed following the SPLI values and the associated return period corresponding to the historical reference. Adapted from Vergnes et al. (2023).

Classification	SPLI values	Return periods
Very low H	< -1.28	> 10-year dry
Low H	[-1.28; -0.84[	Between 5-year dry and 10-year dry
Relatively low H	[-0.84; -0.25[	Between 2.5-year dry and 5-year dry
Around the normal state	[-0.25; +0.25]	Between 2.5-year dry and 2.5-year wet
Relatively high H	] +0.25; +0.84]	Between 2.5-year wet and 5-year wet
High H	] +0.84; +1.28]	Between 5-year wet and 10-year wet
Very high H	> +1.28	> 10-year wet

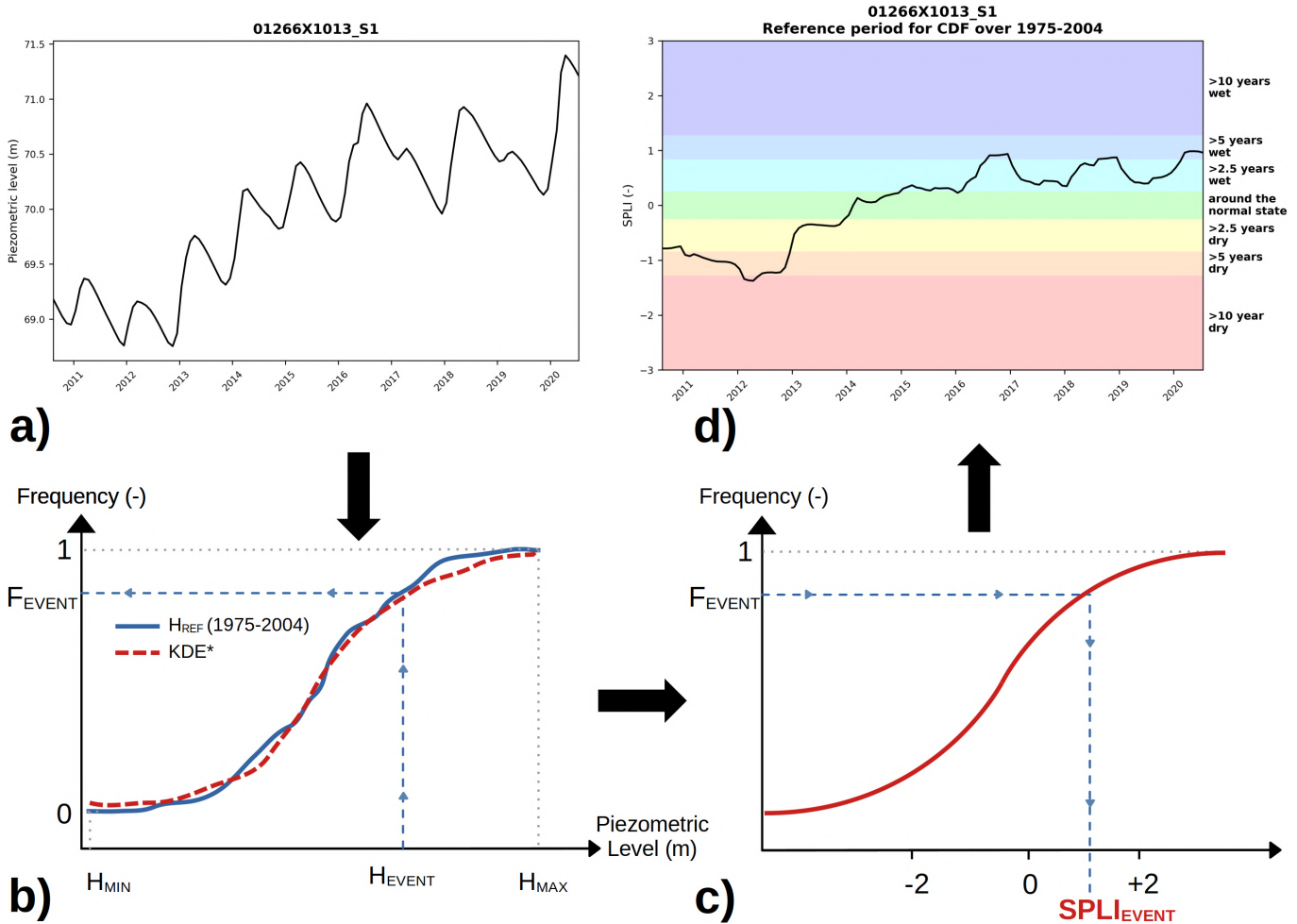


Figure 2. General approach for constructing the SPLI. "KDE" refers to the Kernel Density Estimation used to estimate the best probability density function fitting the reference CDF from reference water table level mean (H_{REF}). The piezometer 01266X1013_S1, located in the Seine-Oise basin, is used as an example to illustrate the conversion of a time series groundwater water level into a SPLI time series, according to the CDF extracted from the reference period.

2.3.2 Groundwater evolution under climate change

215 In this paper, the evolution of the groundwater is first analysed regarding the spatial distribution of the median of the SPLI values from the 3 horizons of Table 1 and under the 3 RCPs. The medians of the SPLI values from each pixel of a model are extracted for each future horizon and each RCP, which illustrates the temporal evolution of the medians of the SPLI in each RCP/horizon couple. This evaluation is performed for each GCM/RCM couple in order to illustrate the uncertainty related to CPs.

220 A second analysis is carried out on occurrence of intense events, by analysing the temporal evolution of the part of the domain that is affected by 10-year return period dry or wet events (see Table 2). In practice, the SPLI values of all models are regrouped and the proportion of area affected by a specific return period is defined as the sum of the surface of each pixel dedicated to this return period, and divided by the total surface of the AquifR domain. This procedure is performed on the results from all the projections. For graphical analyses, a 5-year temporal rolling median SPLI is calculated per RCP with an envelope representing
225 the difference between the min and max values in order to compare future trends between each RCP. Because the year 2005 is characterized by the transition between the historical and the future periods into the simulations provided by the CPs, the period from 2003 to 2007 is excluded from this analysis.

The significance of the trends observed between the reference period and the horizons of the 3 RCPs is assessed using two statistical tests:

- 230 – The Kolmogorov–Smirnov test (Birnbaum and Tingey, 1951) to evaluate the significance of the difference between historical and future trends of SPLI values from 2021 to 2099 ;
- The Mann-Kendall test (Mann and Whitney, 1947) on the future SPLI values to assess if the associated trend significantly evolves over time.

For both statistical tests, the significance threshold is set at $p\text{-value} \leq 0.05$.

235 A third set of analysis concerns hydrogeological extreme events, defined here as as decadal events, i.e., with a probability to occur each year of 0.1 in present day, for both wet and dry events. The spatial distribution of median time proportion corresponding to these extreme wet events is analysed, per future horizon and per RCP.

In the following, the analyses are mostly focused on the results extracted from the RCP8.5. The results corresponding to the RCP2.6 and RCP4.5 will be provided as supplementary material. Furthermore, all the analyses performed on the total set of
240 available CPs (Table A1) are also individually performed on the four storylines selected in the EXPLORE2 project (see section 2.1) in order to compare statistical trends extracted from all the combined CPs, and trends obtained when using few plausible futures which conserve all their physical consistency (Marson et al., 2024). This second approach is therefore more deterministic regarding the scenario represented by the storyline.

3.1 Spatial evolution of the french groundwater level over the 21st century

The SPLI maps for each RCP8.5 projection of the median value over the long-term horizon (Figure 3) show heterogeneity between the different projections from dry to wet values. Some GCM/RCM couples, like the orange storyline (EC-EARTH/HadREM3-GA7-05 couple), lead to a increase in the area dedicated to dry events, specifically 10-year events which
 250 cover almost the entire AquifR domain on the long-term horizon. On the contrary, other couples like the green storyline (HadGEM2-ES/ALADIN63) or the IPSL-CM5A-MR/RCA4 couple lead to predominantly stable or increasing groundwater levels for the three horizons, with a large area characterised by median groundwater level above the 10-year wet level on the full period.

Overall, more GCM/RCM couples induce an increase of the groundwater level over the domain (11 out of 17, $\approx 65\%$), while
 255 4 induce a decrease ($\approx 23\%$) and 2 induce rather stable values ($\approx 12\%$).

Focusing on the purple storyline, the results lead to stable groundwater levels on the northern part of the domain for the short-term horizon while in the Beauce and in the Loire basin, groundwater levels increase (median above 2.5-year wet). This pattern changes over time, with conditions closed to normal for the intermediate and long-term horizon over the major part of the domain, except for the Basse-Normandie region with decreasing trend. The yellow storyline presents the smallest changes.
 260 Groundwater levels over the southern Beauce, the Loiret department and the northern part of the Loire basin slightly decrease (median SPLI below the 2.5-year dry, and around normal elsewhere). Similar results are observed for the long-term horizon, excepted in the northern France (Nord-Pas-de-Calais and Basse-Normandie), where groundwater levels slightly increase (median SPLI between 2.5- and 5-year wet). Let us note that the MARTHE Tarn-et-Garonne and MARTHE Alsace models have an opposite trend with decreasing groundwater levels for all the storylines, corresponding to decadal dry events, from the short-
 265 term horizon for Alsace and from the long-term horizon for Tarn-et-Garonne.

The same analyses for the short-term (Figure B7, appendix B) and the intermediate horizons (Figure B8) under the RCP8.5 are available in supplementary material. Despite the divergent results, two main patterns are distinguishable:

- from the northern part of the AquifR domain to the South of the Loire basin, the median of the groundwater levels increases up to what is today considered as a 5-year wet events on the short-term and intermediate horizons, and to wet
 270 decadal event on the long-term horizon;
- on the contrary, the median of the groundwater levels remains stable in the southern AquifR domain (e.g., Tarn-et-Garonne) for the short-term horizon and decrease then to reach a 5-year dry events in the long term horizon.

These elements suggest a north-south divide in the future evolution of groundwater level under the RCP8.5, and is highlighted by 3 out of the 4 storylines (green, purple and yellow).

275 Under the RCP2.6 (Figures B1, B2 and B3 in supplementary material respectively for the three horizons), projections show the largest heterogeneities. On the long-term horizon, 4 out of 10 GCM/RCM couples (40%) project an increase of the groundwater level to a relatively high value, 3 couples (30%) project almost no change and 3 couples (30%) project a decrease of the

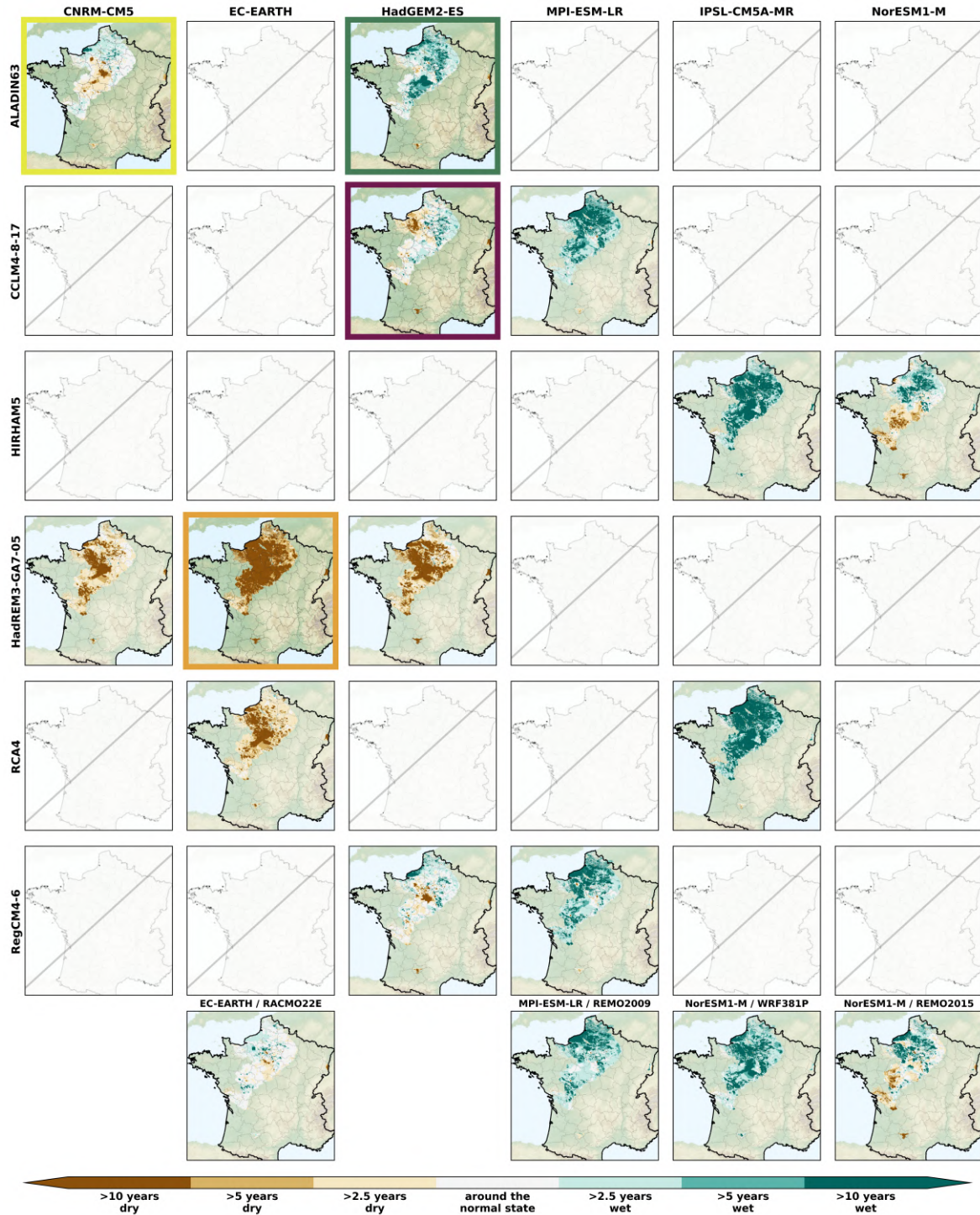


Figure 3. Spatial distribution of the SPLI median over the AquifR domain under the **RCP8.5** on the **long-term horizon (2071-2099)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once. The colored rectangles indicates the GCM/RCM couples corresponding to the storylines (see section 2.1).

groundwater, especially the ones related to the EC-EARTH GCM. These results are similar on the three horizons. Similarly, projections with RCP4.5 for the short-term and intermediate horizons (see Figures B4 and B5) are divergent, preventing any statement as to the future groundwater trend for this scenario. On the long-term horizon (see Figure B5), the results are more homogeneous with 6 out of 9 GCM/RCM couples inducing increasing groundwater level corresponding to high values over more than half of the Aquifer domain, while 3 couples induce either no change or slight decrease of the groundwater level. Due to these large heterogeneities in the results from all the CPs, we focus the further analyses on the storylines, while the results corresponding to all the CPs are available in supplementary material.

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3.2 Evolution of the occurrence of wet and dry events

Figure 4 shows the temporal evolution of the percentage of the surface within the Aquifer domain that falls into one of the six SPLI categories (in line) depicted in Table 2, for the four storylines under the RCP8.5. The left column corresponds to wet events and the right column to dry events. Overall, the results mostly depend on the hypotheses on which the storylines are based on. The results show strong temporal variabilities, mostly on the 10-year events, probably related to climate natural variability. The orange storyline tends to significantly decrease the surface affected by wet events and increase the ones affected by 10-year and 5-year dry events. The surface dedicated to 10-year dry events almost reaches 60% of the Aquifer domain by the end of the 21st century. The green storyline induces an increase the surface dedicated to wet events, i.e., 10-year wet events covering almost 20% of the Aquifer domain (from 3.7% on the historical period), and a decrease of the surface dedicated to dry events, excepted for the 10-year dry event for which the surface slightly increases and reaches 6.3%. The changes induced by the purple and the yellow storylines are smaller, excepted for both wet and dry decadal events for which the contrasts are particularly pronounced. These two storylines tends to increase the decadal events (mainly the purple storyline) and reducing the surface dedicated to 2.5-year events. These results are confirmed by the statistical tests with p-values below 0.05 for almost all the 6 categories of events (see Table C1 and Table C2), meaning that the future is significantly different from the reference period (Kolmogorov-Smirnov test) and changes significantly over the 21st century (Mann-Kendall test), for the four storylines. The results for all the CPs are available in supplementary material (see Figure C1 and Table C3). The results show that the envelopes between the minimum and maximum values are wide, mainly for the decadal events, highlighting the heterogeneity between the projections. The surfaces dedicated to 10-year events increase for both wet and dry events, spreading with time and increasing greenhouse gas emission, especially for wet events. The dry decadal events area is also projected to increase, but with a much less pronounced trend, reaching at most 10.0% under the RCP8.5. The changes of surface proportions corresponding to the 5-year dry or wet events are low, slightly increasing for the wet events, and decreasing for the dry events. Eventually, both dry and wet 2.5-year events are expected to decrease over the 21st century, showing an intensification of extreme events, which is in line with the results from the storylines.

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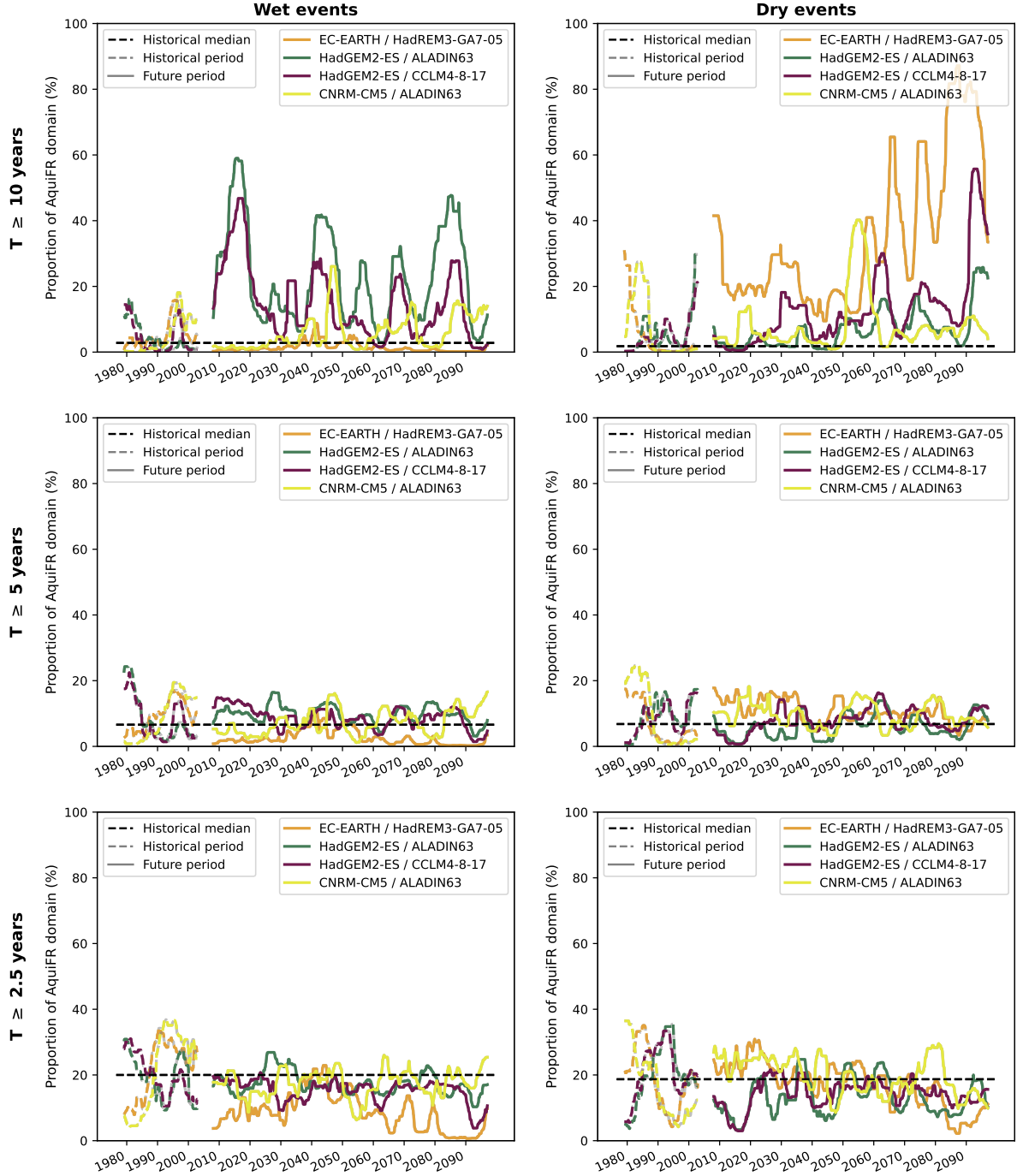


Figure 4. Temporal evolution of the running median of proportion from the Aquifer domain affected by the categories of events from Table 2 for the four storylines. The lines represent the return periods of the events, for the wet events (left) and dry events (right). The gap centered on 2005 corresponds to the exclusion of the 2003-2007 period in the calculation of running medians (see section 2.3). The black line represents the historical median of each category from all the available CPs.

310 3.3 Evolution of the time spent in extreme events

Figure 5 illustrates the maps of the median of the time proportion corresponding to extreme events (i.e., with at least a decadal return period), for both wet (1st line) and dry (2nd line) events for the four storylines on the long-term horizon. The results for the short-term and intermediate horizons are available in supplementary material (see Figure C2). In consistency with the previous analyses, the results are contrasted and depend on the storyline. The orange storyline tends to reduce the time proportion corresponding to wet decadal event to less than 5% over almost all the Aquifer domain while it tends to increase the time proportion of dry decadal events to more than 75% over the entire domain. The green storyline tends to strongly increase the time proportion of wet decadal events while reducing the one corresponding to dry decadal events. The purple storyline induces an increase of both wet and dry decadal events, higher as time goes to 2100, and representing more %50 of the time over half of the Aquifer domain by the end of the 21st century. The results for the yellow storyline are more spatially and temporally contrasted and do not highlight a noticeable future tendency over the 21st century.

The results for all the CPs (see Figure C3) show that on the short-term horizon, the time proportion of decadal wet events corresponds to almost half of the time over half of the Aquifer domain for the three RCPs, and remains to the historical conditions over the remaining part of the domain. Then, this time proportion increases as time goes to 2100, mostly on the northern part of the Aquifer domain. Results for the time proportion corresponding to dry decadal events are more contrasted. On the long-term horizon, the results suggest a decrease of the median of the time proportion in dry decadal event with values on more than half of the Aquifer domain on RCP2.6 and RCP4.5. On RCP8.5, the results show a decrease of the time proportion in the northern part of the Aquifer domain, and higher values on the southern part of the domain, suggesting a North-South contrast in the evolution of the time proportion corresponding to dry decadal events.

330 4 Discussion

4.1 Divergent projections limiting the extraction of clear future tendency

In this study, the evolution of the groundwater is simulated by the Aquifer modelling platform using 36 climatic projections spread over 3 socio-economical scenarios RCPs. Results are analysed based on the Standardised Piezometric Level Index (SPLI), using the 1975-2004 period as reference. The results show that the spatial distribution of the SPLI median differs from one projection to another, leading to an uncertainty that limits the extraction of a clear trend of future groundwater evolution. This uncertainty is not really surprising as the study area is included into the transition zone of the Atlantic region, where expected trends change from being wetter in the North to drier in the South (Goubanova and Li, 2007; Meaurio et al., 2017). Therefore, the climate projections do not agree on the location of the transition zone, inducing the obtained divergence on the evolution of groundwater levels.

Furthermore, this uncertainty, which is often inherent to hydroclimatic modelling chains based on a multi-model approach, is a recurring point in the literature (Knutti et al., 2013) and requires a proper evaluation (Northrop and Chandler, 2014; Evin et al.,

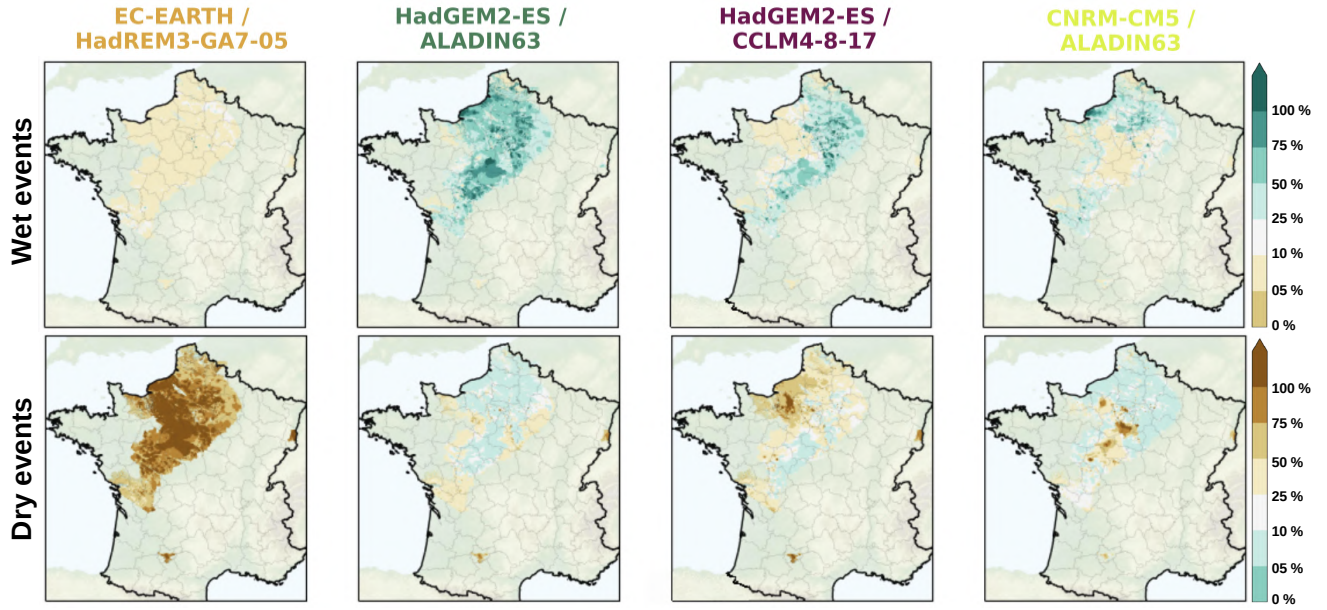


Figure 5. Spatial distribution of median of time proportion corresponding to extreme wet events ($SPLI > +1.28$, 1st line) and extreme dry events ($SPLI < -1.28$, 2nd line) for the long-term horizon for the four storylines (in column) under the RCP8.5.

2019). To be accurate, a rigorous uncertainty analysis must consider the contribution of each element in the modelling chain to the total uncertainty: (1) climate scenarios such as RCPs or, more recently, SSPs (Shared Socioeconomic Pathways) in the CMIP6 global exercise (IPCC, 2022); (2) global (GCMs) and regional (RCMs) climate models; (3) debiasing and downscaling
 345 methods such as ADAMONT (Verfaillie et al., 2017; Evin et al., 2019) or CDF-t (Michelangeli et al., 2009); (4) hydrological component (models and associated parameters); (5) irreducible fraction of uncertainty due to internal climate variability (Hawkins and Sutton, 2009).

As part of the EXPLORE2 project, an evaluation of uncertainty propagation was carried out by Evin et al. (2024) on surface hydrology over France, by estimating the variance inherent in each link in the modelling chain. Their results showed that the
 350 main contributor to the total uncertainty is internal climate variability (> 40%). Then, the following sources contributing the most are the GCMs and the RCMs (> 40% of combined contribution), in similar proportion, especially in North and East of France corresponding to the large majority of the AquifR domain. These elements are in agreement with the literature, showing that the cumulative GCM/RCM contribution often reaches 40% to 80% of the total uncertainty (Vetter et al., 2015; Trambly and Somot, 2018; Lemaitre-Basset et al., 2021; Jeantet et al., 2023), and they are consistent with the analyses showed
 355 in this paper suggesting that the results strongly depends on the GCM/RCM couples. In South of France where the MARTHE Tarn-et-Garonne is included, Evin et al. (2024) showed that the RCPs are the second source contributing the most to the total uncertainty, which can be related to a weaker influence of precipitation in these regions than on the rest of the country, and as a consequence a stronger influence of temperature evolution, over the 21st.

The hydrogeological part might also contribute to uncertainty, and a proper evaluation of this contribution would require a multi-model approach for the hydrogeological component of the modelling chain, which is not the case for the AquifR platform (see section 1). However, Habets et al. (2013) showed as part of the RexHySS project on the Somme and the Seine regions that results from two hydrogeological software packages, based on analogous physical approaches and forced by the same surface fluxes, were similar. Therefore, we can suppose that models that spatially overlap into AquifR may provide similar results too, and that the contribution of hydrogeological components of the modelling chain to the total uncertainty remains low compared to the contribution from the climate components. Moreover, part of the uncertainty is linked to the fact the climate projection cannot be fully unbiased. This is rather explicit when computing SPLI over the historical period, since the projection are not compared to present day observations or reference simulation, but to present day climate simulation, which are all different. In order to illustrate how this impact the hydrogeological projection analysis, we compare the CDFs obtained from CPs with a reference CDF obtained using the reference atmospheric forcings over the historical period. To be consistent with the bias correction method of CPs in the EXPLORE2 project (Marson et al., 2024), the SAFRAN historical reanalysis product (Vidal et al., 2010; Le Moigne et al., 2020) is used as the meteorological reference. For each model, the evaluation is carried out by first calculating a CDF of the model extracted per CP over the historical period. Second, the spatial mean of CDFs from each CP is calculated with a 95% confidence interval. Third, from the simulations obtained by forcing AquifR with SAFRAN on the historical period, a reference CDF is calculated. Fourth, the average CDF obtained from the CPs is compared to the reference CDF. This evaluation is performed for each of the 12 months and Figure 6 illustrates results for January.

For almost all models, the CDFs from CPs are relatively close and distributed on either side of the reference CDFs, with average projected CDFs following the trends of the reference CDFs quite well. This indicates that the average distribution of groundwater level obtained from CPs is similar to the distribution obtained from the SAFRAN historical reanalysis over the historical period. Similar analyses were carried out on the 12 months of the hydrological year and led to similar results. The largest differences are observed in March and April, suggesting that the CPs diverge on this period, i.e., the end of the wet period and the beginning of the dry period and so the end of the recharge period of water tables. This period is also characterised by significant inter-annual variability, which is difficult to represent in climate models. Overall, these results suggest that the construction of SPLI by the AquifR simulations is not noticeably affected by the use of CPs. Therefore, the discrepancies between the SPLI values observed on the future horizons are unlikely to be induced by the construction of the CDFs from the CPs on the historical period, and are more likely due to the divergences from the CPs on the future period, and as so from the climate components of the modelling chain (GCMs and RCMs), which is in agreement with Evin et al. (2024) on surface hydrology, as mentioned-above.

However, for a specific model, the CDFs from CPs are never fully merged, suggesting discrepancies directly induced by the adjustment of the CDFs by CPs. Therefore, if these CDFs are too divergent, this may lead to SPLI values related to different categories of events from one CP to another (Table 4), in particular due to the presence of threshold effects on the studied aquifers. This may contribute to the uncertainty associated with the SPLI, and then on both sign (dry/wet) and severity of the corresponding event.

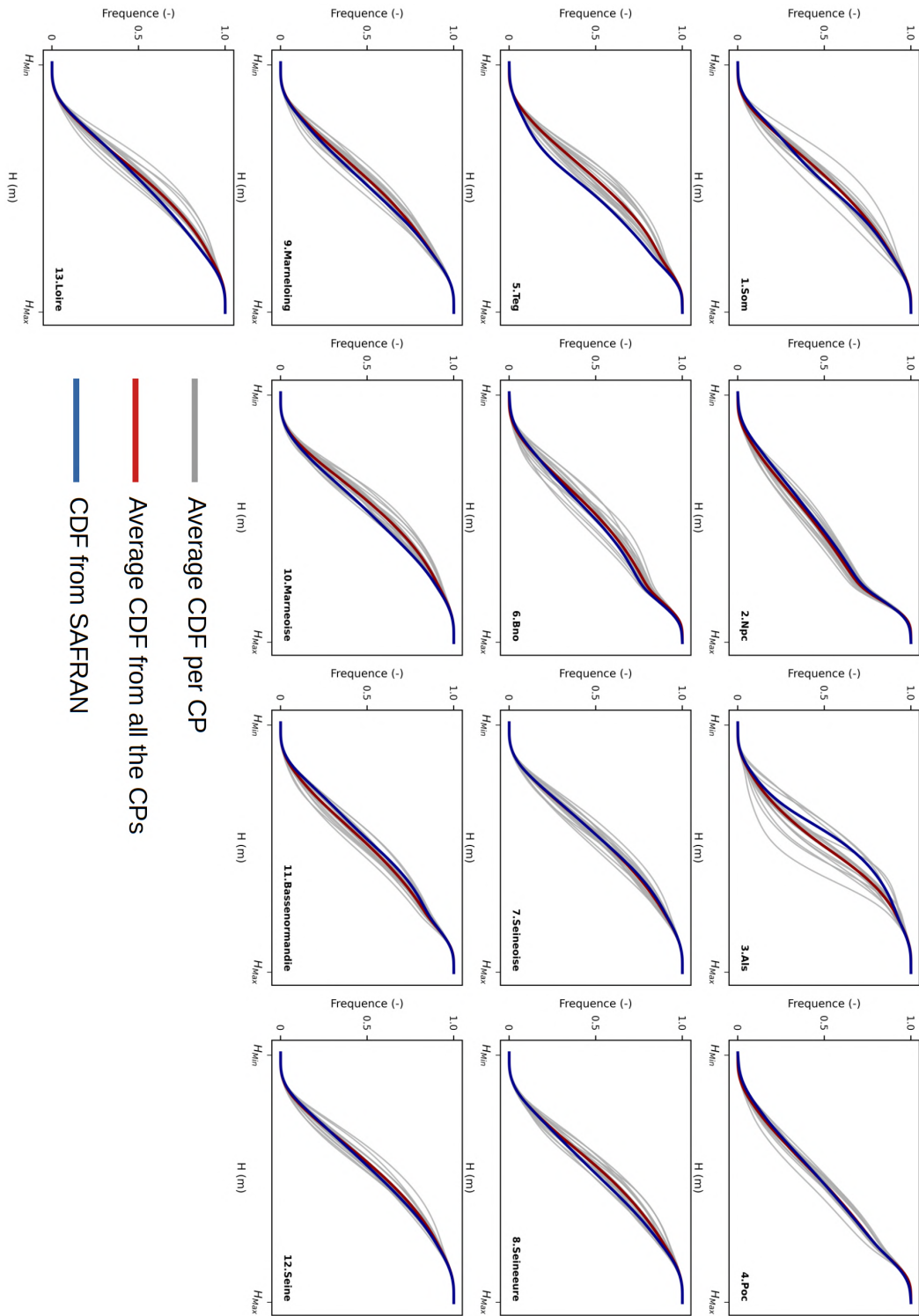


Figure 6. Comparison of CDFs from the reference reanalysis SAFRAN with those from CPs calculated on the historical period (see Table 1), for the month of January. The IDs of each model correspond to the abbreviations from Table A2 in supplementary material.

Let us note that the discrepancies of the CDFs of the CPs in present day attest that the bias correction method is not fully
395 efficient, which is expected. Indeed, even a perfect bias correction method would lead to different results due to the internal
variability included in each CP. More robust studies are required, accounting for both the need of an accurate method and the
complexity of hydrogeological modelling limiting the current uncertainty analysis.

4.2 Groundwater evolution over the 21st century

400 Faced to the divergences observed between all the available CPs in the multi-model ensemble approach, the extraction of re-
liable future trends is quite challenging and strongly depends on the RCP considered. As regards the RCP8.5, two tendencies
have been extracted, mostly thanks to the use of storylines, which showed some similar future evolutions despite being based
on contrasted future evolutions consistent with their design assumptions (Shepherd et al., 2018; Shepherd, 2019; Baulenas
et al., 2023), which improves confidence in the results. First, groundwater level from the northern part of the AquifR domain
405 (i.e., Seine, north of Loire catchment, Basse Normandie and Nord Pas de Calais) is expected to increase toward wetter events,
mostly corresponding to 10-year wet groundwater level of the reference period. The green storyline induces this increase from
the short-term horizon over most of the AquifR domain, while this increase starts from the long-term horizon for the yel-
low (Nord Pas de Calais and Basse-Normandie) and the purple (on the Beauce and the Loire catchment) storylines. Second,
groundwater level from the southern part of the AquifR domain (i.e., south of Loire catchment and Tarn-et-Garonne) and from
410 the Alsace catchment is expected to decrease at least to levels corresponding to 5-year dry events on the reference period on
the South of the AquifR domain on the long-term horizon. The orange storyline enhances this decrease to the whole AquifR
domain, reaching levels corresponding to 10-year dry events on the reference period. The yellow storyline also induces a slight
decrease of groundwater level from south of Loire to the southern part of the AquifR domain.

This North-South contrast in the evolution of groundwater levels under the RCP8.5 is highlighted by both the majority of the
415 CPs and by 3 out of the 4 storylines, and appears to be the consequence of the North-South contrast observed in future rainfall
projected by climate models used in the EXPLORE2 project (Marson et al., 2024). In this paper, the limited spatial representa-
tion of South of France into the AquifR platform does not allow us to establish with certainty the existence of this North-South
divide. However, our results are in agreement with Vergnes et al. (2023), which predict an increase in groundwater level in the
northern part of the French metropolitan area as time goes to 2100, and a decrease in the southernmost sectors of France, using
420 a subset of the RCP8.5 DRIAS projections. Moreover, these conclusions are also in line with the main results obtained as part
of the EXPLORE2 project on groundwater recharge (Lanini et al., 2024) and surface hydrology (Sauquet et al., 2024; Evin
et al., 2024) over the 21st century in France.

However, some differences with the conclusions extracted from the literature are to be noticed. Indeed, our conclusions for
the northern France are not consistent with the results of the EXPLORE 2070 project which, as mentioned in section 1, sug-
425 gested a global decrease of both recharge and groundwater level over France (Habets et al., 2013; Carroget et al., 2017). The
divergence might come from that CPs from the CMIP5 global project are wetter than the ones from the CMIP3 global project
(Meehl et al., 2007) from which the Explore 2070 project was based on, especially over northern France (Dayon et al., 2018).

Hydrological systems are therefore directly affected by this additional amount of water into the water balance between the two versions of the projections. In this way, the consistency between the present results and the ones from Vergnes et al. (2023) was to be expected as they used the hydrogeological MARTHE model, included in the Aquifer platform, and CPs provided by the DRIAS-2020 database, which is included into the CP database established by EXPLORE2. However, the main difference is that the MARTHE hydrological software package was configured on a coarser spatial grid of 2 km x 2 km, and their study is based on 5 selected regionalized CPs, while in this paper 17 different GCM/RCM combinations have been used. The use of a larger panel of CPs allows us to better integrate the uncertainty associated with the modelling chain, in particular the contribution of the CPs, which constitutes the main originality of this study.

Moreover, most of studies dealing with surface hydrology state that the seasons will be more contrasted under climate change, e.g., winter flows will be higher while summer will be lower (Sauquet et al., 2024), induced by a seasonal regime change of rainfall and evapotranspiration balances (Soubeyroux et al., 2021; Marson et al., 2024). However, by assessing the spatial distribution of SPLI for each one of the 12 months of the year (not shown), we found similar results for each month, suggesting no modification in the seasonal regime of groundwater level. This phenomenon may come from the slow temporal dynamics characterizing the aquifers in the study area, particularly those close to the Parisian Basin, constituting a large part of the Aquifer domain. Indeed, these aquifers are subject to variations observed on timescales that are often longer than the hydrological year and even multi-decadal (Baulon et al., 2022), making it difficult to observe sub-annual variations.

Let us note that the storylines inducing contrasted yet possible future evolutions highlight their usefulness to groundwater decision-makers, especially when they do not converge. The northern part of the Aquifer domain, i.e., from Nord Pas-de-Calais to the South of the Loire basin, is the sector where the contrast between the storylines is the largest, particularly in the long-term horizon. In this context, the storylines can invite the decisions-makers to establish their policy using the less favorable projection, i.e., the "worst case scenario" (or precautionary principle), or using no-regrets measures based on the consequences of climate change on other surface variables such as the different seasonal flows (Sauquet et al., 2024) or the 20-year return period quantile of the annual maximum daily flow to characterise floods (Tramblay et al., 2024).

The extraction of tendencies for the RCP2.6 and the RCP4.5 was more difficult, because the projections are too divergent to give confidences on the evolution of the groundwater, especially on the short-term and the intermediate horizons. On the long-term horizon under the RCP2.6, the results are still very divergent but we should note a slight increase of groundwater levels, with levels locally reaching the 10-year wet events levels from the historical period. On the long-term horizon, the results are still quite divergent but highlight an increase of groundwater with values reaching the 5-year to 10-year wet return period of the reference. Under the RCP4.5, this result is in line with the statement established by Marson et al. (2024) on the climate aspect of the EXPLORE2 project, which projects a 3.5% increase in precipitation on the long-term horizon under this RCP in North of France, where most of the Aquifer domain is located. This additional amount of precipitation could increase water supply and ultimately raise groundwater levels in these areas.

As mentioned in the introduction section, no anthropisation impacts on water resource was addressed in this study, which constitutes a major limitation of this work. Indeed, groundwater abstractions currently applied to the studied aquifers, thus defined according to current water availability and water demand, are maintained in the future and do not change regardless

of groundwater level evolution and groundwater availability to meet future water demand. This assumption might be irrelevant as for some projections groundwater level is supposed to decrease over the 21st century, specifically in the southern AquifR domain. In such cases, current groundwater abstractions need to be adapted (Stollsteiner, 2012) to future conditions. In further assessments, including adapting groundwater abstraction would be an important way to improve our analysis.

4.3 Hydrogeological extreme events under climate change

In this study, hydrogeological extreme events are defined as decadal events, i.e., with a probability to occur each year of 0.1 in present day, for both wet and dry events. The results show that the surface affected by extreme wet events increase by the end of the 21st century as both time goes to 2100 and greenhouse gases are released by the RCP. Under the RCP8.5, extreme wet events increase by a factor of 7 on the long-term horizon, which is supported by 3 out of 4 of the storylines (green, purple and yellow). The increase of wet events may have consequences on surface water leading to an increased risk of flooding, as shown by Trambly et al. (2024) in northern France, due to the strong influence of groundwater dynamics on the amount of water in rivers and wetlands (Guillaumot et al., 2024). Let us note that the orange storyline induces an different future trend characterized by a total disappearance of extreme wet events.

Conversely, the results also show an increase in extreme dry events, which is confirmed by the four storylines. It should be noted that even the green storyline induces this increase of extreme dry events, despite its design assumption leading to a larger amount of precipitation, and that the orange storyline leads to an larger increase of a factor of 25 of the extreme dry events, covering almost this entire AquifR domain. In this case, groundwater recharge may decrease, phenomenon which is already observed nowadays in some locations, e.g., the Champagne region (Sobaga et al., 2024). The areas where this increase is larger are Alsace, Poitou-Charentes and Tarn-et-Garonne on the RCP8.5. However, for most of the CPs and the 3 remaining storylines (green, purple and yellow), this increase is lower than the one for wet events. Therefore, the meteorological droughts announced in the EXPLORE2 project (Marson et al., 2024) seem to not noticeably involve hydrogeological droughts in the large majority of the AquifR domain. This is a noticeable difference with recent hydrological drought assessments which clearly indicate an intensity of drought events, whether in terms of low flows observed or none flow periods, specifically in South of France (Dayon et al., 2018; Lemaitre-Basset et al., 2021; Trambly et al., 2024). This result is also in contradiction with the results from the EXPLORE 2070 project which suggested a strong increase of hydrogeological droughts (Stollsteiner, 2012; Habets et al., 2013; Carroget et al., 2017). As mentioned in section 4.2, the CPs used in the EXPLORE2 project are wetter than the ones used in the EXPLORE 2070 project (Dayon et al., 2018). As such, the ones from EXPLORE2 are likely to induce fewer dry events than in the EXPLORE 2070 project. Furthermore, the aquifers corresponding to the study area are defined by annual or multi-annual temporal dynamics (Baulon et al., 2022) and often involve groundwater-river interactions where the groundwater feeds the river (Guillaumot et al., 2022). Therefore, droughts may be observed at the surface without any direct effect on groundwater.

5 Conclusions

In this study, the purpose is to identify the main impacts of climate change on groundwater levels in the French regions covered by the **AquiFR** platform: Nord Pas-de-Calais, Basse-Normandie, Parisian Basin, Loire, Poitou-Charentes, Alsace and Tarn-et-Garonne. For this purpose, the hydrogeological modelling platform **AquiFR**, gathering 11 different models (a model being the combination of a study aquifer with the associated hydrogeological software package), is connected to a hydroclimatic modelling chain using a multi-model ensemble approach, with 36 climate projections under RCP2.6, RCP4.5 and RCP8.5. The future evolution of groundwater level is assessed using the **SPLI**, a normalized indicator of groundwater level, in order to compare various types of aquifers at once. The results show future trends strongly divergent, mainly depending on the GCM/RCM couples, either on the spatial distribution of median **SPLI** or on areas associated with extreme decadal events, defined as 10-year events, i.e., characterised by return periods of more than 10 years.

Under the **RCP8.5**, the divergences from the 17 CPs are large, but two main tendencies have been extracted, mostly thanks to the use of four storylines defined in the **EXPLORE2** project. First, an increase in groundwater levels (with return periods greater than 5 years) is expected in the northern part of the **AquiFR** domain (Nord Pas-de-Calais, Parisian Basin, Normandie), which is supported by 3 out of the 4 storylines. Second, a decrease in groundwater levels is expected in the southern part (Poitou-Charentes and Tarn-et-Garonne), but with a lower intensity than for the increase in north of the **AquiFR** domain. The all four storylines confirm this evolution, and the orange storyline (the driest one) extend this increase of dry event to the entire **AquiFR** domain, to groundwater level reaching 10-year dry events on the reference historical period (1975-2004).

The **RCP8.5** produces the largest amplification of both dry and wet extreme groundwater levels, and induces the most pronounced North-South differentiation, with a transition zone on the northern border depending on the GCM/RCM couple. Although this study alone is insufficient to prove the existence of a North-South divide due to the limited spatial extent in South of France, the results are consistent with several similar studies dealing with climate change impacts on French hydrology, especially the joined researches carried out as part of the **EXPLORE2** project on groundwater recharge (Lanini et al., 2024) and surface hydrology (Sauquet et al., 2024), which justifies the authors' confidence in this conclusion. Furthermore, the use of the storylines might encourage the decision-makers to follow the precautionary principle and choose the worst case situation to establish a sustainable groundwater management policy when these are not convergent.

For the **RCP2.6** and **RCP4.5**, the results are too divergent on the short-term horizon (2021-2050) and the intermediate-term horizon (2041-2070) to extract reliable future trends. While still being quite divergent, the results on the long-term horizon are more convergent and show an increase of groundwater level mostly in the northern **AquiFR** domain, i.e., Normandie, Nord Pas-de-Calais, Parisian Basin. For the **RCP4.5**, this increase of groundwater levels corresponds to decadal wet events on the historical period. For the most remote areas (Tarn-et-Garonne and Alsace), the results are too divergent from one GCM/RCM couple to another to extract reliable future trends.

Several potential ways of improvements to this work are conceivable, such as integrating more models into the **AquiFR** platform and then increasing its representativeness for the different French hydrogeological contexts, especially in South of France. Similarly, the use of other hydrogeological modelling software per model could make a significant contribution to the relia-

530 bility of the study, particularly in terms of accurately assessing the propagation of uncertainties along the modelling chain. Eventually, considering the very close relationship between water policy (including water use) and water availability, some future work should integrate socio-economic considerations into physically-based models, then making water demand related to water availability.

535 *Code availability.* As part of the AquiFR project led by the OFB ("Office Français pour la Biodiversité" in French for French Office for Biodiversity), the AquiFR modelling platform is not directly hosted on any public repository.

Data availability. The climate and hydrogeological projections (water table levels and corresponding SPLI values) are available on the DRIAS-Eau database (<https://drias-eau.fr/>, last access on 25th of October, 2024).

Author contributions. AJ, JPV, SM and FH conceptualized the work. AJ and JPV performed the simulations and analyses. AJ drafted the
540 paper. JPV, SM and FH all revised the paper and contributed to its analyses and discussions.

Competing interests. The authors declare that they have no conflict of interest.

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Supplementary material

Appendix A

The elements from Appendix A are related to the Material and Method section. Table A1 regroups all the GCM/RCM combinations available in this study, with the RCPs used to force them, and Table A2 regroups the characteristics of the 13 models
800 included in the AquifR platform.

Table A1. Availability of climate projections. The numbers (2.6, 4.5, and 8.5) refer to the RCPs used by the GCM (rows)/RCM (columns) couples. “-” indicates missing data.

	ALADIN 63	RACMO 22E	HadREM3 -GA7-05	RCA4	HIR HAM5	WRF 381P	CCLM4 -8-17	RegCM4 -6	REMO 2009	REMO 2015
CNRM -CM5	2.6									
	4.5	-	8.5	-	-	-	-	-	-	-
	8.5									
EC- EARTH		2.6		2.6						
	-	4.5	2.6	4.5	-	-	-	-	-	-
		8.5	8.5	8.5						
IPSL-CM5 -MR				4.5	8.5	-	-	-	-	-
				8.5						
HadGEM2 -ES	8.5	-	2.6	-	-	-	4.5	2.6	-	-
			8.5				8.5	8.5		
MPI-ESM -LR							2.6		2.6	
	-	-	-	-	-	-	4.5	2.6	4.5	-
							8.5	8.5	8.5	
NorESM1-M					4.5					2.6
	-	-	-	-	8.5	8.5	-	-	-	4.5
										8.5

Table A2. Characteristics of the 13 studied models included in the AquifR platform. The IDs refer to each model illustrated on Figure 1.

Model IDs	Abbreviation	Catchment	Surface (km ²)	Hydrogeological model
1	Som	Somme	7506	MARTHE
2	Npc	Nord – Pas-de-Calais	13332	MARTHE
3	Als	Alsace	1079	MARTHE
4	Poc	Poitou-Charente	19326	MARTHE
5	Teg	Tarn-et-Garonne	1139	MARTHE
6	Bno	Basse-Normandie	7646	MARTHE
7	Seineoise	Seine – Oise	15968	EauDyssée
8	Seineure	Seine – Eure	9318	EauDyssée
9	Marneloing	Marne – Loing	10861	EauDyssée
10	Marneoise	Marne – Oise	7285	EauDyssée
11	Bassenormandie	Basse-Normandie	3626	EauDyssée
12	Seine	Seine	65696	EauDyssée
13	Loire	Loire	38746	EauDyssée

Appendix B

The figures from Appendix B are related to the spatial repartition of the SPLI median over the AquifR domain under the RCP2.6 (Figure B1, Figure B2 and Figure B3) and under the RCP4.5 (Figure B4, Figure B5 and Figure B6) respectively on the short-term, intermediate-term and long-term horizons. The similar ones are available under the RCP8.5 (Figure B7 and Figure B8) on the short-term and intermediate-term horizons.



Figure B1. Spatial distribution of the SPLI median over the AquifR domain under the **RCP2.6** on the **short-term horizon (2021-2050)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.

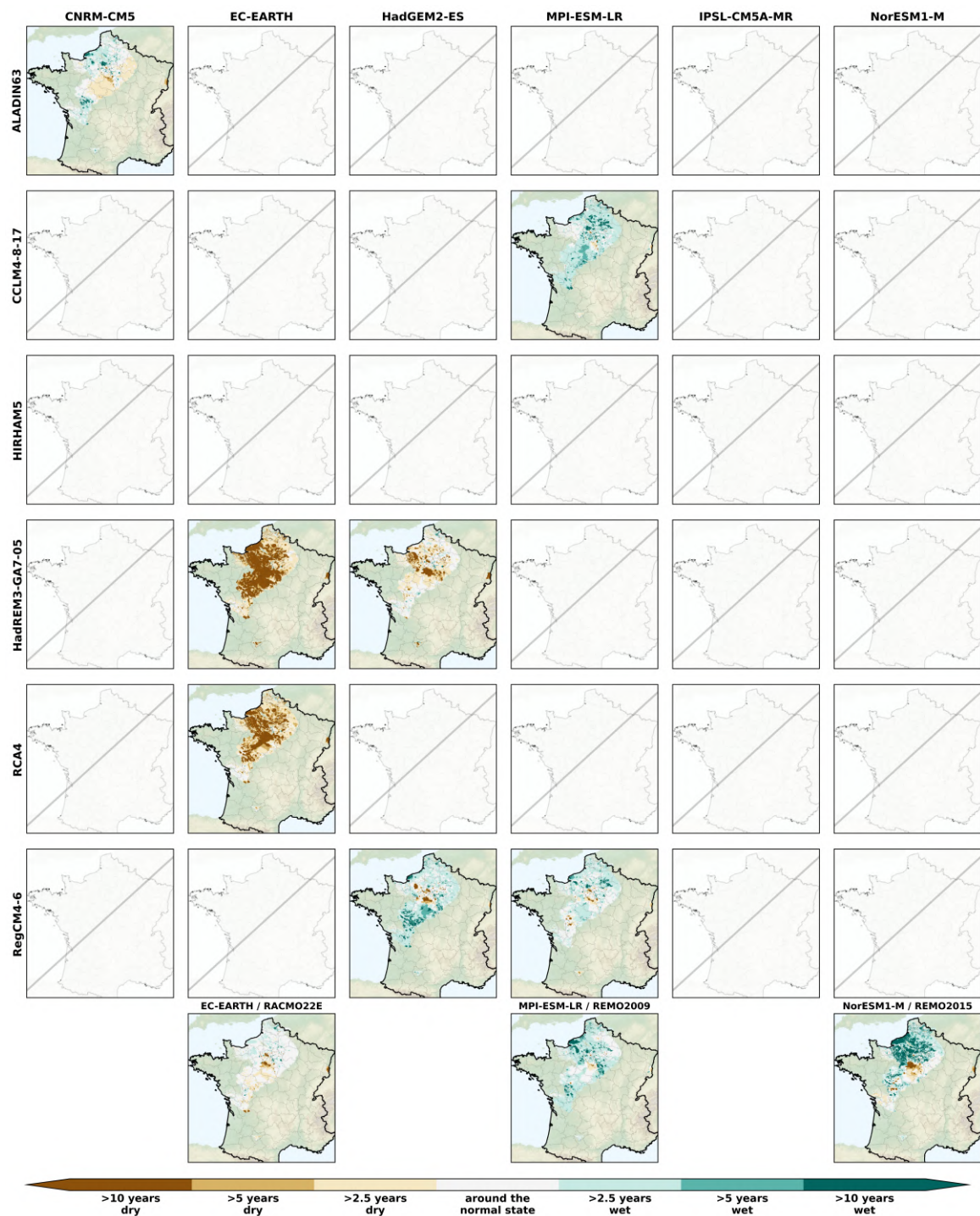


Figure B2. Spatial distribution of the SPLI median over the AquifR domain under the **RCP2.6** on the **intermediate-term horizon (2041-2070)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.

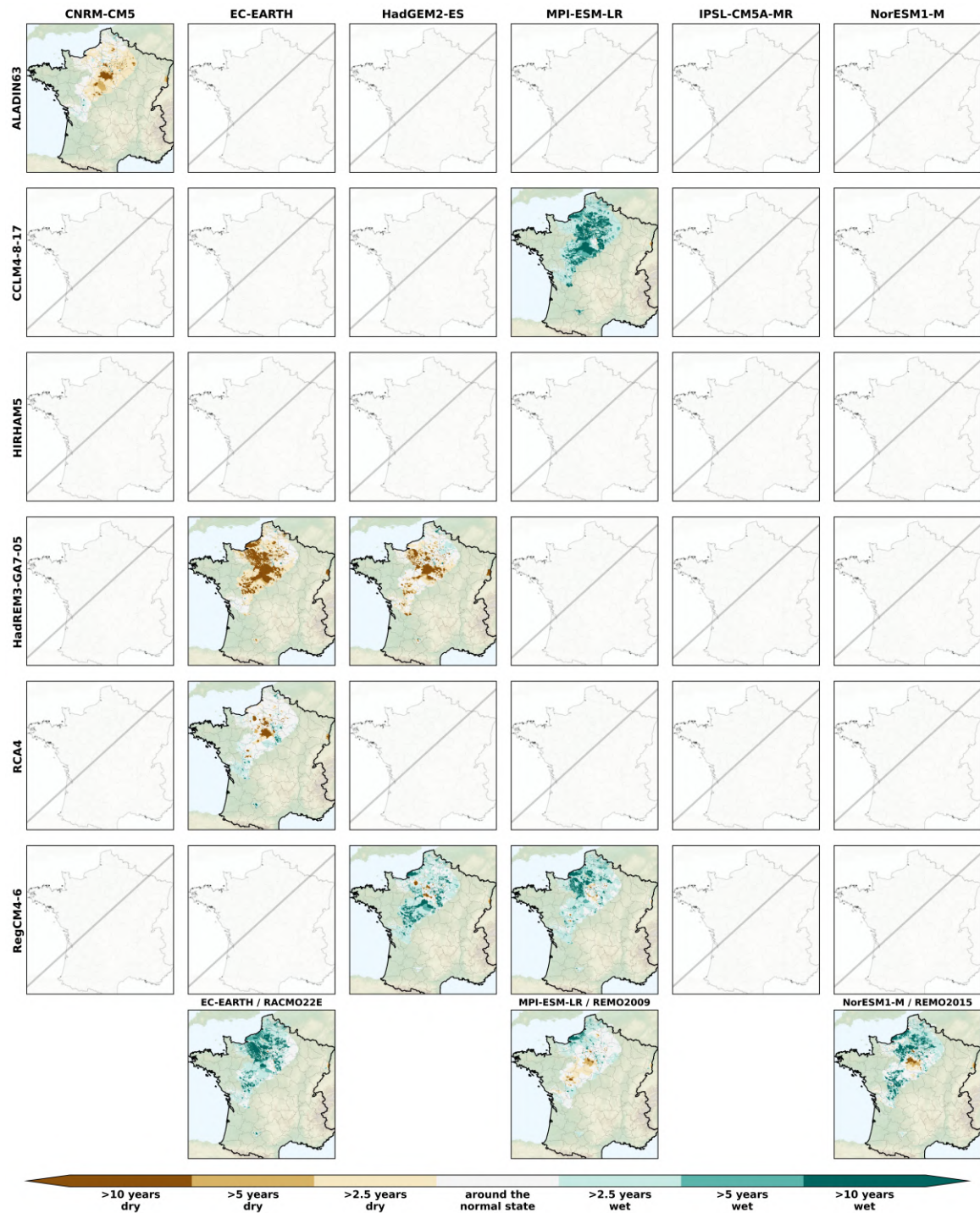


Figure B3. Spatial distribution of the SPLI median over the AquifR domain under the **RCP2.6** on the **long-term horizon (2071-2099)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.



Figure B4. Spatial distribution of the SPLI median over the AquifR domain under the **RCP4.5** on the **short-term horizon (2021-2050)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.



Figure B5. Spatial distribution of the SPLI median over the AquifR domain under the **RCP4.5** on the **intermediate-term horizon (2041-2070)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.



Figure B6. Spatial distribution of the SPLI median over the AquifR domain under the **RCP4.5** on the **long-term horizon (2071-2099)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.



Figure B7. Spatial distribution of the SPLI median over the AquifR domain under the **RCP8.5** on the **short-term horizon (2021-2050)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once. The colored rectangles indicates the GCM/RCM couples corresponding to the storylines (see section 2.1).



Figure B8. Spatial distribution of the SPLI median over the AquifR domain under the **RCP8.5** on the **intermediate-term horizon (2041-2070)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once. The colored rectangles indicates the GCM/RCM couples corresponding to the storylines (see section 2.1).

Appendix C

810 The elements from Appendix C are related to the analyses performed on the temporal evolution of the running median affected by the categories of events for the four storylines (see Table C1 and Table C2) and for all the CPs (see Figure C1 and Table C3), and for the time proportion spend in extreme events for all the CPs (Figure C3).

Table C1. Results from Kolmogorov-Smirnov (KS) test and Mann-Kendall (MK) test for the orange and green storylines under the RCP8.5 on each category of events from Table 2. The direction of the trend is provided if both tests are significant, as well as the corresponding median areas affected for all three horizons.

		Historical		Orange			Green			
Temporal periods		1975	2021	2041	2021	Future general trend	2021	2041	2021	Future general trend
		2004	2050	2070	2050		2050	2070	2050	
≥ 10-year wet	KS p.value	-		< 0.001		↘		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	3.7	1.8	1.7	0.3		17.7	21.1	19.3	
≥ 5-year wet	KS p.value	-		< 0.001		↘		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	7.8	4.0	3.3	0.6		11.2	9.1	9.5	
≥ 2.5-year wet	KS p.value	-		< 0.001		↘		< 0.001		↘
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	19.6	12.7	11.5	2.6		19.6	15.9	16.8	
≥ 2.5-year dry	KS p.value	-		< 0.001		↘		< 0.001		↘
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	18.8	20.7	18.3	10.1		12.8	14.4	11.3	
≥ 5-year dry	KS p.value	-		< 0.001		↗		< 0.001		↘
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	7.0	11.3	9.5	8.5		4.2	6.4	5.9	
≥ 10-year dry	KS p.value	-		< 0.001		↗		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	2.3	18.2	21.8	58.7		2.2	6.4	10.2	

Table C2. Results from Kolmogorov-Smirnov (KS) test and Mann-Kendall (MK) test for the purple and yellow storylines under the RCP8.5 on each category of events from Table 2. The direction of the trend is provided if both tests are significant, as well as the corresponding median areas affected for all three horizons.

		Historical		Purple			Yellow			
Temporal periods		1975	2021	2041	2021	Future general trend	2021	2041	2021	Future general trend
		2004	2050	2070	2050		2050	2070	2050	
≥ 10-year wet	KS p.value	-		< 0.001		↗		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	3.7	12.3	8.8	7.2		4.9	5.3	9.4	
≥ 5-year wet	KS p.value	-		< 0.001		=		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	7.8	8.2	8.0	7.5		6.9	7.0	10.1	
≥ 2.5-year wet	KS p.value	-		< 0.001		↘		< 0.001		=
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	19.6	15.7	15.5	14.7		18.7	16.6	19.3	
≥ 2.5-year dry	KS p.value	-		< 0.001		↘		< 0.001		↘
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	18.8	16.6	15.7	14.1		22.3	16.1	16.5	
≥ 5-year dry	KS p.value	-		< 0.001		=		< 0.001		↗
	MK p.value	-		0.177				< 0.001		
	AquiFR coverage (%)	7.0	7.7	9.2	8.2		8.5	10.3	8.3	
≥ 10-year dry	KS p.value	-		< 0.001		↗		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001		
	AquiFR coverage (%)	2.3	7.0	10.6	18.1		3.2	6.6	6.3	

Table C3. Results from Kolmogorov-Smirnov (KS) test and Mann-Kendall (MK) test for all the available climate projections on each category of events from Table 2. The direction of the trend is provided if both tests are significant, as well as the corresponding median areas affected for all three horizons.

		Historical		RCP2.6			RCP4.5				RCP8.5			
Temporal periods		1975	2021	2041	2021	Future general trend	2021	2041	2021	Future general trend	2021	2041	2021	Future general trend
		2004	2050	2070	2050		2050	2070	2050		2050	2070	2050	
≥ 10-year wet	KS p.value	-		< 0.001		↗		< 0.001		↗		< 0.001		↗
	MK p.value	-		< 0.001				< 0.001				< 0.001		
	AquiFR coverage (%)	3.7	7.7	7.2	13.5		10.1	9.8	16.3		9.6	12.8	16.7	
≥ 5-year wet	KS p.value	-		< 0.001		↗		< 0.001		↗		< 0.001		=
	MK p.value	-		< 0.001				< 0.001				0.660		
	AquiFR coverage (%)	7.8	8.2	8.4	10.0		9.2	8.9	10.2		9.0	9.7	9.0	
≥ 2.5-year wet	KS p.value	-		< 0.001		=		< 0.001		=		< 0.001		↘
	MK p.value	-		0.001				0.004				< 0.001		
	AquiFR coverage (%)	19.6	19.1	18.1	18.9		19.6	17.7	18.5		18.3	17.4	14.1	
≥ 2.5-year dry	KS p.value	-		< 0.001		↘		< 0.001		↘		< 0.001		↘
	MK p.value	-		< 0.001				< 0.001				< 0.001		
	AquiFR coverage (%)	18.8	15.4	15.0	12.6		15.0	15.1	12.0		15.1	14.0	10.5	
≥ 5-year dry	KS p.value	-		< 0.001		↘		< 0.001		↘		< 0.001		↘
	MK p.value	-		< 0.001				0.011				< 0.001		
	AquiFR coverage (%)	7.0	6.2	6.9	4.3		5.3	6.3	4.3		6.6	6.5	5.5	
≥ 10-year dry	KS p.value	-		< 0.001		↗		< 0.001		=		< 0.001		↗
	MK p.value	-		< 0.001				0.603				< 0.001		
	AquiFR coverage (%)	2.3	5.0	6.2	3.7		3.1	4.3	3.3		6.1	6.2	10.0	

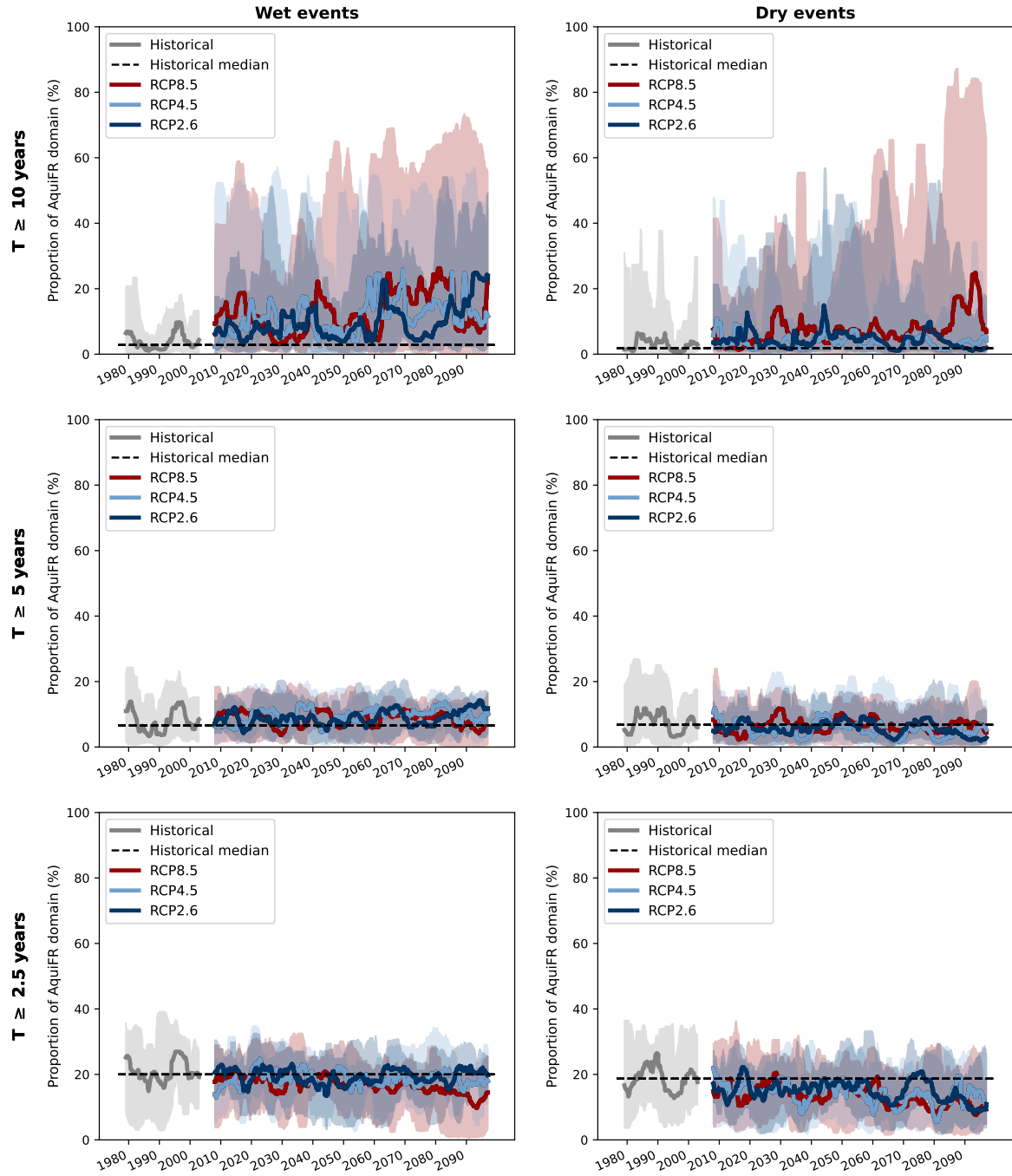


Figure C1. Temporal evolution of the 5-year running median of proportion of area from the Aquifer domain affected by the categories of events from Table 2. From top to bottom are represented the 3 return periods, and from left to dry the wet and dry events. The minimum and maximum values over the set of GCM/RCM couples are also plotted. The gap between the historical curve (in grey) and the future curves under the three RCPs corresponds to the exclusion of the 2003-2007 period centred on 2005 in the calculation of running medians (see section 2.3). The dashed black line represents the median value over the historical period gathering all the available projections.

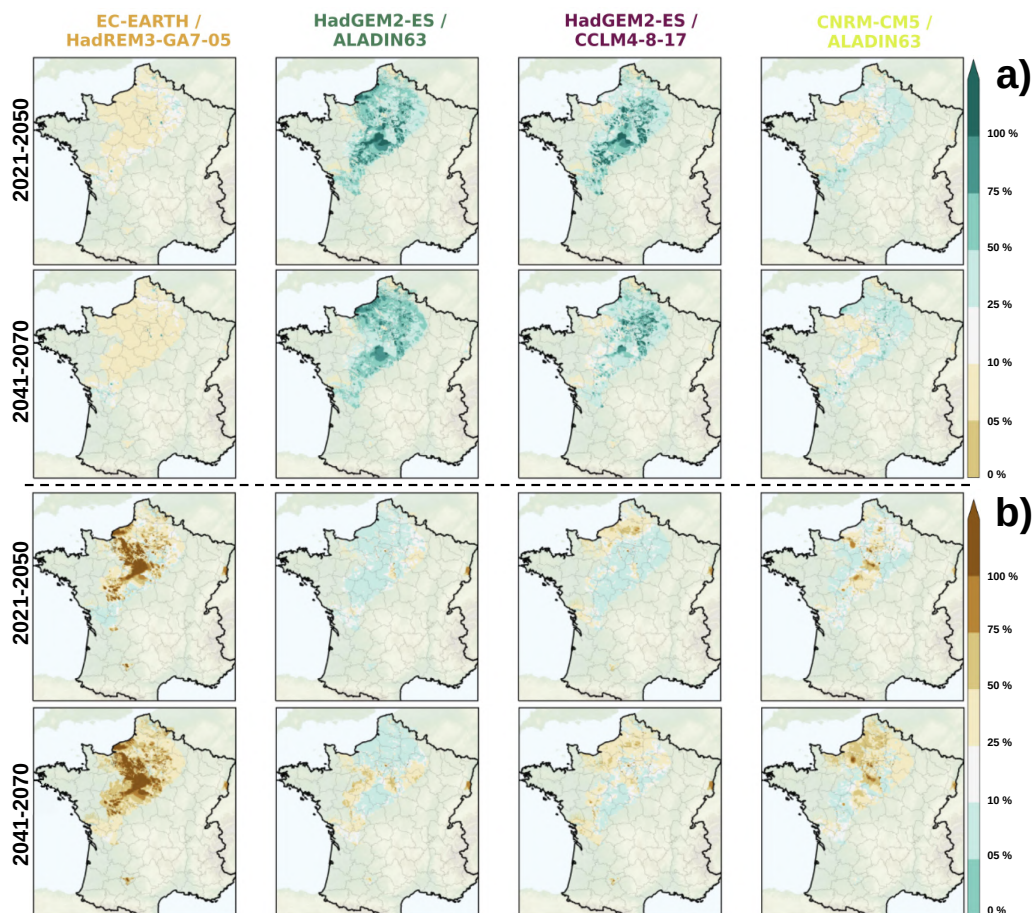


Figure C2. Spatial distribution of the median of the time proportion corresponding to extreme wet events (SPLI > +1.28, a)) and extreme dry events (SPLI < -1.28, b)) for the short-term and intermediate horizons (in line) for the four storylines (in column).

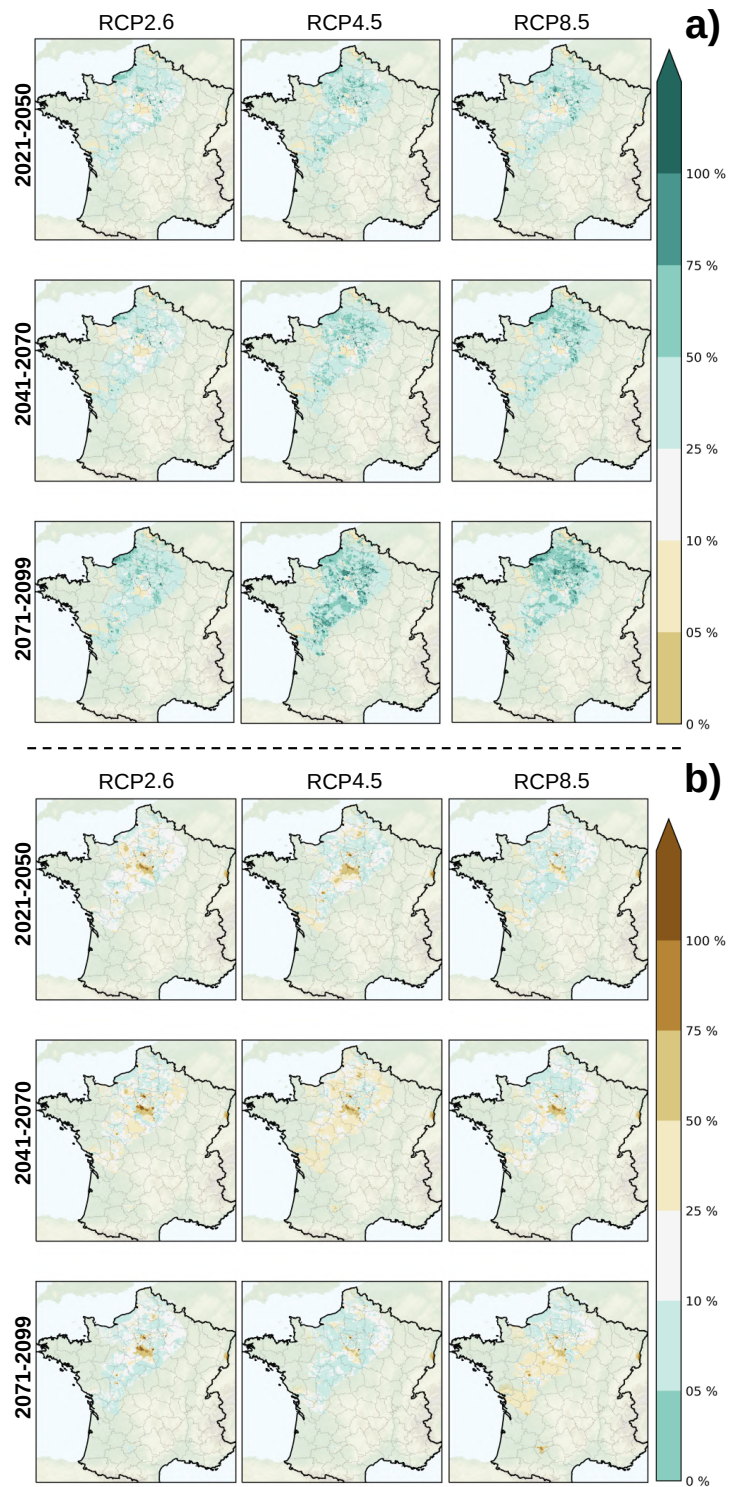


Figure C3. Spatial distribution of the median of the time proportion corresponding to extreme wet events (SPLI > +1.28, a)) and extreme dry events (SPLI < -1.28, b)) per future horizon (in line) and per RCP (in column), from all the CPs.