

Climate change impacts on groundwater simulated using the Aquifer 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 has become~~ 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-use~~ the hydrogeological modelling platform Aquifer ~~together-with-forced by~~ 36 regional climate projections from Eurocordex (CMIP5) ~~from three Representative Concentration Pathways (RCPs)~~, bias-corrected according to a state-of-the-art method, ~~based on three Representative Concentration Pathways (RCPs)~~: RCP2.6, RCP4.5 and RCP8.5. In order to better reflect the uncertainties, ~~4-four~~ storylines based on the RCP8.5 scenario have been selected to ~~be representative of represent~~ possible futures that can illustrate the impacts of worst-case scenarios ~~and- to~~ 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 ~~of groundwater level~~ that provides return periods based on the distribution value over a reference period, ~~here in this case~~ 1975-2004. ~~We found-The analyses revealed~~ significant scatters between regional climate models. ~~Overall, a rise-The predominant signal is an increase~~ 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-which is consistent with~~ 3 out of the 4 storylines, ~~together-with-~~ ~~This accompanied by~~ an increase in the 10-year low groundwater levels mostly observed in South of France, which is shared by the four storylines. This ~~highlights a finding underscores a discernible~~ North-South ~~differentiation distinction~~. The increase in high and low flow events is quite common in surface hydrology, but is less ~~common for groundwater, which has-prevalent in groundwater hydrology, which is characterised by~~ a longer residence time.

1 Introduction

In France, groundwater supports 70% of drinking water, ~~for both supply of drinking water to households-supplying for both domestic~~ (Maréchal and Rouillard, 2020) and agricultural ~~purposes-The latter accounts sectors, the latter accounting~~ for one-third of agricultural withdrawals (Pasquier, 2017). Therefore, understanding and anticipating future groundwater temporal evolution is crucial for stakeholders and decision-makers involved in the sustainable management of water resources, espe-

cially because this evolution depends on both human activities and climate (Baulon et al., 2020; Guillaumot et al., 2024). Furthermore, In addition, the Intergovernmental Panel on Climate Change (IPCC) states asserts 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 impacted in the coming decades by due to climate change (IPCC, 2014, 2022). Among the projected 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. More recent projects used climate projections from the CMIP5 global exercise (Taylor et al., 2012), which were 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 particularly severely affected: the Loire basin, with a decrease in recharge of between where recharge decreases by 25 and to 30% over half of its surface; and especially South-West France, with decreases of where the decreases ranges between 30 and 50%. Completed with The EXPLORE 2070 project, which was completed with a surface hydrology assessment, the EXPLORE 2070 project allowed to better measure the enabled the magnitude of the challenge of defining national adaptation or attenuation strategies , regarding for numerous sectors of activity , e.g. , (e.g. energy and agriculture) to be better measured (Carroget et al., 2017).

However, more recent studies suggest that the impacts impact of climate change on French hydrological systems, including groundwater, are is more contrasted, especially particularly in northern France (Costantini et al., 2023; Vergnes et al., 2023), highlighting the need of for a new general assessment of climate change impacts over the the impact of climate change on French hydrology. Following the In line with 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 , with regard to groundwater, this project is provides an opportunity to integrate larger study study larger areas and more aquifers of interest.

In such a context, the study studying the impact 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 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 Ultimately, the challenge 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).

60 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 Aquifer (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 Aquifer 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~~this limitation, the Aquifer system is already operational for historical reanalysis of groundwater, real-time monitoring and seasonal forecastof 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~~have already been used by Habets et al. (2021) to force Aquifer. ~~Since, However, since then, the~~ projections have been updated and a new assessment is required. Furthermore, Vergnes et al. (2023) have also already assessed the impact of climate change on French groundwater resources, but using a ~~single-layer~~single-layer aquifer model and a coarser spatial configuration than Aquifer, with a set of ~~5~~five climate projections. ~~All these elements underline the interest~~These elements highlight the importance of the present ~~work~~study. As part of the EXPLORE2 project, ~~the aim of this study is~~we aim to assess the impact of climate change projected by regional climate models on several French aquifers of interest. ~~For this purpose~~To this end, the hydrogeological modelling platform Aquifer is used to simulate hydrogeological projections ~~using~~based on a multi-model ensemble 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), which have been downscaled with a method combining weather typing and quantile mapping approaches, ~~that are made available on a public database (DRIAS, Soubeyrou et al. (2021)).~~ These projections are available on the DRIAS public database (Soubeyrou et al., 2021).

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

2.1 Regionalized climate projections from EXPLORE2

The climate projections (CPs) used to force the AquifR platform ~~mainly come primarily originates~~ from the DRIAS-2020 database (DRIAS 2021; <http://www.drias-climat.fr/>, last access the 25th of October, 2024) ~~that which~~ provides downscaled and unbiased climate projections on the French ~~domain. It region. This database~~ is based on a subset of projections from the Euro-CORDEX project (CooRdinated Downscaling EXperiment – European Domain; Jacob et al. (2020)), which is included in CMIP5 (IPCC, 2014). As part of the ~~implementation of the~~ EXPLORE2 database ~~implementation~~, 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 resulting in~~ 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 that follow specific socio-economic~~ trajectories through the 21st century. However, GCM outputs have a coarse spatial resolution ~~of~~ around 2.5°, i.e., between 100 and 200 km², which is insufficient to adequately represent local meteorological ~~phenomenons phenomena~~ and extreme events, ~~and thus prevents their direct use. This prevents them from being directly used~~ as climate forcing in hydrological models for ~~studies at regional or local sealesscale studies~~. Thus prior to use a statistical downscaling 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 with~~ 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 is clustered into one of~~ four weather regimes, based on the ~~cluster clustering~~ of the geopotential height at 500 hPa ~~of from~~ 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 regime/seasons couples season combinations~~ (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 to~~ the quantile distributions of RCMs climate variables ~~being, which are~~ adjusted according to the meteorological reference.

The historical meteorological reference used is the SAFRAN reanalysis (Le Moigne et al., 2020), ~~providing which provides~~ "pseudo-observed" data ~~useful for bias correction all over across~~ 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~~ comprises 6 GCMs coupled with 9 RCMs, and forced by 3 RCPs : (1) RCP2.6, a stringent mitigation scenario ~~assuming an efficient environmental international~~ which assumes an efficient international environmental policy (van Vuuren et al., 2007); (2) RCP4.5, an intermediate ~~stabilization~~ stabilisation 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~~ one to three RCPs, for a total of 36 simulations (Table A1 in supplementary material, appendix A), all downscaled and ~~bias-corrected~~ bias-corrected by ADAMONT.

Following the recommendations of the EXPLORE2 project, the analyses of CPs were ~~done on~~ conducted over four time periods ~~regrouping comprising~~ 1 historical period and 3 future horizons for a total ~~period~~ time frame ranging from 1975 to ~~2099, considering 2099~~ This considers that an hydrological year is set from august 01st to july 31th (Table 1). Furthermore,

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

four storylines, i.e., CPs based on contrasted trends, were selected 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;
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 AquifR modelling platform

AquifR 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 over~~ a sixty-year period (Vergnes et al., 2020), and has demonstrated good performance in simulating groundwater ~~level~~ levels, compared to observed piezometric heads from the ADES ("Accès aux Données sur les Eaux Souterraines") database (<http://www.adeseafrance.fr/>, last access the 29th November 2024, Chery and Cattani (2003)). Nowadays, the AquifR platform is used in an operational context for real-time monitoring and seasonal forecasting on the main sedimentary basins and aquifers for groundwater decision-makers (Habets

2.2.1 The SURFEX modelling platform

A specific feature of AquifR 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. ~~This is achieved~~ using several land surface schemes ~~dedicated~~ to each land use category. The groundwater recharge and surface runoff simulated by SURFEX ~~is~~ ~~are~~ used to force the hydrogeological models implemented in AquifR.

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 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 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~~ ~~have been~~ integrated into the AquifR 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 ~~an~~ explicit representation of river-aquifer exchanges and ~~simplified transfer~~ ~~a simplified transfer process~~ within the unsaturated zone (Philippe et al., 2011).

EauDyssée is an updated version of the MODCOU modelling software (Ledoux, 1980) ~~gathering comprising~~ 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~~. ~~This approach is~~ 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 ~~for river routing~~, 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~~ ~~developed by~~ 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 using~~ a 3-dimensional finite volume approach to solve the hydrodynamic equation based on Darcy's law and mass conservation on a regular rectangular grids, ~~and~~ 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 forced by the runoff~~ 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 mostly~~ located in the large sedimentary basin in the North part of France, ~~including spanning the~~ Poitou-Charentes ~~region~~, 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 covering~~ an area of around 1,100 km² East of France, and MARTHE Tarn-et-Garonne, of a similar size, which is the only ~~model located~~ 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 packages, and the ~~obtained might models resulting models may~~ overlap spatially (to account for ~~the~~ 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 ID numbering~~ presented in Table A2, from the uppermost surface layer to the deepest layer, and is applied to all spatial projection results in this article.

2.3 Method used to analyse the climate change projections

2.3.1 Standardized Piezometric Level Index

~~In the following, the~~ The following analyses use the Standardized Piezometric Level Index (SPLI; Seguin (2015)) to examine the evolution of the groundwater level over the Aquifer domain ~~is analysed using the Standardized Piezometric Level Index (SPLI; Seguin (2015)), a normalized~~. The SPLI is a normalised 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's ~~intrinsic hydrogeological heterogeneity~~. The advantage of the SPLI is that it ~~makes it easy to interpret the state of provides an easy-to-interpret indication of whether~~ the groundwater levels ~~in term of is~~ above or below ~~mean the median~~

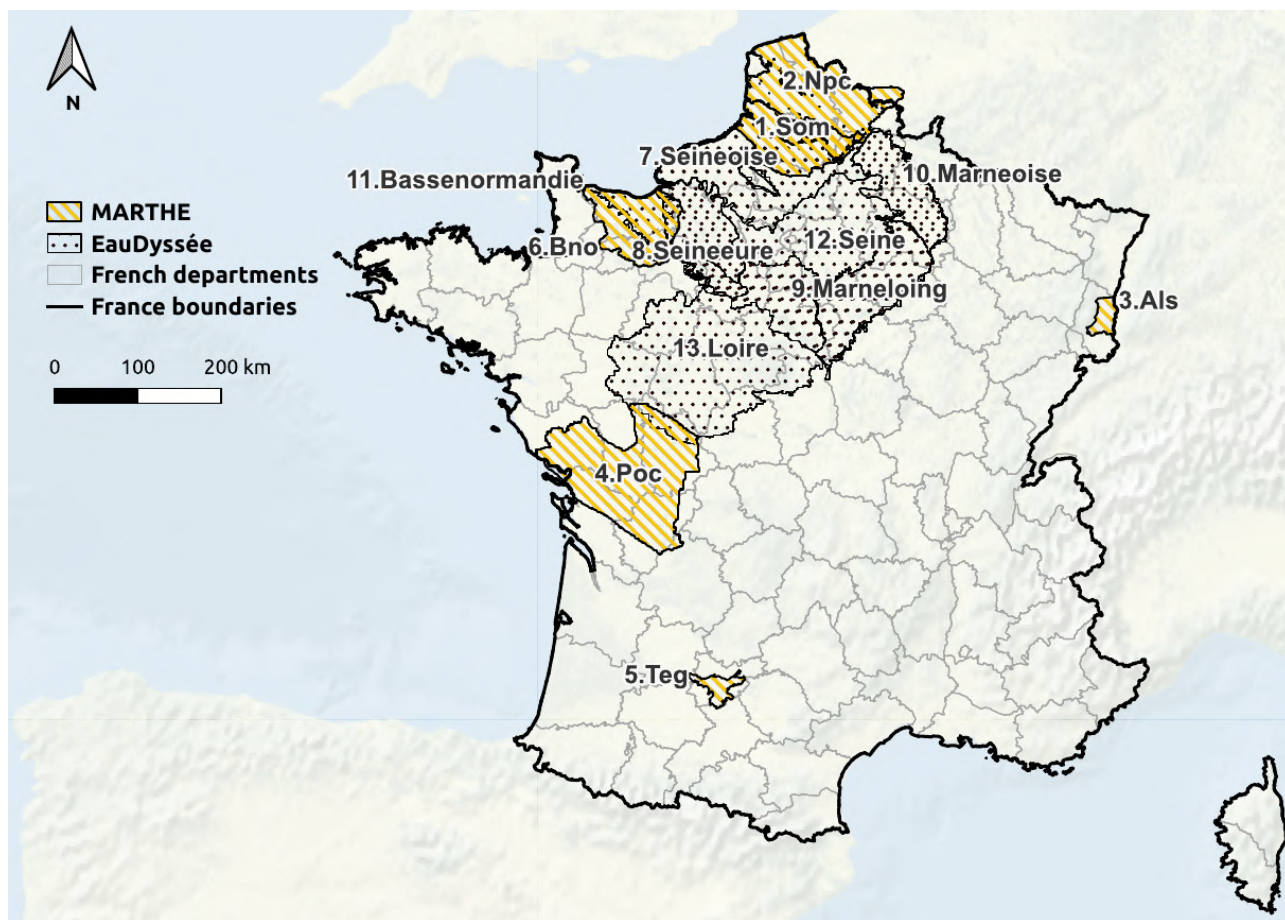


Figure 1. Spatial distribution of the AquiFR models. The numbers refer to the IDs of each model regrouped in supplementary material (see Table A2).

215 state for the given month. The greatest advantage ~~comes with~~ lies in mapping, as ~~map maps~~ 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.

The SPLI is based on the same approach ~~than as~~ the well-known Standard Precipitation Index (SPI; McKee et al. (1993)).
 220 ~~The first step consists in extracting~~ First, 12 series of monthly groundwater ~~level levels are extracted~~ from the reference historical time series, ~~separately one for each month~~ from January to December, from ~~an a~~ historical series of N years (N = 30). ~~Then~~ Second, monthly cumulative distribution functions (CDFs) are extracted from the monthly groundwater levels ~~and they are~~ which are then 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 Python package (Pedregosa et al., 2011). ~~Eventually~~ Thrid,
 225 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~~ Eventually, each groundwater level value 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.

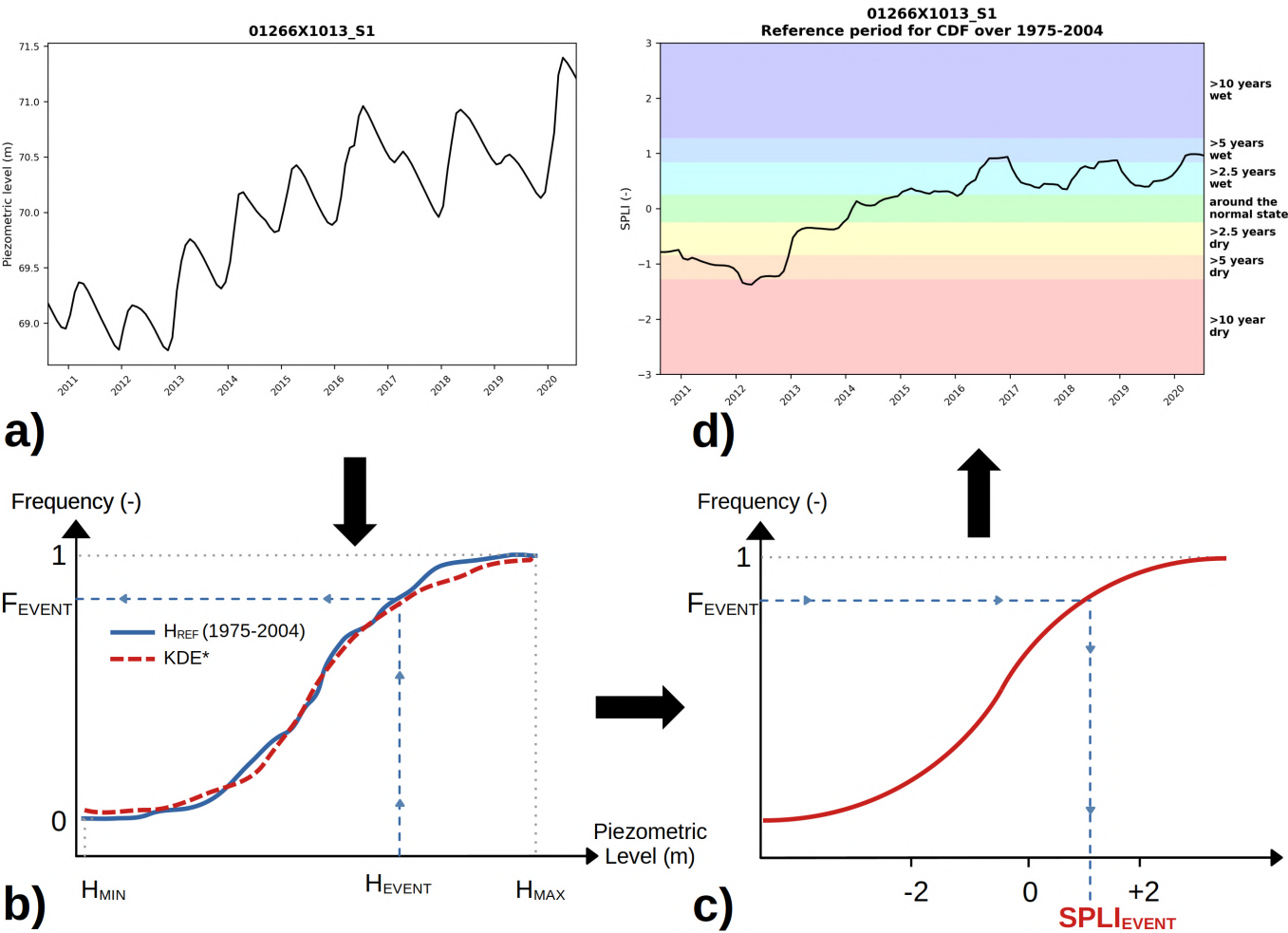


Figure 2. General approach for constructing the SPLI. "KDE" refers to the Kernel Density Estimation used to estimate the best probability density function fitting the reference CDF from reference water table level mean (H_{REF}). The piezometer 01266X1013_S1, located in the Seine-Oise basin, is used 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.

230 The SPLI values are ~~centered-centred~~ on 0, which corresponds to a simulated groundwater level ~~closed-close~~ to the median of the groundwater levels in the reference series. ~~A negative value indicates~~ Negative values indicate a lower level, i.e., for ~~an~~ event events 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	$\geq +1.28$	≥ 10 -year wet

235 **2.3.2 Groundwater evolution under climate change**

In this paper, the evolution of the groundwater is first analysed ~~regarding in term of~~ the spatial distribution of the median of the SPLI values ~~from across~~ 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~~ illustrating 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
240 uncertainty related to CPs.

A second analysis is carried out on ~~occurence~~ the occurrence of intense events, by ~~analysing~~ examinig the temporal evolution of the ~~part~~ proportion of the domain that is affected by 10-year return period dry or wet events (see Table 2). In practice, the SPLI values ~~of from~~ all models are regrouped and the proportion of ~~area~~ surface affected by a specific return period is defined as the sum of ~~the surface of each pixel~~ each pixel's surface dedicated to this return period, and divided by the total surface area
245 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 for each~~ RCP with an envelope representing the difference between the ~~min and max values~~ in order to compare minimum and maximum values, to enable comparison of future trends between each RCP. ~~Because As~~ the year 2005 ~~is characterized by~~ marks the transition between the historical and the future periods ~~into in~~ the simulations provided by the CPs, the period from 2003 to 2007 is excluded from this analysis.
250 The significance of the trends observed between the reference period and the horizons of the 3 RCPs is assessed using two statistical tests:

- The Kolmogorov–Smirnov test (Birnbaum and Tingey, 1951) is used 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~~ is used to assess whether the associated trend of future SPLI values significantly evolves over time.

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

A third set of analysis ~~concerns~~ focuses on hydrogeological extreme events, which are 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~~ the median proportion of time corresponding to these extreme wet events is analysed, per future horizon and per

RCP.

~~In the following , the analyses are mostly focused~~ The following analyses mostly focus 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 available CPs (Table A1) are also ~~individually performed~~ performed individually on the four storylines selected in the EXPLORE2 project (see section 2.1) in order to compare the statistical trends extracted from all the combined CPs, and the trends obtained when using few plausible futures ~~which that~~ conserve all their physical consistency (Marson et al., 2024). This second approach is therefore more deterministic regarding the scenario represented by the storyline.

3 Results

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 such as~~ the orange storyline (EC-EARTH/HadREM3-GA7-05 couple), lead to a increase in the area ~~dedicated~~ corresponding to dry events, specifically 10-year events which ~~cover span~~ almost the entire AquifR domain on the long-term horizon. On the contrary, other couples like the green storyline (HadGEM2-ES/ALADIN63) ~~or and~~ 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 throughout the entire period.

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

Focusing on the purple storyline, the results ~~lead to indicate~~ stable groundwater levels ~~on in~~ 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~~ close to normal for the intermediate and long-term horizon over

the major part of the domain, except ~~for in~~ the Basse-Normandie region with decreasing trend. The yellow storyline ~~presents~~
285 ~~the smallest shows the least~~ changes. Groundwater levels ~~over the in~~ southern Beauce, the Loiret department and the northern
part of the Loire basin ~~slightly decrease decrease slightly~~ (median SPLI below the 2.5-year dry, and around normal elsewhere).
Similar results are observed for the long-term horizon, ~~excepted except~~ 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 show~~ an opposite trend with decreasing groundwater levels for
290 all the storylines, corresponding to decadal dry events, from the short-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 From~~ the northern part of the AquifR domain to the ~~South southern part~~ of the Loire basin, the median of the
295 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 decadal event on the long-term horizon;
- ~~on 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 findings suggest a North-South~~ divide in the future evolution of groundwater level under
300 the RCP8.5, ~~and is as~~ highlighted by 3 out of the 4 storylines (green, purple and yellow).

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 ground-
water level to a relatively high value, 3 couples (30%) project almost no change and 3 couples (30%) project a decrease of
the groundwater ~~level~~, especially the ones related to the EC-EARTH GCM. These results are ~~similar on consistent across~~ the
305 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 trend in groundwater levels~~ 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 AquifR domain, while 3 couples induce either no
change or slight decrease of the groundwater level.

310 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.

3.2 Evolution of the occurrence of wet and dry events

Figure 4 ~~shows illustrates~~ the temporal evolution of the percentage of the surface within the AquifR ~~domain surface area~~ that
315 falls into one of the six SPLI categories (in line) ~~depicted, as defined~~ 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 depend largely~~

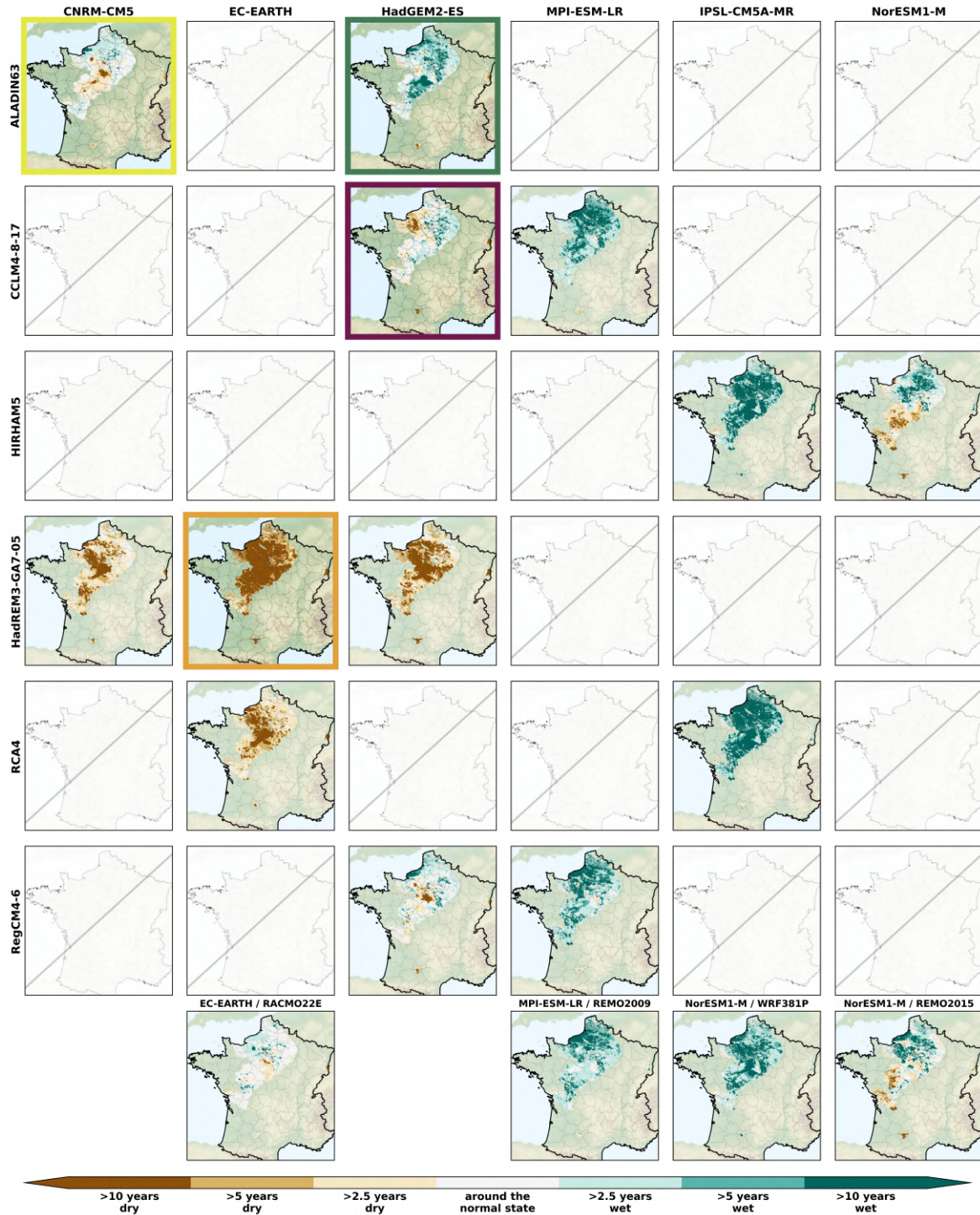


Figure 3. Spatial distribution of the SPLI median over the AquifR domain under the **RCP8.5** on the **long-term horizon (2071-2099)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once. The colored rectangles indicates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

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~~ corresponding 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~~ related 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~~ except for the 10-year dry event ~~for which~~ where the surface slightly increases ~~and reaches to~~ 6.3%. The changes induced by the purple and the yellow storylines are smaller, ~~excepted~~ except for both wet and dry decadal events ~~for which~~ where the contrasts are particularly pronounced. These two storylines tends to increase the decadal events (mainly the purple storyline) and ~~reducing the surface dedicated~~ reduce the surface allocated 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 which~~ highlights the heterogeneity between the projections. The surfaces ~~dedicated~~ related to 10-year events increase for both wet and dry events, spreading with time and increasing greenhouse gaz emission, ~~especialy~~ particularly for wet events. The surface related to dry decadal events ~~area~~ is also projected to increase, ~~but~~ albeit 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 indicating~~ an intensification of extreme events, which is in line with the results aligns with the findings from the storylines.

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., those 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 vary~~ depending on the storyline. The orange storyline tends to reduce the time proportion corresponding to wet decadal ~~event events~~ to less than 5% over almost ~~all the Aquifer domain~~ while it tends to increase the entire Aquifer domain, while increasing the time proportion of dry decadal events to more than 75% over the ~~entire whole~~ domain. The green storyline ~~tends to strongly increase~~ strongly increases the time proportion of wet decadal events while reducing the one corresponding to dry decal events. The purple storyline induces an increase ~~of in~~ 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

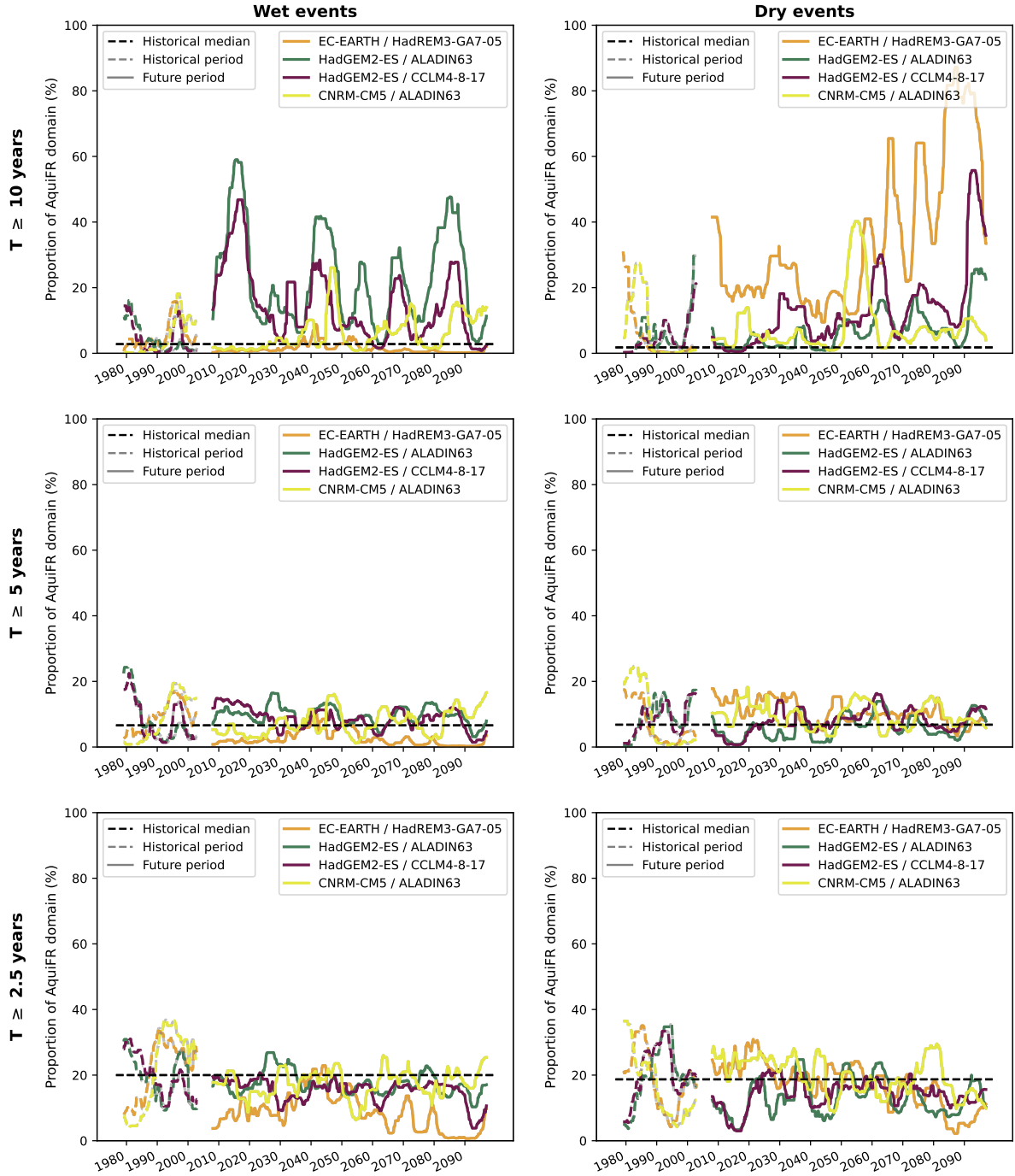


Figure 4. Temporal evolution of the running median of proportion from the Aquifer domain affected by the categories of events from Table 2 for the four storylines. The lines represent the return periods of the events, for the wet events (left) and dry events (right). The gap centered on 2005 corresponds 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.

not highlight a noticeable future tendency over the 21st century.

The results for all the CPs (see Figure C3) show that ~~on~~, in the short-term horizon, the time proportion of ~~decade~~decadal wet events corresponds to almost half of the time over half of the AquifR domain for the three RCPs, ~~and remains~~. This proportion remains close to the historical conditions over the remaining part of the domain. Then, this time proportion increases as time goes to 2100, ~~mostly on~~ primarily in the northern part of the AquifR 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 AquifR domain ~~on~~ under the RCP2.6 and RCP4.5. ~~On~~ Under the RCP8.5, the results show a decrease of the time proportion in the northern part of the AquifR 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.

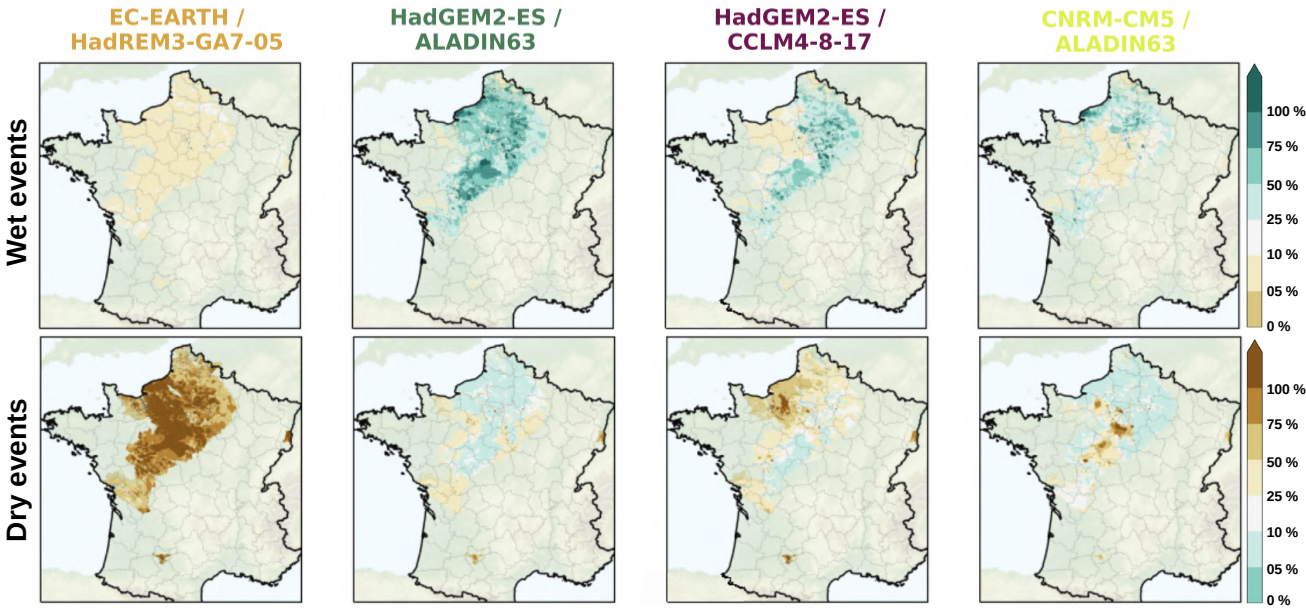


Figure 5. Spatial distribution of median of time proportion corresponding to extreme wet events ($SPLI > +1.28$, 1st line) and extreme dry events ($SPLI < -1.28$, 2nd line) for the long-term horizon for the four storylines (in column) under the RCP8.5.

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 AquifR modelling platform using 36 climatic projections spread over 3 ~~socio-economical~~ socio-economic scenarios RCPs. ~~Results~~ The results are analysed based on the Standardised

Piezometric Level Index (SPLI), using the 1975-2004 period as reference. ~~The results show~~ They demonstrate that the spatial distribution of the SPLI median ~~differs from one projection to another, leading to~~ varies between the projections, resulting in an uncertainty that ~~limits the extraction of~~ prevents a clear trend ~~of future groundwater evolution from being identified regarding the future evolution of groundwater~~. This uncertainty is ~~not really surprising to be expected~~ as the study area ~~is included into~~ falls within the transition zone of the Atlantic region, where expected trends ~~change from being wetter~~ shift from a wetter climate in the North to ~~drier~~ a drier climate in the South (Goubanova and Li, 2007; Meaurio et al., 2017). Therefore, ~~there is a lack of consensus among the CPs regarding the climate projections do not agree on the~~ location of the transition zone, ~~inducing the obtained divergence on the~~ thereby inducing divergence in the future evolution of groundwater levels.

Furthermore, this ~~uncertainty, which is often inherent to~~ inherent uncertainty that is frequently observed in hydroclimatic modelling chains based on a multi-model approach ~~, is~~ has been identified a recurring point in the literature (Knutti et al., 2013) and requires a proper evaluation (Northrop and Chandler, 2014; Evin et al., 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 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~~ In the context 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~~ indicated that the main contributor to the total uncertainty is internal climate variability ($> 40\%$). ~~Then~~ Subsequently, 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~~ accordance with the literature, ~~showing which states~~ that the cumulative GCM/RCM contribution often reaches 40% to 80% of the total uncertainty (Vetter et al., 2015; Tramblay and Somot, 2018; Lemaitre-Basset et al., 2021; Jeantet et al., 2023), ~~and~~. Moreover, they are consistent with the analyses showed in this paper suggesting that the results strongly depends on the GCM/RCM couples. In South of France ~~where~~, including the MARTHE Tarn-et-Garonne ~~is included~~, ~~Evin et al. (2024) showed model~~, Evin et al. (2024) demonstrated that the RCPs ~~are the second~~ constitute the third source contributing the most to the total uncertainty, which can be ~~related~~ attributed to a weaker influence of precipitation in these regions than on the rest of the country, and as a consequence a ~~stronger~~ heightened influence of temperature evolution, over the 21st.

The hydrogeological part ~~might~~ may also contribute to uncertainty, and a proper evaluation 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 demonstrated by~~ Habets et al. (2013) as part of the RexHySS project on the Somme and the Seine regions ~~that results~~, the simulated outcomes derived 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~~ analogous results, and that the contribution of hydrogeological components of the modelling chain to the total uncertainty remains ~~low~~ negligible compared

to the contribution from the climate components. ~~Moreover~~Furthermore, 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~~maintain consistency 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 Aquifer 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 suggests that the~~mean distribution of groundwater level obtained from CPs is ~~similar~~analogous 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~~analogous results. The largest differences are ~~observed~~evident in March and April, ~~suggesting~~indicating 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 Aquifer 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~~. Instead, it is more likely that these discrepancies are due to the divergences from the CPs on the future period, and ~~as so~~thus from the climate components of the modelling chain (GCMs and RCMs), ~~which~~. This statement is in agreement with the results highlighted by 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~~Consequently, if these CDFs are too divergent, this may ~~lead to SPLI values related~~result in SPLI values pertaining to different categories of events from one CP to another (Table 4), ~~in particular~~particularly 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.

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

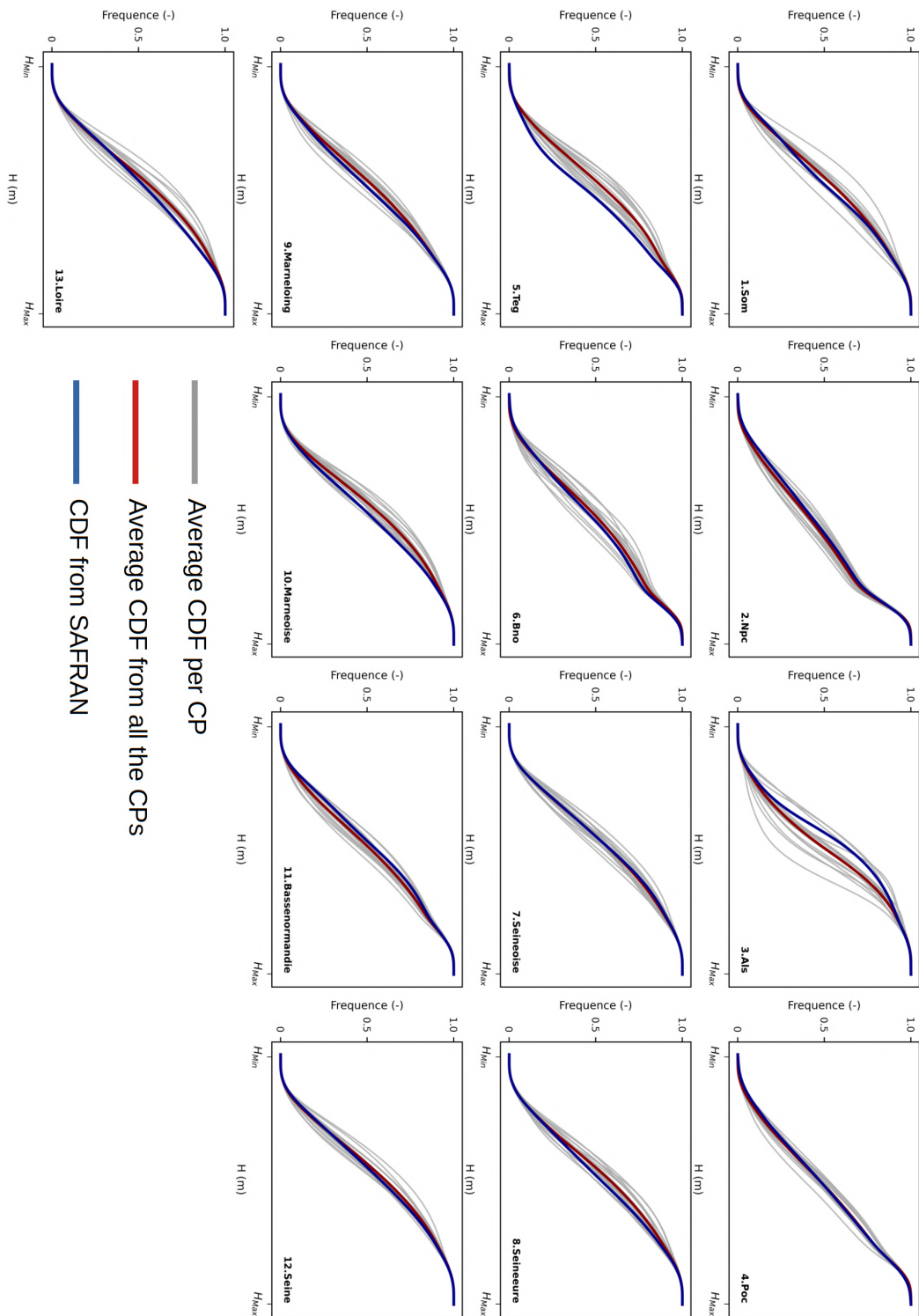


Figure 6. Comparison of CDFs from the reference reanalysis SAFRAN with those from CPs calculated on the historical period (see Table 1), for the month of January. The IDs of each model correspond to the abbreviations from Table A2 in supplementary material.

4.2 Groundwater evolution over the 21st century

Faced to the divergences observed between all the available CPs in the multi-model ensemble approach, the extraction of reliable 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~~ identified, primarily through to
440 the utilisation of storylines which demonstrate analogous 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 (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
445 over most of the AquifR domain, while this increase starts from the long-term horizon for the yellow (Nord Pas de Calais and Basse-Normandie) and the purple (on the Beauce and the Loire catchment) storylines. Second, a decrease in groundwater level from the southern part of the AquifR domain (i.e., south of Loire catchment and Tarn-et-Garonne) and from 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 entire~~ AquifR domain,
450 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 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~~ precipitation projections derived from climate models used in the EXPLORE2 project (Marson et al., 2024). In
455 this paper, the ~~limited~~ spatial representation of South of France into the AquifR platform ~~does not allow us to establish with certainty is limited, which prevents~~ the existence of this North-South divide from being highlighted with certainty. However, ~~our results the results of this study~~ are in agreement with Vergnes et al. (2023), ~~which who~~ 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 a subset of the RCP8.5 DRIAS projections. Moreover, these conclusions are also ~~in line consistent~~ with the
460 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~~ Nevertheless, some differences with our findings and the conclusions extracted from the literature are to be noticed. Indeed, ~~our conclusions the conclusions drawn~~ for the northern France are not consistent with the results of the EXPLORE 2070 project which, as mentioned in section 1, suggested a global decrease of both recharge and groundwater level over France
465 (Habets et al., 2013; Carroget et al., 2017). The divergence ~~might may~~ 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 particularly~~ 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

470 MARTHE model, included in the Aquifer platform, and CPs provided by the DRIAS-2020 database, which ~~is~~are included into the CP database established by EXPLORE2. However, the main difference is that the MARTHE hydrological software package was ~~configured~~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
475 main originality of this study.

Moreover, most of studies ~~dealing with surface hydrology~~addressing surface hydrology under climate change state that the seasons will be more contrasted ~~under climate change~~in the future, e.g., winter flows will be higher while summer will be lower (Sauquet et al., 2024), ~~induced by~~shift that can be attributed to 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
480 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~~be attributed to the slow temporal dynamics ~~characterizing~~characterising the aquifers in the study area, particularly those close to the Parisian Basin ~~, constituting which constitute~~ a large part of the Aquifer domain. Indeed, these aquifers are subject to variations ~~observed on timescales that are often longer than that often extent beyond~~ the hydrological year and even span multi-decadal (Baulon et al., 2022), ~~making it difficult to~~. This
485 renders the observation of observe sub-annual variations a highly arduous undertaking.

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~~most pronounced, particularly in the long-term horizon. In this context, the storylines can ~~invite~~encourage the decisions-makers to establish their
490 policy ~~using the less favorable~~based on the less favourable 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~~an arduous task, because the projections are
495 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 quite divergent, yet they do underscore~~ an increase of groundwater with values ~~reaching that reach~~ the 5-year to 10-year wet return period of the reference. Under the RCP4.5, this result is in
500 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 encompassing the majority~~ 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~~stated in the introduction section, ~~no anthropisation impacts on water resource was addressed in this study~~this

505 ~~study does not address the impacts of anthropisation on water resources~~, 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 ~~supposedly~~ 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 may be rendered moot by the fact that, according to several projections,~~ groundwater level is ~~supposed-expected~~ to decrease over 510 the 21st century, specifically in the southern AquifR domain. In such cases, ~~it is imperative that~~ 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~~ ~~could prove to be a pivotal element in enhancing the efficacy of~~ our analysis.

4.3 Hydrogeological extreme events under climate change

515 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-increases~~ 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 a trend~~ 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~~ ~~could affect surface~~ 520 ~~water, resulting in~~ an increased risk of flooding, as shown by Trambalay 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~~ ~~predicts a~~ different future trend ~~characterized~~ ~~characterised~~ by a total disappearance of extreme wet events.

Conversely, the results also show an increase in extreme dry events, ~~which is as~~ confirmed by the four storylines. It should be 525 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~~. ~~Furthermore~~, the orange storyline leads to ~~an larger increase of a much larger increase, by~~ a factor of 25 of the extreme dry events, covering almost ~~this the~~ entire AquifR domain. In this case, groundwater recharge may decrease, ~~phenomenon which is already observed nowadays a phenomenon already observed~~ in some locations ~~nowadays~~, e.g., the Champagne region (Sobaga et al., 2024). The areas where ~~this increase is~~ ~~these increases are~~ larger are Alsace, Poitou- 530 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 do not appear to~~ noticeably involve hydrogeological droughts in the large majority of the AquifR domain. This is ~~a noticeable difference with~~ ~~differs notably from~~ recent hydrological drought assessments, which clearly indicate an intensity of drought events, whether in terms of low flows observed or ~~none flow periods~~, 535 ~~specifically periods of no flow, particularly~~ in South of France (Dayon et al., 2018; Lemaitre-Basset et al., 2021; Trambalay et al., 2024). This result ~~is also in contradiction with~~ ~~contradicts~~ 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 those used in the EXPLORE
540 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~~, whereby the groundwater feeds the river (Guillaumot et al., 2022). Therefore, droughts may be observed at the surface without ~~any~~ having a direct effect on groundwater.

5 Conclusions

545 ~~In this study, the purpose~~ The purpose of this study is to identify the main impacts of climate change on groundwater levels in the French regions covered by the Aquifer platform: Nord Pas-de-Calais, Basse-Normandie, Parisian Basin, Loire, Poitou-Charentes, Alsace and Tarn-et-Garonne. ~~For this purpose~~ To achieve this, the hydrogeological modelling platform Aquifer, ~~gathering which gathers~~ 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~~. The latter is based on a multi-model
550 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-normalised~~ indicator of groundwater level, ~~in order to compare which allows~~ various types of ~~aquifers at once~~ aquifer to be compared simultaneously. The results show ~~future trends strongly divergent, mainly that future trends diverge~~ depending on the GCM/RCM couples, either on the spatial distribution of median SPLI or on
555 years.

Under the **RCP8.5**, the divergences from the 17 CPs are ~~large~~ substantial, but two main ~~tendencies have been extracted~~ trends have been identified, 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 Aquifer domain (Nord Pas-de-Calais, Parisian Basin, Normandie), ~~which is a statement~~ supported by 3 out of the 4 storylines. Second, a decrease in
560 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~~ North of the Aquifer domain. ~~The all~~ All four storylines confirm this evolution, and the orange storyline (the driest one) ~~extend~~ extends this increase of dry event to the entire Aquifer domain, ~~to groundwater level with groundwater levels~~ 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~~ along the northern border ~~depending which depends~~ on the
565 GCM/RCM couple. ~~Although~~ While 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~~ those from several other studies dealing with climate change impacts on French hydrology, especially the joined researches carried out ~~as part of in~~ the EXPLORE2 project on groundwater recharge (Lanini et al., 2024) and surface hydrology (Sauquet et al., 2024), which justifies the authors'
570 confidence in this conclusion. Furthermore, the use of the storylines ~~might~~ may encourage the decision-makers to ~~follow~~ adopt the precautionary principle and ~~choose~~ select the worst case situation ~~to establish~~ when establishing 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
575 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~~ in 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~~ diverge too much from one GCM/RCM couple to another to extract reliable future trends.

~~Several potential ways of improvements to this work are conceivable~~ There are several potential ways in which this work could
580 be improved, such as integrating more models into the AquiFR platform ~~and then increasing to enhance~~ its representativeness for the different French hydrogeological contexts, especially in South of France. Similarly, ~~the use of~~ using other hydrogeological modelling software per model could ~~make a significant contribution to~~ substantial improve the reliability 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
585 integrate socio-economic considerations into physically-based models ~~, then making water demand related to~~ to make water demand dependent on water availability.

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.

590 *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 conceptualised the work. AJ and JPV performed the simulations and analyses. AJ drafted the paper. JPV, SM and FH all revised the paper and contributed to its analyses and discussions.

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Supplementary material

850 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 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			2.6				4.5	2.6		
	8.5	-	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)

860 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.

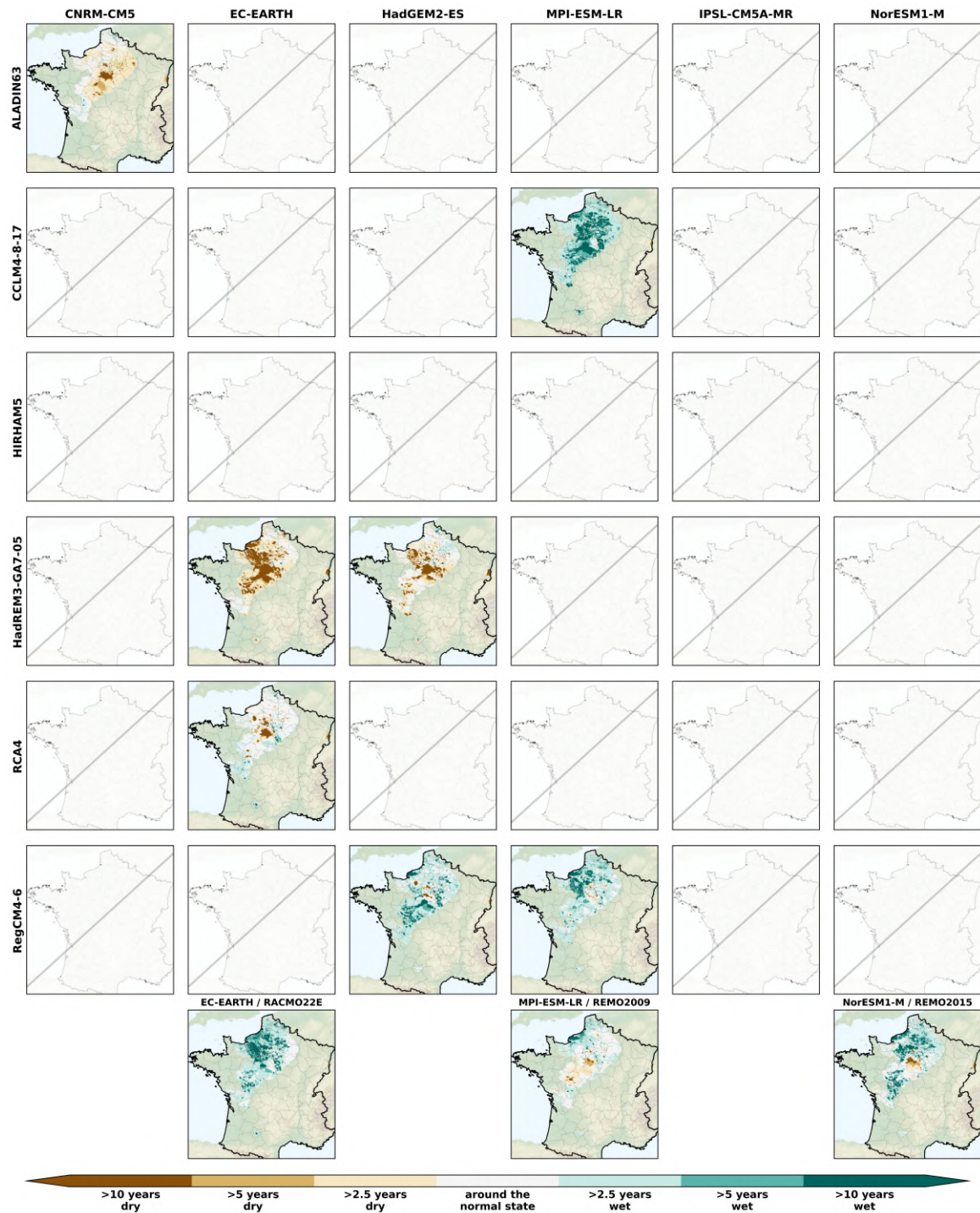


Figure B3. Spatial distribution of the SPLI median over the AquifR domain under the **RCP2.6** on the **long-term horizon (2071-2099)**, following the different GCM (in column) / RCM (in line) combination. The last line corresponds to couples where RCMs are used only once.



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

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	

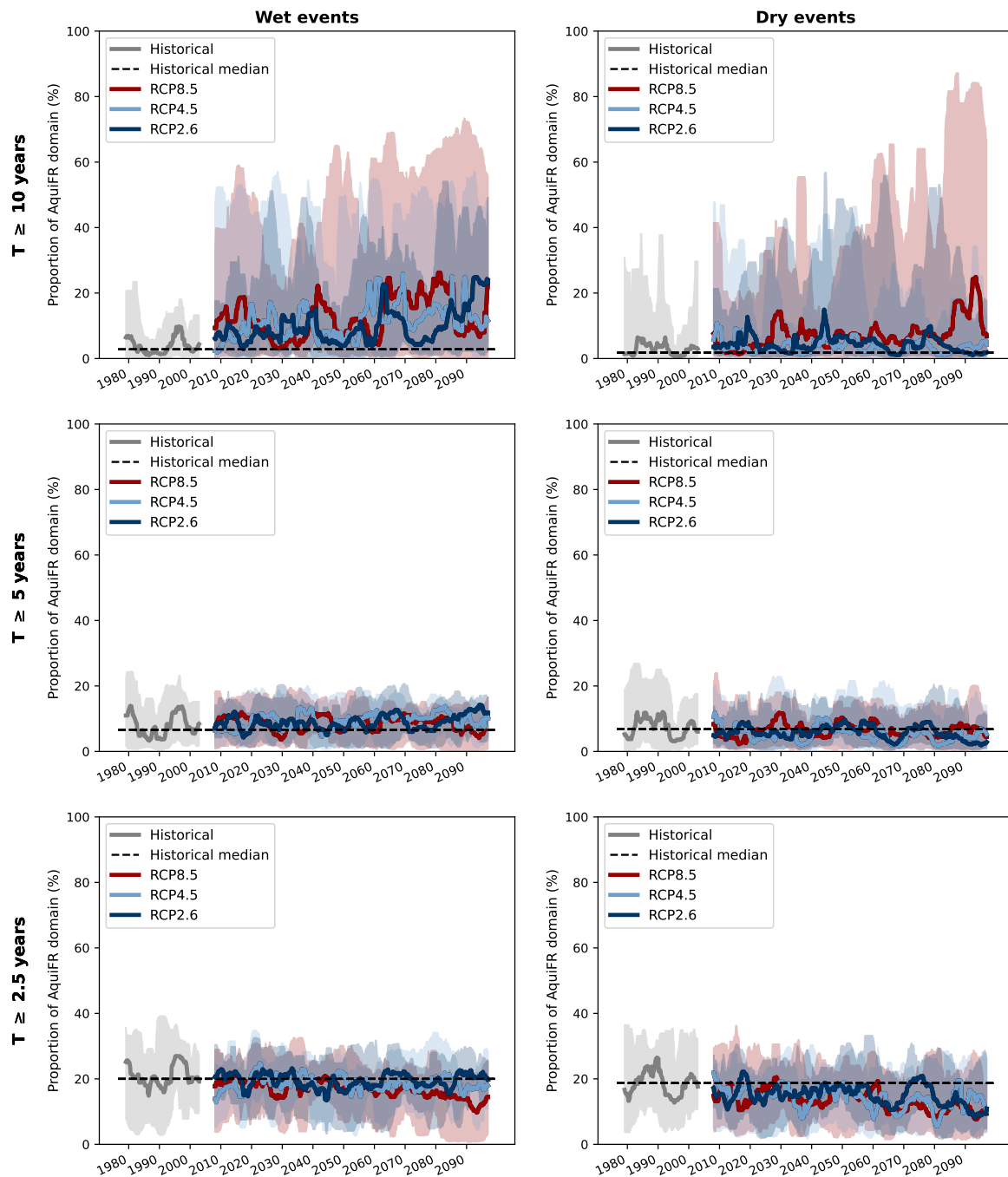


Figure C1. Temporal evolution of the 5-year running median of proportion of area from the Aquifer domain affected by the categories of events from Table 2. From top to bottom are represented the 3 return periods, and from left to dry the wet and dry events. The minimum and maximum values over the set 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.

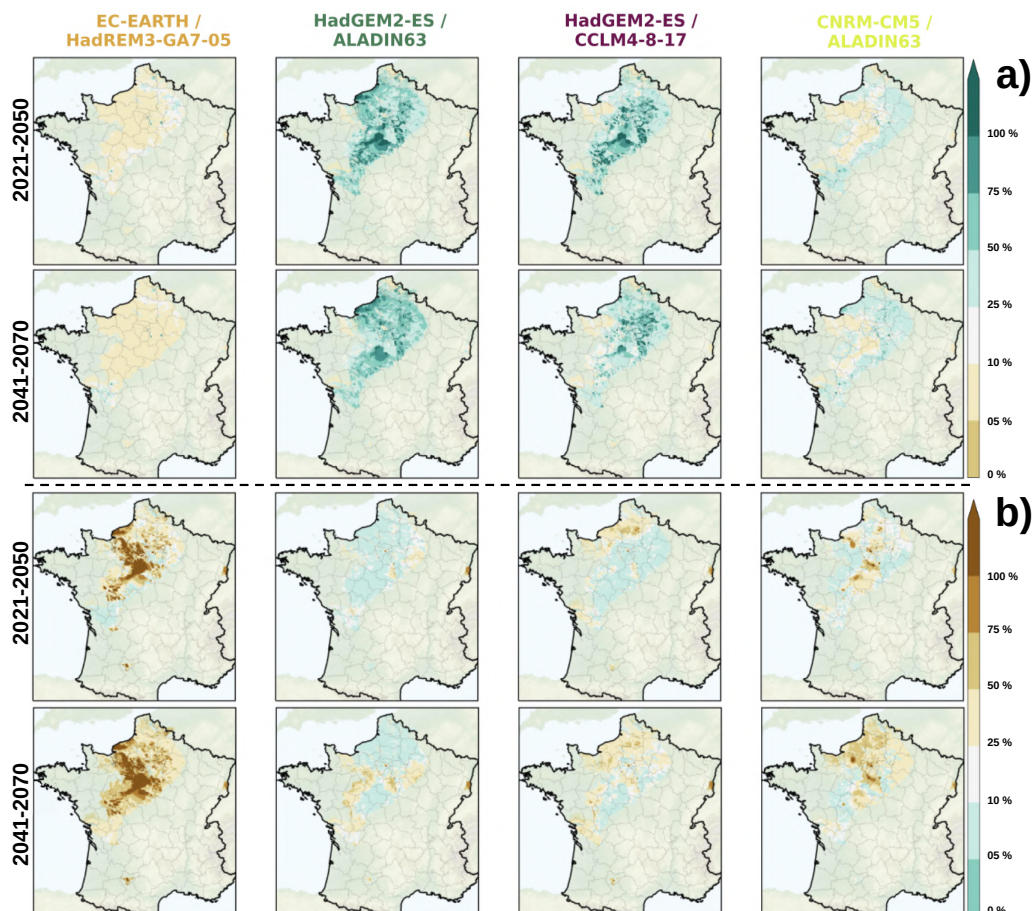


Figure C2. Spatial distribution of the median of the time proportion corresponding to extreme wet events ($\text{SPLI} \geq +1.28$, a)) and extreme dry events ($\text{SPLI} \leq -1.28$, b)) for the short-term and intermediate horizons (in line) for the four storylines (in column).

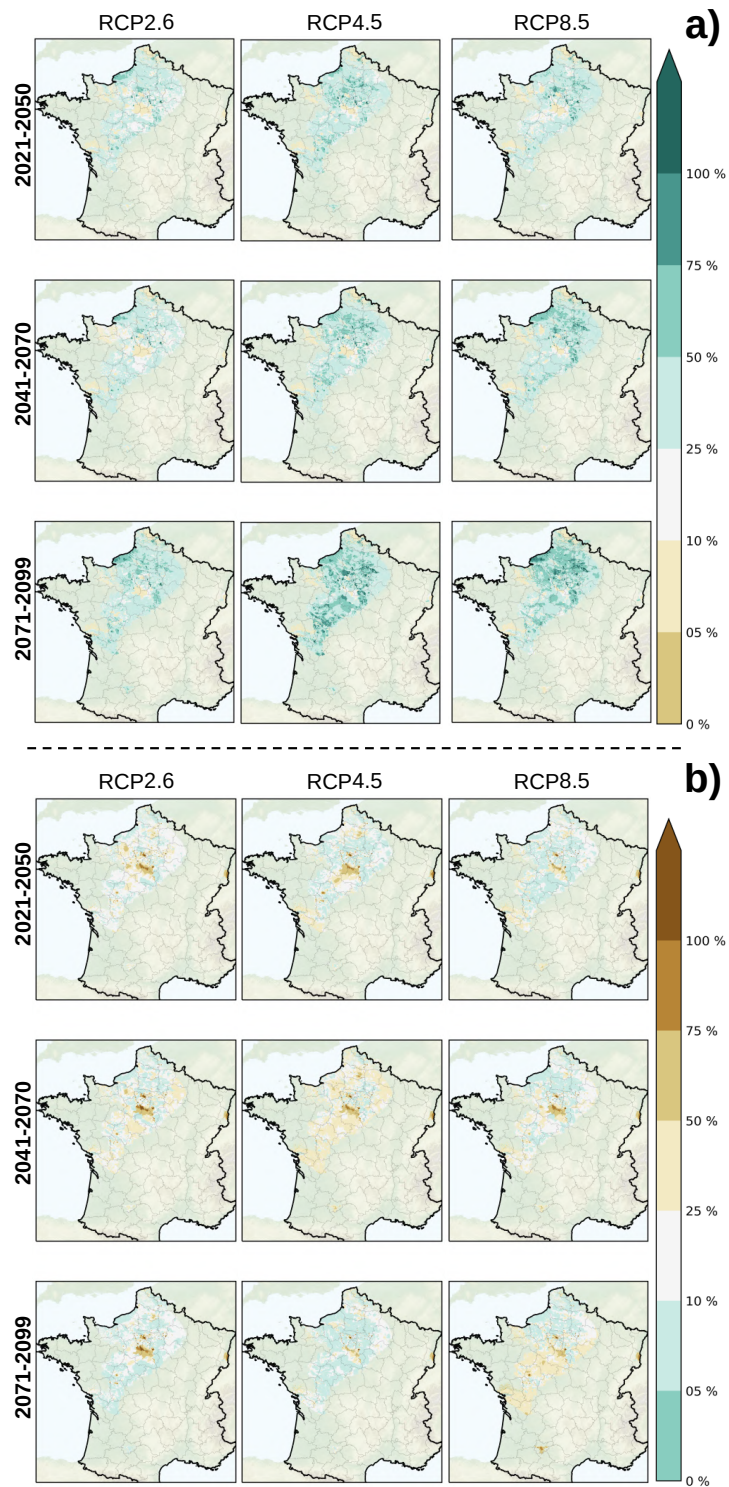


Figure C3. Spatial distribution of the median of the time proportion corresponding to extreme wet events (SPLI $\geq +1.28$, a)) and extreme dry events (SPLI ≤ -1.28 , b)) per future horizon (in line) and per RCP (in column), from all the CPs.