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PILOT DESCRIPTION AND ASSESSMENT

France

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LIST OF ABBREVIATIONS & ACRONYMS

TACTIC	Tools for Assessment of Climate change Impact on Groundwater
EGDI	European Geological Data Infrastructure
GSOs	Geological Survey Organisations of Europe
BRGM	Bureau de Recherche Géologique et Minière – French geological survey
IGN	Institut national de l'information géographique et forestière
ONEMA - OFB	Office français pour la biodiversité
CC	Climate Change
GW	Groundwater
EP	Effective Precipitation
IDPR	Indice de Développement et de Persistance des Réseaux
BFI	Baseflow Index
EPIR	Effective Precipitation Infiltration Ratio
EMD	Empirical Mode Decomposition
EEMD	Ensemble Empirical Mode Decomposition
IMF	Intrinsic Mode Functions
WLF	Water Level Fluctuation
AMO	Atlantic Multidecadal Oscillation

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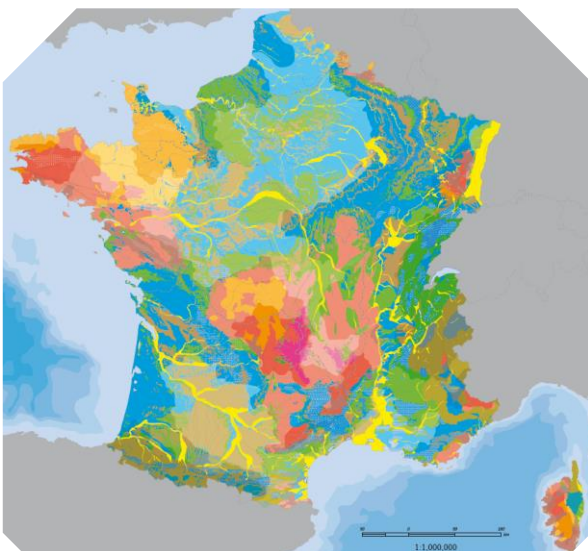
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1 EXECUTIVE SUMMARY

Pilot name	France	
Country	France	
EU-region	North Western Europe, Central and Eastern Europe and Mediterranean region	
Area (km ²)	543 940 km ²	
Aquifer geology and type classification	Multiple	
Primary water usage	Drinking water, irrigation, industry	
Main climate change issues	Groundwater ressource management Drought and groundwater flooding risk prevention	
Models and methods used	Effective precipitation and potential recharge map: Water budget approach, Effective Precipitation Infiltration Ratio Vulnerability analysis: analysis of long-term piezometric time series, trends analysis (monotonic and non-linear), low-frequency variability	
Key stakeholders	Water Agency, French environmental ministry, Biodiversity French Agency	
Contact person	Hélène Bessière, BRGM French Geological survey, h.bessiere@brgm.fr	

This report describes the work undertaken by the French Geological Survey (BRGM) as part of TACTIC WP4 to calculate historical and future potential recharge in the metropolitan France territory and to analyse groundwater vulnerability to climate change with time series analysis.

Five main climates can be observed in the territory, which will evolve differently: oceanic, altered oceanic, semi-continental, mountain and mediterranean. The evolution of those climates will mostly have impacts on temperature and evapotranspiration, thus on effective rainfall available for

groundwater recharge. Aquifers can be grouped in five main themes (terminology used in the French hydrogeological referential BDLISA): alluvial, sedimentary (the most important), bedrock, intensively folded rocks and volcanism (very few). Groundwater recharge is also depending on soils types and land use. Pilot area's land use is mostly agricultural (near 60%).

Historical and future effective precipitation and potential recharge map

The methodology applied to assess the potential groundwater recharge at the country scale combines a water budget approach and the use of an Effective Precipitation Infiltration Ratio. It is applied to evaluate both present and future groundwater recharge. The change factors were applied to the SAFRAN (Meteo France climate model) daily data for the period 01/01/1981 – 31/12/2010, to produce climate data that can be used to simulate future effective precipitation.

At the annual time scale, the “highest” impact scenario predicts a light decrease of precipitation around the Mediterranean sea, but a high increase (up to 10%) in the North-East and North-West parts of France. Temperature increase are particularly important in the South-West part where they reach 2.7°C. PET increase everywhere, between 4 and 10%. The distribution of effective precipitation anomalies computed with the highest impact scenario shows an unexpected pattern, with a decrease of effective precipitation in the middle part of France (between 2.5 and 15%) and an increase elsewhere (up to 17% in Alsace). These results are strongly linked to the precipitation change factor maps.

The “lowest” impact scenario actually shows also marked changes. Precipitation strongly decrease, especially in summer, with annual reduction showing a gradient pattern from 20% in South-West to 4% in North-East. Temperature increases remain under 2.5°C all over France (between 1.2°C in Bretagne to 2.16°C in Centre-East). Effective precipitation anomalies are negative everywhere except along the North border where they are slightly positive. The effective precipitation reduction reaches 33% in the South-West, and gradually decreases northwards.

The “highest” impact scenario results are unexpected and far from other published results. On the other side, the “lowest” impact scenario results are in the same range and show comparable patterns as previous results obtained by BRGM with the same methodology but with different climate data (ensemble simulation with 4 GCM and 2 downscaling methods). The main differences concern the Paris basin and the North part of France. The important decrease of effective precipitation in the South-West region is of the same order of magnitude of the TACTIC results (-30 - -40%) as in the EXPLORE 2070 exercise but higher than in BRGM 2019 results (-20% - -30%).

Vulnerability analysis

The assessment of long-term evolution of groundwater levels is conducted with a non-influenced boreholes database through metropolitan France (Baulon et al., 2020): 215 boreholes with more than 24 years of data. The selected wells span over multiple hydrogeological contexts: alluvial aquifers, sedimentary aquifers, volcanic and bedrock aquifers. Most of selected wells are situated into sedimentary aquifers, mainly in the Parisian Basin, and sporadically in the Aquitaine Basin.

The vulnerability of aquifers to climate change is assessed via monotonic and non-linear trend analyses. The monthly groundwater levels averages and monthly cumulative effective precipitation are used to conduct it. Analyses is performed on two reference periods (1996-2019 and 1976-2019) providing the best compromise between the length of groundwater time series and their spatial distribution through metropolitan France and northern France, respectively.

For each groundwater time series, an effective precipitation time series is assigned to it via the development of an indicator (Manceau et al., 2020). The indicator time series (expressing the effective precipitation) allowing the maximization of the correlation coefficient with monthly groundwater levels is selected as it is the most representative mesh of the groundwater level behaviour.

The study of filtered groundwater levels and effective precipitation has been done via several approaches: (i) the estimation of monotonic trends on these filtered data (*i.e.* EEMD residues or non-linear trends), (ii) the clustering of these non-linear trends, (iii) the questioning of if these non-linear trends are “trends” or only segments of lower frequency variabilities.

The monotonic trends detected on filtered data reveal few differences with monotonic trends estimated on raw data (*i.e.* unfiltered data) on the longest reference period (1976-2019), particularly for groundwater levels. However on shorter period (1996-2019), greater discrepancies appear with monotonic trends estimated on raw data: magnitudes of trends are very often accentuated and even trend direction can be impacted.

Sometimes, we can observe opposite detected monotonic trends between filtered groundwater levels and effective precipitation that may be related to several phenomena: (i) a wrong selection of effective precipitation mesh at the beginning of the analysis leading to a non-linear trend in effective precipitation that does not represent the non-linear trend in groundwater levels, (ii) a long-term anthropogenic influence on aquifers (*e.g.* long-term pumping) and the non-linear trend of groundwater levels no longer represents the one of effective precipitation, (iii) a dephasing between the non-linear trend of groundwater levels and effective precipitation due to the response time of aquifers, (iv) a distortion or modulation of oscillation amplitude induced by catchment and aquifers properties, (v) asymmetry discrepancies between non-linear trends of groundwater levels and effective precipitation also induced by catchment and aquifer properties.

In summary, multiple interpretations of groundwater level trends can be made. These trends may be linked to (i) anthropogenic impacts (*e.g.* groundwater pumping, changes in land cover that may generate a decrease in groundwater recharge), (ii) climate change that may result in a decrease in groundwater recharge, (iii) a segment of low-frequency oscillations which could appear as a trend on the short-term. Without taking into account the anthropogenic impacts (which data are often poorly referenced), the most limiting factor to make the distinction between points (ii) and (iii) remains the availability of groundwater levels data. Therefore, it highlights the complexity to define whether trends in hydroclimate variables can be related to climate change or simply being part of a lower-frequency oscillation originating from large-scale atmospheric or oceanic circulation. In addition, anthropogenic forcing may also impact these large-scale patterns (*e.g.* Dong et al., 2011; Caesar et al., 2018).

2

INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infrastructure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The specific TACTIC activities focus on the following research questions:

- What are the challenges related to groundwater- surface water interaction under future climate projections (TACTIC WP3)?
- Estimation of renewable resources (groundwater recharge) and the assessment of their vulnerability to future climate variations (TACTIC WP4).
- Study the impact of overexploitation of the groundwater resources and the risks of saline intrusion under current and future climates (TACTIC WP5).
- Analyse the effectiveness of selected adaptation strategies to mitigate the impacts of climate change (TACTIC WP6).

The present document reports the TACTIC activities in the pilot France undertaken by the French Geological Survey (BRGM) as part of WP4. WP4 is divided into seven tasks that cover the following activities: Review of tools and methods and identification of data requirements (Task 4.1), identification of principal aquifers and their characteristics aided by satellite data (Task 4.2), recharge estimation and its evolution under climate change scenarios in the principal aquifers (Task 4.3), analysis of long-term piezometric time series to evaluate aquifer vulnerability to climate change (Task 4.4), assessment of subsidence in aquifer systems using DInSAR satellite data (Task 4.5), development of a satellite based net precipitation and recharge map at the pan-European scale (Task 4.6), and tool descriptions and guidelines (Task 4.7).

Two different works are presented in this report and they are related to Task 4.3 and Task 4.4.



The first part of the work aims at the estimation of recharge under current and future climate. This is undertaken using a water budget approach to estimate effective precipitation and the use of an Effective Precipitation Infiltration Ratio to deduce potential recharge.

The second part of the work aims to assess aquifer vulnerability to climate change thanks to the analysis of long-term piezometric time series. The main challenges of this study is the great diversity of aquifer systems in France (confined/unconfined, porous/fissured, alluvial/sedimentary/volcanic, etc) and the lack of very long term time series of groundwater levels and information on abstraction data.

3

PILOT AREA

The pilot area is the whole metropolitan France territory. This area is characterized by several types of climate, aquifers, soils and landscape, and thus will not be affected by climate change the same way depending on the region.

Five main climates can be observed in the territory, which will evolve differently: oceanic, altered oceanic, semi-continental, mountain and mediterranean. The evolution of those climates will mostly have impacts on temperature and evapotranspiration, thus on effective rainfall available for groundwater recharge.

Groundwater recharge is also depending on soils types and land use. Pilot area's land use is mostly agricultural (near 60%), and at this scale, soils represents mostly the high influence of the mineral material nature where the soils have been formed and are still evolving. Those characteristics influence infiltration and transport of rainfall from the surface to the water table. Storage and groundwater transport is then depending on the aquifers characteristics. On the pilot area, aquifers can be clustered in five main themes (terminology used in the French hydrogeological referential BDLISA): alluvial, sedimentary (the most important), bedrock, intensively folded rocks and volcanism (very few). Those formations are bound with multiple landscape characterizing the area, mostly influenced by formations of basins (Paris, Aquitan, and South-East), and several massifs and mountains (the Alps, the Pyrenees, the Massif Central, The Jura, the Vosges and the Armorican Massif).

In a previous study (Explore 2070), climate models projection results predict a virtually systematic decline from 10 to 25% in water table recharge, due to temperature rise and effective rainfall decrease.

These characteristics of the pilot area are developed below to describe the area. They will most likely be used to explain the different results of the study.

3.1 Site description and data

3.1.1 Location of pilot area and data available.

The assessment of long-term evolution of groundwater levels will be conducted with a non-influenced boreholes database through metropolitan France (Baulon et al., 2020). In this report, 215 boreholes among the 254 boreholes constituting this dataset will be used because their length is upper than 24 years and their spatial distribution through metropolitan France is correct. Originally, groundwater level time series are provided by BRGM via the database ADES (<https://ades.eaufrance.fr/>).

The selected wells for this study answer to few criteria:

- The length of groundwater time series must be higher than 24 years.
- A minimum amount of data in a month. This minimum amount is divided in two parts. The date of sampling frequency change is identified in each time series. The minimum sampling frequency is at least one monthly data before this date, and three data per month after this date (which appeared as the best compromise).
- The length of consecutive gaps must be lower than 3 years for time series starting after 1950; and lower than 10 years for time series starting before 1950. It allows time series in the new database to preserve the low-frequency in data.
- A minimum influence of pumping on groundwater levels.

The spatial distribution of the selected boreholes is presented in Figure 1.

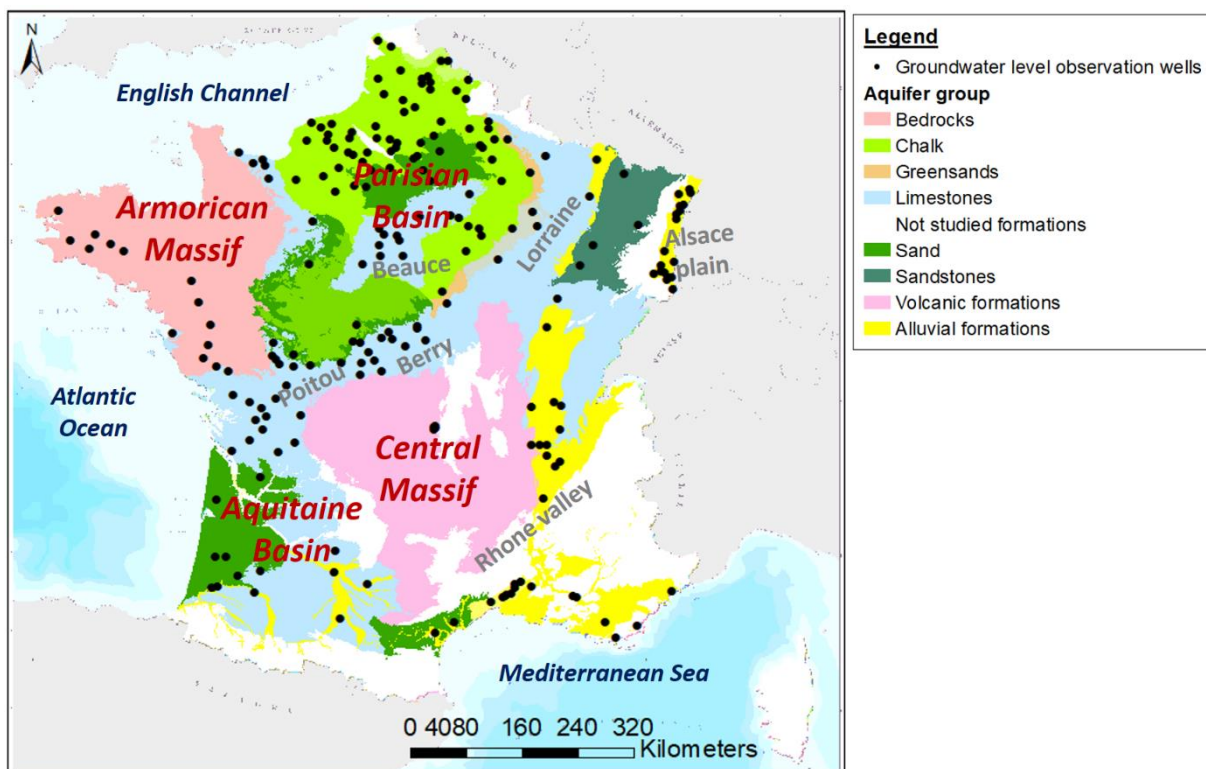


Figure 1: Spatial distribution of sparsely or non-influenced groundwater boreholes through metropolitan France.



The selected wells span over multiple hydrogeological contexts: alluvial aquifers, sedimentary aquifers, volcanic and bedrock aquifers. Most of selected wells are situated into sedimentary aquifers, mainly in the Parisian Basin, and sporadically in the Aquitaine Basin. Each well has been attached to a hydrogeological area based on groundwater bodies and its dynamic.

Concerning the aquifers captured by the selection of wells, the Seno-Turonian chalk aquifer of the Parisian Basin is the most represented, followed by Jurassic limestone aquifers (Lorraine, Berry, Poitou) on the edge of the Parisian Basin, and the Eocene limestones of Beauce aquifer. Wells located in the Aquitaine Basin mainly capture the Jurassic limestone aquifer of the northern Aquitaine Basin, and the multiple sedimentary hydrogeological formations in the southern part (sands, limestones). Finally, most of wells selected in the Rhone valley monitor alluvial and fluvio-glacial formations.

Alluvial aquifers are also well represented in the dataset, especially the Rhine/Vosges recent or ancient alluvium in Alsace region, Garonne alluvium in Toulouse region, and recent alluvium in the Mediterranean region.

Some wells are located in Central Massif volcanic aquifers in various formations with different dynamism. Finally, bedrocks aquifers are monitored by few selected wells in Armorican Massif.

Table 1 synthesizes the number of wells by major hydrogeological entity.

Table 1 *Number of wells by major hydrogeological entity/area.*

Hydrogeological entities	Number of boreholes
Seno-Turonian chalk of Artois-Picardy	18
Seno-Turonian chalk of Normandy/Picardy	30
Seno-Turonian chalk of Champagne	8
Jurassic limestones from Sarthe to Bessin	5
Lutetian and Ypresian sands of Paris Basin	3
Jurassic limestones of Lorraine and Côte-des-Bars	4
Triassic sandstones of Lorraine	2
Upper Eocene limestones of Paris Basin	4
Alluvial formations of Alsace	18
Limestones of Beauce	8
Chalk of Bourgogne and Gâtinais	4
Triassic limestones of Lorraine	1
Bedrocks of Britain	10
Jurassic limestones of Berry	9
Jurassic limestones of Poitou	6
Fractured Jurassic limestones of northern Aquitaine Basin	7
Alluvial and fluvio-glacial formations of Rhone valley	11
Volcanic formations of Central Massif	5
Various calcareous formations of Aquitaine Basin	3



Plio-Quaternary sands of Aquitaine Basin	3
Alluvial formations of Mediterranean region	11
Alluvial formations of Garonne	3
Other (smaller) hydrogeological entities	42

Before the data analysis, a visual check of groundwater level time series was achieved in order to remove or correct erroneous data. As we wanted to qualify groundwater dynamism considering also the annual timescale, we decided to work on monthly averages. Then, missing months in these time series were filled by linear interpolation to perform spectral analyses.

3.1.2 Climate

This part is based on Meteo-France description of the metropolitan France climate.

(www.meteofrance.fr)

3.1.2.1 Climate type

On a global scale, metropolitan France benefits from a temperate climate. Rainfall are distributed throughout the year, and relatively mild temperatures (Figure 2). These characteristics are due to the latitude and the dominance of winds coming from the Atlantic.

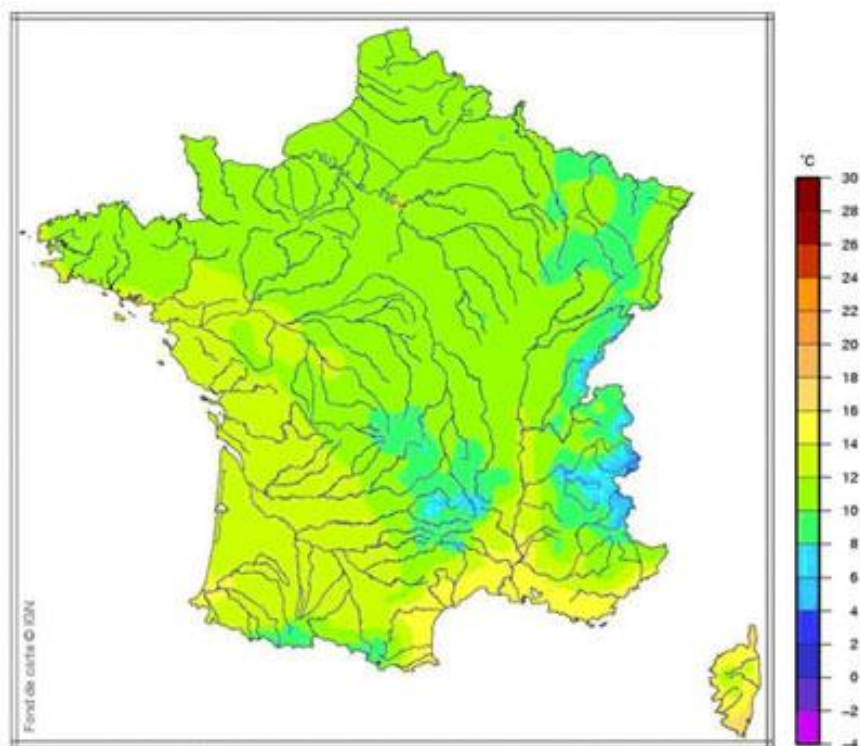


*Figure 2: Average annual temperature (°C, 1981 – 2010 normal).
(Meteo-France, map background IGN)*

However, regions experience climates variations, according to their latitude, their altitude and the distance from the sea, reinforced by their position compared to the three important mountains (Pyrenees, Massif Central, Alps).

3.1.2.2 Five main types of climates

At first glance, there are five main climates types in metropolitan France: oceanic, altered oceanic, semi-continental, mountain and mediterranean (Figure 3).



Figure 3: The five main climates in France.
(Meteo-France) Shadow areas correspond to transition zones.

- Oceanic climate is characterized by mild temperatures and relatively abundant rainfall (in connection with Atlantic disturbances), distributed throughout the year with a slight maximum from October to February. The oceanic climate is typical of the Brittany coasts and Lower Normandy. Further north, to the Belgian border, winters are colder. Further south, the lower Loire Valley, Vendée and Charentes have lower rainfall. In Aquitaine, the proximity of the Pyrenees increases rainfall in winter and spring.
- Altered oceanic climate is a transition zone between the oceanic climate, mountain climates and the semi-continental climate. Temperature differences between winter and summer increase with the remoteness of the sea, and rainfall is lower than at seaside (except near reliefs). This climate is located in the Massif Central western and northern foothills, in the Paris Basin, Champagne, eastern Picardy and Nord-Pas-de-Calais.
- Semi-continental climates are characterised by hot summers and rough winters, with many days of snow and frost. Annual rainfall is relatively high, except in Alsace, because of the protective effect of the Vosges. The rains, often stormy, are more important in summer. This climate is typical of the north-eastern quarter of France (Alsace, Lorraine, Ardennes, Argonne, Franche-Comté and part of Burgundy) and some steep sided plains sheltered from the west winds, from the Massif Central and the Alps.
- Mountain climate temperatures decrease quickly with altitude. Cloudiness is minimal in winter and maximum in summer, and there are significant variations in winds and precipitations from a location to another.



- Mediterranean climate is characterized by mild winters and hot summers, sunshine and frequent high winds. The few rainy days are irregularly distributed over the year. Dry winters and summers are followed by very wet springs and autumns, often as stormy rain (40% of the annual total rainfall in 3 months). This precipitation can bring 4 times more water than the monthly average in a given place in a few hours, especially near the relief (episode Cevennes). The regions concerned by the Mediterranean climate are located in the South East between sea and mountains.

3.1.2.3 Metropolitan France scale

Average temperatures

Autumn and winter average temperature varies with the "continentality" of the area. The further the place is from the Atlantic Ocean or the Mediterranean, the lower the temperature: took apart mountain regions, the temperature is the lowest on the north-east of France (Figure 4). During spring and summer, temperatures vary with the latitude of the area. It depends mainly on the presence or absence of clouds, hence this increase from north-west to south-east, (effect tempered by the mountain massifs).

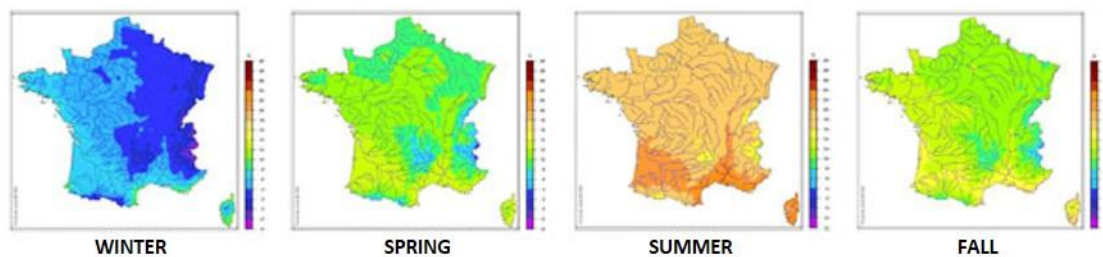


*Figure 4: Average seasonal temperature (°C, 1981 – 2010 normal).
(Meteo-France, map background IGN)*

Average annual rainfall

Average annual rainfall amounts vary from 500 mm for the drier regions (Mediterranean coasts, Anjou, Paris Basin) to more than 1500 mm for mountain regions (Figure 5Figure 7). Rainfall depends both on the altitude of the place and the ocean proximity. Thus, Atlantic and Channel coasts are rainier than Anjou and Paris Basin, and certain valleys (Alsace, Allier Valley, Upper Loire Valley) are protected from rainfall by their bordering reliefs. In Brittany and on Atlantic coasts, precipitation is due to Atlantic disturbances.



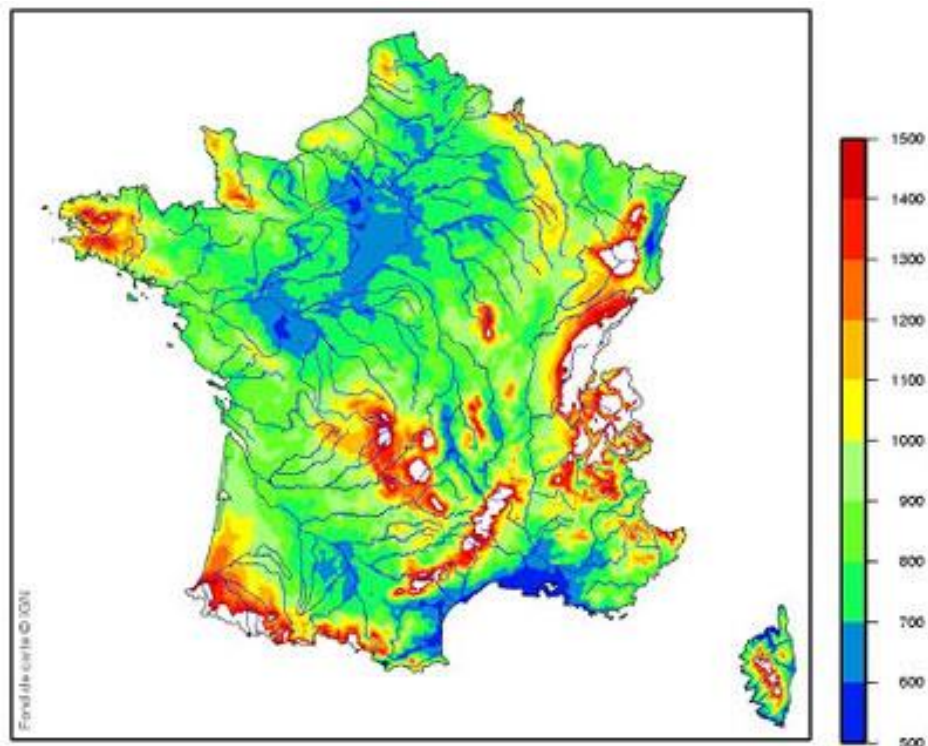


Figure 5: Cumulative annual rainfall (mm, 1981 – 2010 normal).
(Meteo-France, map background IGN)

The winter months are the rainiest. On the other hand, in the northeast, the summer months are wetter than the winter months because of the predominance of thunderstorms. Around the Mediterranean, especially on the Cevennes and the Black Mountain, precipitation occurs mainly in the form of intense rainstorms during autumn or spring (Figure 6).

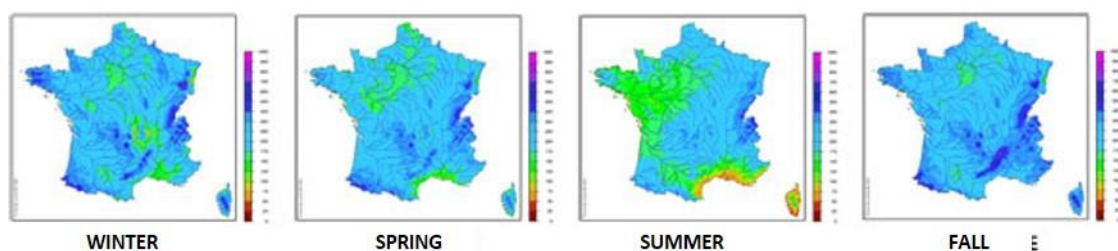


Figure 6: Cumulative seasonal rainfall (mm, 1981 – 2010 normal).
(Meteo-France, map background IGN)

Average annual number of rainy days

The number of days per year with rain (precipitation of the day greater than 1 mm, Figure 7) varies from 40 (Mediterranean coasts) to 180 (Armorican Massif, Vosges). Comparison between the annual precipitation map and the average number of rainy days map, it occurs that with equal amounts of



precipitation, south of France experiences fewer rainy days than north, but because of thunderstorms the rains are less frequent but more intense.

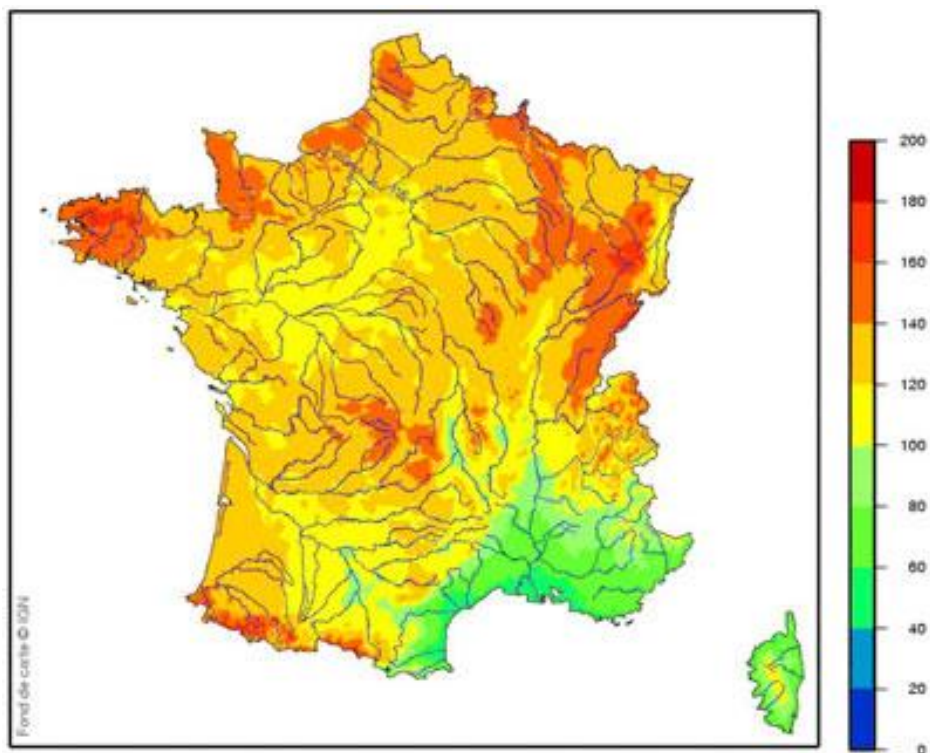


Figure 7: Average annual number of days with rainfall superior to 1 mm (1981 – 2010 normal).
(Meteo-France, map background IGN)

Average annual insolation

The average annual hours of sunshine increase from 1500 hours in northern France to 2800 hours in the south (figure 8).

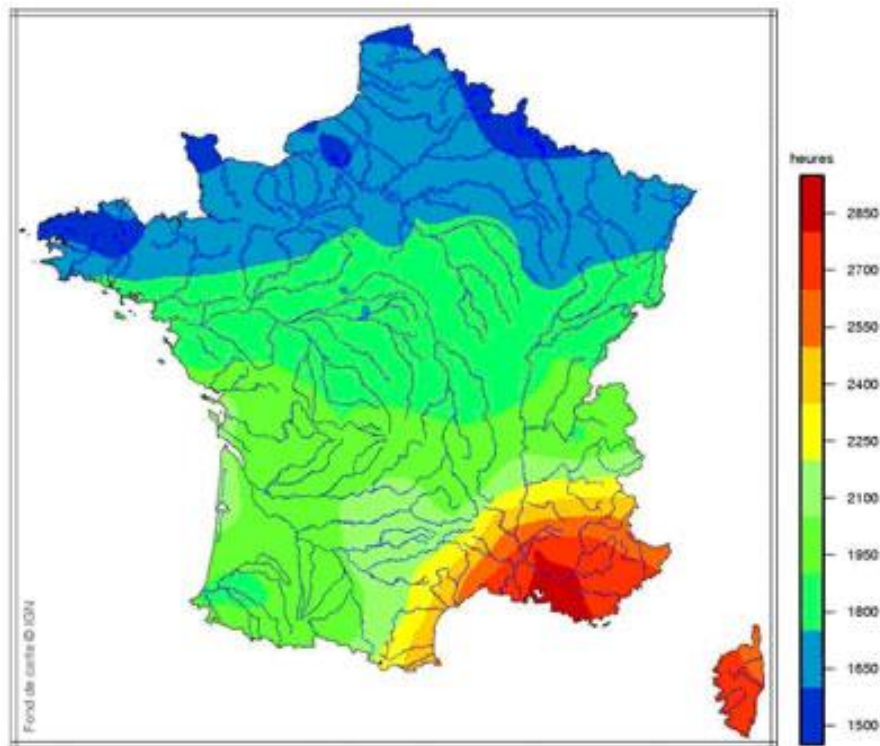


*Figure 8: Average annual insolation in hours (1991 – 2010 normal).
(Meteo-France, map background IGN)*

Precipitation and evapotranspiration

In metropolitan France latitudes, the actual evapotranspiration is very low between November and March, more or less strong the rest of the year according to the soil water reserve (UK). The effective rainfall will therefore be positive during this period, and none the rest of the year. Nevertheless, an important rainy sequence can still prevail over the evapotranspiration and generate an infiltration towards the aquifer. On the opposite, rainfall deficits occurring in winter can result in low effective rainfall.

3.1.3 Topography

The metropolitan France covers an area of 551 695 km². Its summit is le Mont Blanc, which is at 4810m above the sea levels.

Landscape is composed of six massifs (the Alps, the Pyrenees, the Massif Central, The Jura, the Vosges and the Armorican Massif), and three basins (Paris, Aquitaine and South-East basins).

The area is surrounded by both land frontier and seas. The height land frontiers are common with Belgium, Luxembourg, Germany, Switzerland, Italy, Monaco, Spain and Andorra.

Groundwater in France is almost entirely drained away to four seas: the North Sea, the Channel, the Atlantic Ocean and the Mediterranean, via five principal rivers, which are the Seine, The Loire, The Garonne, The Rhone and the Rhine.



Most of the watercourses in the southern two-thirds of France drain into the Atlantic, through the basins of the Loire, the Garonne and the Adour. The eastern watershed for this area is along the eastern edge of the Massif Central, reaching to within 25 miles of Lyon.

Watercourses in south-eastern and central eastern France mostly flow out to the Mediterranean, via the Rhone. Only the extreme south and southeast of the Massif Central, i.e. the southern edge of the Cévennes mountains, drains into the Mediterranean. Water from areas between the Morvan and the Vosges, notably the Saône Basin, flows south to the Rhone (the two rivers meet at Lyon), and thence down to the Mediterranean.

The extreme east of France, Alsace to the east of the Vosges and Lorraine to the north and northwest of the Vosges, have rivers that drain into the North Sea, directly or indirectly via the Rhine.

A small northwest quarter of France has rivers, notably the Seine and the Somme, that flow into the Channel.

3.1.4 Land use

This part is based on the “Atlas regional 2016” (Regional Atlas 2016) edited by “Le service de l’observation et des statistiques (SOeS)” (statistics and observation service).

Artificialized areas are mostly localised in large agglomerations areas and grow with demographic and economic development. They evolve near the large urban centers (notably in the West of the territory), along main existing and future axes of communication. Artificialization increases at the level of agricultural land and natural habitats, in particular by separating from natural environment.

The land use framework in France metropolitan evolve slowly. National territory remains mostly agricultural (near 60% of the surface area, figure 9). However, from 2006 to 2012, artificialization continues to grow, mainly to the extent of agricultural land (for 87% of areas newly artificialized). Despite the artificialisation grows slower between the period running from 2006 to 2012 than from 2000 to 2006, the agricultural land decrease remains as important through these two periods.

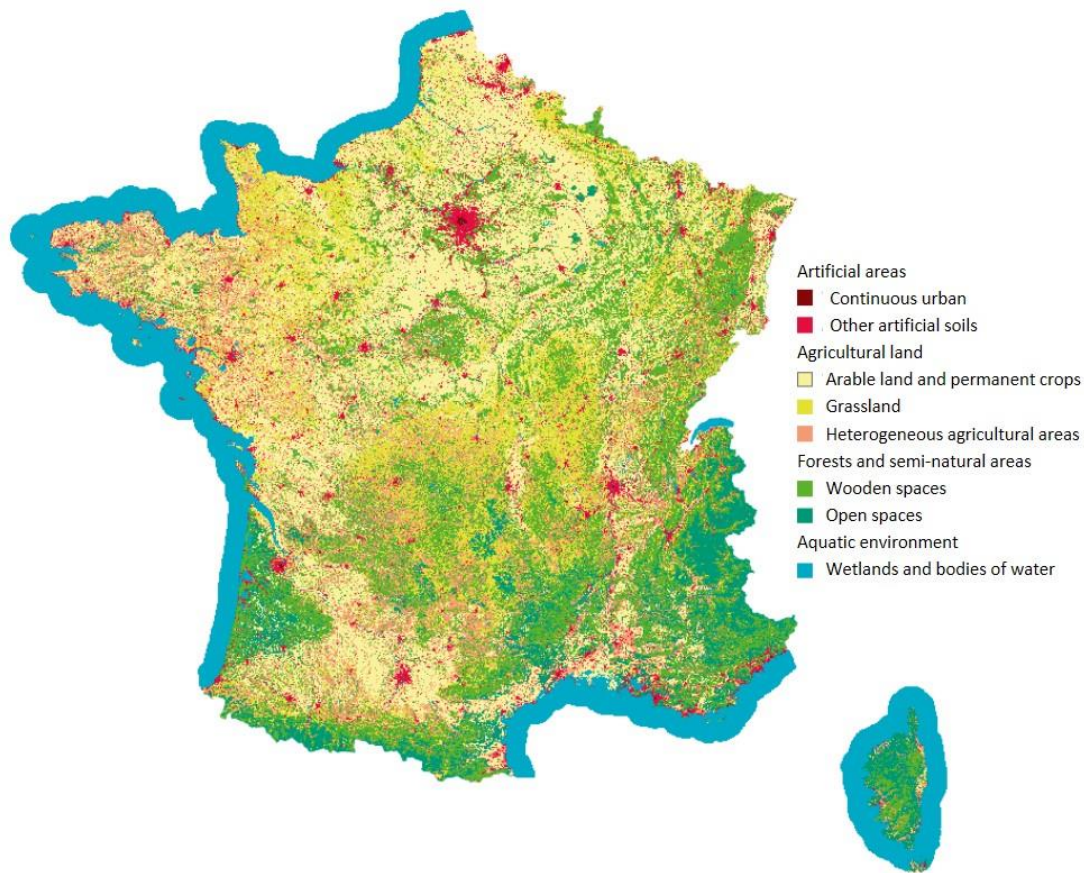


Figure 9: Map of the land use in France (from the Atlas Régional, SOeS, 2016).

3.1.5 Soil types

This part is based on report “L’état des sols de France” (State of the soils of France), the “Référentiel pédologique 2008” (pedologic referential 2008) and the World reference base for soils resources 2006.

Soils mapping is the way to define soil units geographic extension, for a given scale. As a synthesis, it determines the soils spatial framework, based on their formation forcings (geology, climate, topography, vegetation).

It allows to perform spatialized inventories of soils for a given area, and consequently to constitute a supporting tool for public policies. However, according to the scale of the map and its objectives, a distinction can be made on the soil units only, or on groups of soil units.

Thus, small scales with national or continental vocation, such as 1/1 000 000 are used for wide representations, for scientific or didactic purposes. Their also used for decision helping at national or European scales. Units are here groups of soil units. For example, the soils map of France (Figure 10) represents mostly the high influence of the mineral material nature where the soils have been formed and are still evolving.



The distribution of soil types is strongly marked by the great diversity of rocks that are encountered in France:

- The Landes and Sologne's sandy rocks;
- Brittany and Vosges' granites;
- Alps, Brittany and Massif Central's schists;
- Paris and Midi basins hard limestones;
- Champagne's chalks;
- marls within the east and in Limagne;
- Massif Central's basalts;
- Aquitaine, Paris Basins and Alsace's eolian limes;
- Camargue's fluvatile and fluviomarine alluviums;
- marshes of the West.
- On a third of the territory, limes deposits from the Quaternary era (between -50,000 and -10,000 years) mark the soils of Beauce, Ile-de-France and Picardy. Also present in Brittany, Brie or in the Garonne valley, their composition varies according to their origin (wind, fluvatile or colluvial).



Figure 10: Map of the main different soils at the whole metropolitan scale.

Map from: Inra, Base de données Géographique des Sols de France à 1/1 000 000 (GISSol).

Legend using the French « Référentiel Pédologique 2008 (RP2008) » terminology.

A correspondence table between the RP2008 and the World Reference Base 2006 (WRB) is available in the 5th annex of the Référentiel pédologique (2008).

3.1.6 Geology/Aquifer type

This part is based on the work of Jean-Christophe Maréchal and Josselin Rouillard (BRGM)



3.1.6.1 Geology

French geology consists of a large spectrum of various rocks (Figure 11), leading to very different types of aquifers located in sedimentary basins (depicted in orange to yellow), alluvial plains (light yellow), limestone rocks (blue and dark green) and crystalline rocks (red and brown).



Figure 11: Geological map of France.

3.1.6.2 Aquifer types

Alluvial aquifers

These aquifers (Figure 12) are the main providers (about 45%) of groundwater use in France. They have a very important role in the satisfaction of human needs of the country being favourably located in alluvial plains where the most fertile agricultural lands are located and most cities established. With their high yields of wells for low costs (shallow water table) and their natural ecological role at the origin of wetlands. Besides the diffuse recharge from rainfall, the water balance of alluvial aquifers is highly dependent on groundwater flow from neighbouring aquifers and interaction with surface water. The depletion induced by pumping in the alluvial aquifer increase these inflows. This contributes to improve the well yields but threatens water quality due to the intrusion of poor quality surface water.

At the alluvial aquifers scale, the largest abstraction rates are pumped from the Alsace alluvial aquifer, the Lyon plain and Isere river valley.

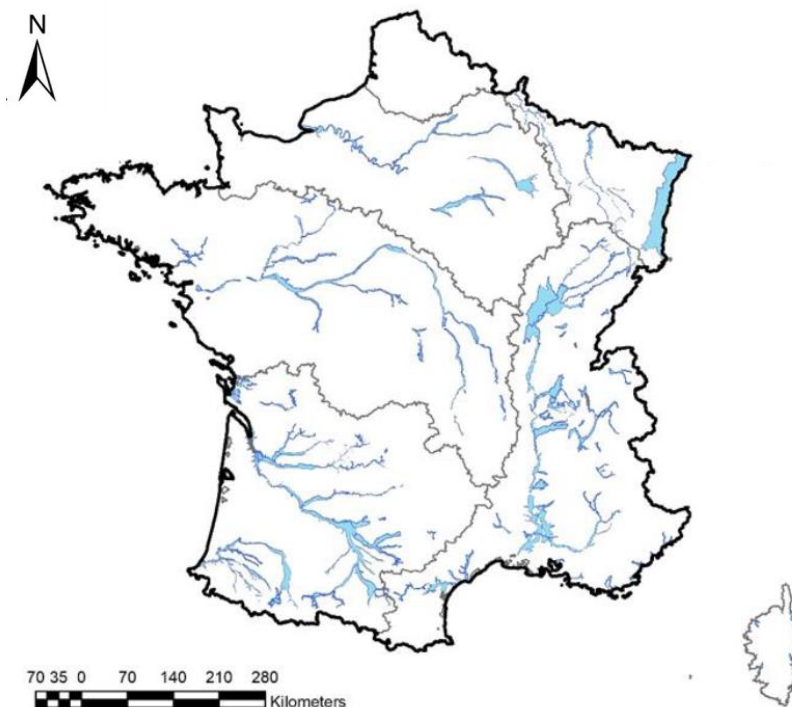


Figure 12: Alluvial aquifers map France.

Sedimentary aquifers

There are three main large sedimentary basins in France: Paris, Aquitaine and southeast basins (Figure 13). According to their structure and flow regimes, these aquifers can be classified according to three types:



- Large single-layer unconfined aquifers, mainly constituted by chalk and limestone rocks. The main aquifers in this category are the chalk aquifer in northern France and a large part of Paris basin, Beauce aquifer, and Landes sandy aquifer.
- Multi-layers aquifers constituted by heterogeneous tertiary sediments located in the centre of Aquitaine (Figure 13) and Paris basins. They are constituted by a shallow unconfined aquifer and several deep confined aquifers.
- Large deep confined aquifers mainly constituted by sands or sandstones (Albien aquifer in the Paris basin) or limestone (Carboniferous rocks in the north). Initially artesian, these aquifers are now highly exploited (Inferior Trias sandstones, inframollasic aquifer in Aquitaine basin), and artesianism has mostly disappeared.

Paris and Aquitaine are the main basins constituted by sedimentary aquifers, with high yields in permeable layers. Chalk aquifers from northern France provide $\sim 360 \text{ Mm}^3/\text{yr}$, multi-layers Aquitaine basin ~ 350 to $450 \text{ Mm}^3/\text{yr}$.

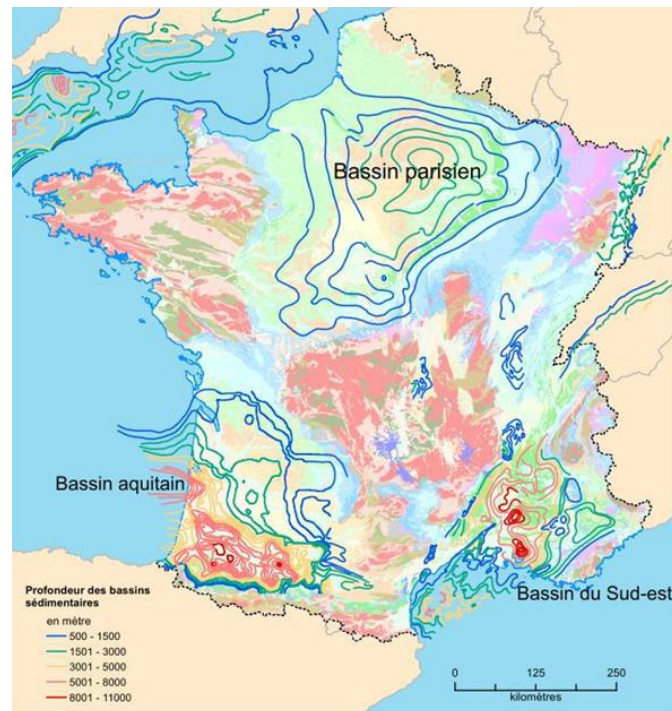


Figure 13: Location of the three main sedimentary basins (Paris, Aquitain and South-East).

The calcareous Beauce aquifer, located north of Orleans (centre of France), is one of the largest aquifers in the country. The aquifer contains an average water volume of 20 billion m³, which extends over 9000 km². This area is one of the big-gest producers of cereals in Europe. Agricultural land represents 6000 km², i.e. more than 70% of the total area, 50% of which (3000 km²) is irrigated (Lejars et al. 2012). The irrigated area in the Beauce increased by 50 percent between 1988 and 2000, mainly driven by cash-crops in the summer (Lejars et al. 2012). The groundwater abstraction has increased also. The conservation of the Beauce aquifer is now reached thanks to an agreement called 'Beauce Aquifer Charter' ('charte nappe de Beauce') which allowed to limit the abstracted volumes for irrigation.

The Paris Basin is the largest sedimentary basin in France. It starts with Permian and Triassic and ends with Tertiary deposits. Vertically, at least seven aquifer layers can be found, the deeper of which are brackish. The main aquifers are the chalk aquifer from Upper Cretaceous (light green on Figure 13), the Albien green sands (dark green), the Lower Jurassic limestone (light and medium blue) and the Vosges Lower Trias sandstones (magenta). Large Tertiary aquifers (Beauce, Brie, yellow) stand above the basin.

Crystalline and volcanic rock aquifers

Crystalline rocks are mainly located in two large mountain ranges: the Armorican Massif range in the west and Central Massif range at the centre of the country (Figure 14). Vosges, Pyrenees and Alps mountains constitute other outcrops. These fractured rocks also mainly constitute Corsica Island.

The typical geological profile in weathered crystalline aquifers follows the lithological description by Dewandel et al. (2006) which, from top to bottom, consists of:

- Red soil from the first decimeteres to the first meter.
- Sandy regolith of a few meters thickness: yellowish colour, sandy-clay composition, sandy texture with many quartz grains.
- Saprolite from about 3 meters to 13 – 24 meters deep, derived from in situ weathering of crystalline rock: yellowish to brownish colour, coarse sand-size clasts texture and laminated structure. This horizon exhibits preserved fractures.
- Granite or gneiss rocks. The upper part of the hard rock is highly weathered and fractured but the fracture frequency decreases rapidly with depth.

In flat areas (Brittany), these aquifers are exploited through shallow (50-100 m deep) boreholes while in mountainous areas (Pyrenees, Alps, Central Massif), water is drained from natural springs. Water abstraction rates are generally low: a few m³/hour.

Volcanic rocks are mainly located in the Massif Central. The total amount of groundwater supplied by Massif Central volcanic rock aquifers is ~40 Mm³/yr. These aquifers provide low yields but they often represent the sole source of supply for small villages or small agriculture farms.

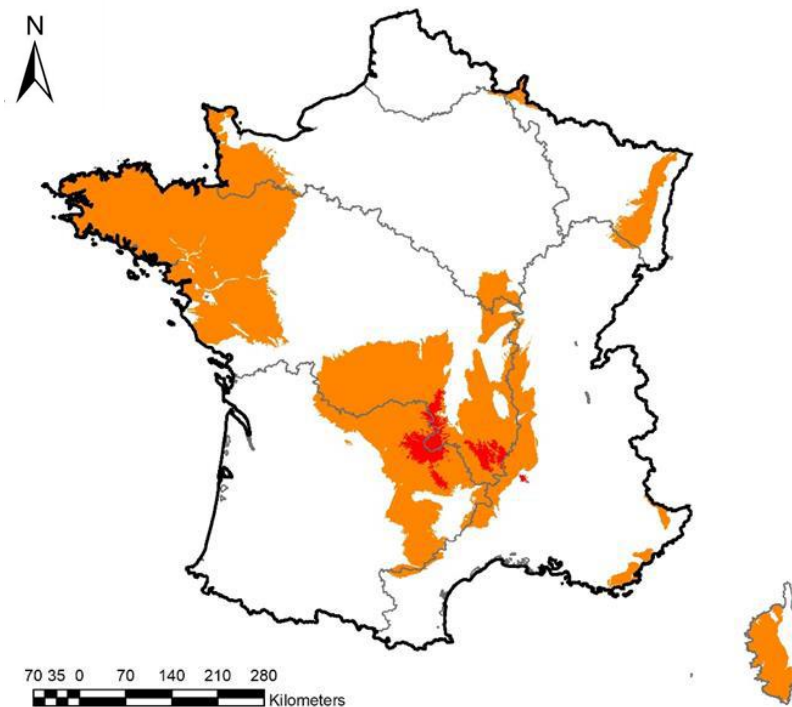


Figure 14: Map of crystalline rocks (red: granite, brown: schist).

Karst aquifers

Karst aquifers are widespread in France with a higher presence in the southern part of the country (Figure 15). Their main advantage is the high permeability of the karst drainage network that drains the whole system and can supply very large amounts of water. They are replenished very quickly through diffuse and localized recharge. Karst aquifers supply 40 % of drinking water supply in France.

Close to the Mediterranean coast, the limestone massifs have been affected by the Messinian salinity crisis (6 M years ago) which consists in a lowering of the Mediterranean sea due to the closing of the Strait of Gibraltar. This eustatic and tectonic phenomenon has increased the erosion and karstification potential of rivers and groundwater in the associated region, creating deep karst cavities and karst drainage networks. An example is the well-known Fontaine de Vaucluse karst spring which has been explored at a depth of 315 meters. This deep development of karstification leads to high volume of stored groundwater which can be pumped under an active management scheme like the Lez aquifer at high rates from a single pumping station. Thanks to this Messinian crisis, deeper karst systems are located under low permeability rock cover (Arc karst aquifer close to Marseille for example).

Apart from the Mediterranean coast, other productive karst aquifers include: La Rochefoucauld aquifer and la Touvre spring supplying Angoulême city, la Chartreux spring supplying Cahors city, and the Arcier spring in Jura mountains supplying Besançon city.

Due to fast groundwater flows in the karst conduits and direct infiltration of water in sinkholes, karst aquifers are highly vulnerable to surface pollution.



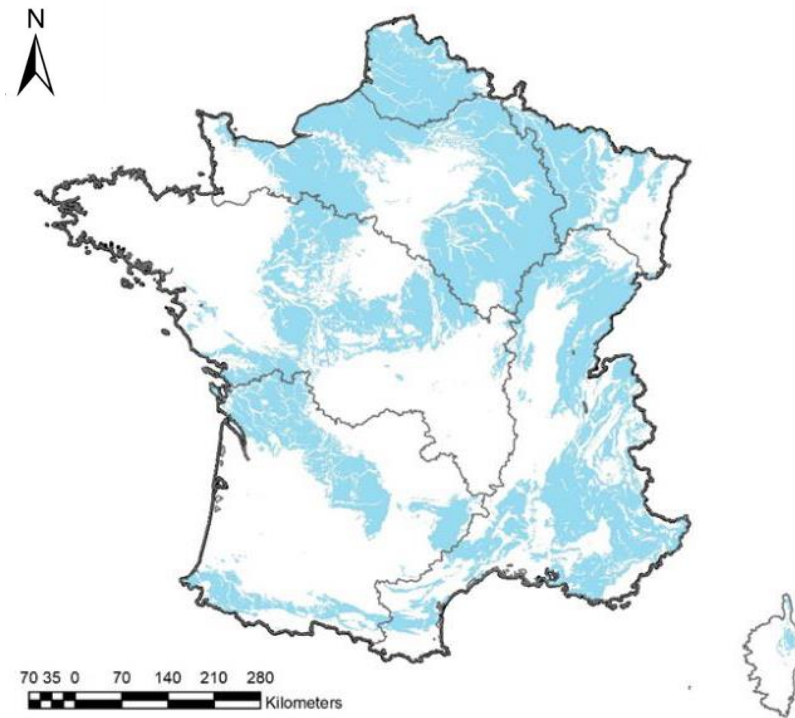


Figure 15: Map of karstifiable carbonate rocks (blue), modified from Chen et al. 2017.

3.1.7 Abstractions/irrigation

Total water abstraction in France is about 38.5 billion m³ in 2013, with the vast majority is (70%) abstracted from surface water to serve as cooling water for electricity production (21.6 billion m³) and to supply navigation canals (5.5 billion m³) (AFB, 2017). Other uses (drinking water, agriculture, industry) use a total of 11.4 billion m³, of which about 50% is from groundwater origin.

About 66% of abstracted water for drinking water is from groundwater (3.7 billion m³ compared to 1.866 billion m³ from surface water). Groundwater is a strategic resource for drinking water supply given its higher quality compared to surface water, and thus the lower treatment costs. Groundwater represent about 36% of water abstracted for agriculture (1.035 billion m³ compared to 1.766 billion m³ from surface water). About 31% of abstraction for industrial use, which includes factories, commercial firms and various public buildings, is based on groundwater (930 M m³ compared to 2,700 M m³ from surface water).

Overall, total water abstraction for drinking water has been reducing since 2003 (- 15% between 2003 and 2013) (Figure 16); for industrial water abstraction, a reduction can be observed since 1998 (-27% between 1998 and 2013). No significant evolution in overall water abstraction in agriculture can be seen since 2008 when monitoring and reporting became more consistent nation-wide.

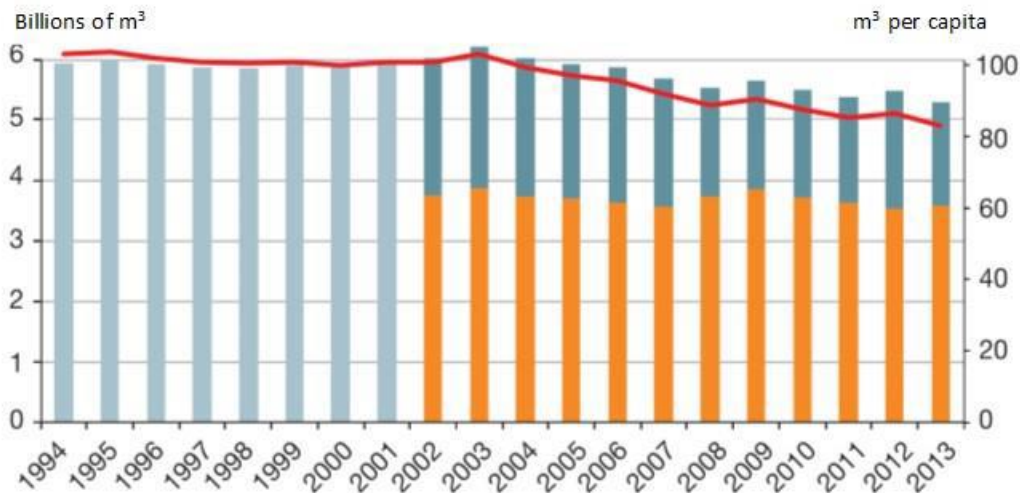


Figure 16: Evolution of water abstraction for drinking water supply.

In light blue: total abstraction. In dark blue: surface water abstraction. In orange: groundwater abstraction. Red line: abstraction water per capita. Source: modified from Banque nationale des prélèvements quantitatifs en eau, ONEMA-SOeS on 2013 data (CGDD, 2017).

3.1.7.1 Groundwater use in agriculture

80% of water use in agriculture in France serves to irrigate crops, while the remaining 20% is used for livestock water supply and cleaning. Figures on irrigation are however difficult to obtain accurately as water meters are not systematically installed on individual water pump and reporting of abstracted volumes is not systematic.

From 500,000 ha in 1970, the surface of irrigated land has steadily increased until 2000 when it reached a maximum of 1.57 million ha or 6% of total used agricultural area. In 2010, the area of irrigated land has not changed significantly while the area of used agricultural land has reduced (-900,000 ha or -3.5% from 26.16 million ha) as well as the area of agricultural area equipped for irrigation (-312,000 ha or -12% from 2.6 million ha). Overall, irrigation appears to be maintained where it is regularly used, and may help to maintain small unit agricultural holdings economically viable in a context of general consolidation of agricultural units and abandonment of agricultural land (Loubier et al., 2013).

The internal irrigation rate of agricultural holdings practicing irrigation in 2010 was 32%, a number that has slightly increased since 2000 and indicating that irrigation is becoming a more important part of some agricultural units. However, apart from specific situations, irrigation in France is not essential for agricultural production as it can be in arid countries; rather, it is used to:

- secure yields against climate risks
- increase average yields
- improve product quality.

On average, irrigation is responsible for about 2,000 m³ of water abstracted per ha.

Most agricultural land equipped for irrigation is situated in the southwest, centre, northeast, southwest of France. The main irrigated crops are maize and cereal production, as well as potatoes,



vegetable cropping and fruit production. Maize represented 41% of all irrigated land in 2010, down from 50% in 2000. This evolution is partly related to the reduction in European subsidies for this crop, as well as stricter restriction on water use and higher prices for other cereal crops, in particular wheat.

Both collective and individual irrigation increased steadily until 2000. Traditionally, collective irrigation from surface water was developed in the Southern regions while individual irrigation from groundwater was developed in the northern regions (Figure 11). Of the 2.6 million ha equipped for irrigation, only represent 4% is equipped for surface irrigation, 4% for micro-irrigation and 92% for overhead irrigation (CGAER, 2017).

In 2010, a sharp reduction in area equipped through collective irrigation systems can be observed, while areas equipped with individual irrigation systems has continued its rise (Loubier et al., 2013). The same trend occurs in the Mediterranean rim where most irrigation is traditional carried out through collective systems. At the time, a reduction of 50% in surface water irrigation is observed in these regions. These trends suggest a move towards more water efficient systems, although it also poses local challenges for groundwater recharge via the distribution canals and surface irrigation practices.

The development of irrigation has led to increasing societal conflicts across France, especially in the agricultural productive regions of the west and southwest of France which underwent a significant increase in irrigation for maize and cereal production in the 1980s and 1990s. Assuring minimum ecological flows is a significant challenge as a result of cumulative pumping in rivers and through individual boreholes in alluvial and sedimentary aquifers (CGEDD-CGAAER, 2015).

3.1.7.2 Groundwater and drinking water supply

Drinking water supply network provides water to domestic users as well as all buildings equipped with sanitary infrastructure (e.g. schools, hospitals, hotels, sports, etc) and small businesses and industries. Water consumption per capita is estimated at 165 litre per day (ONEMA, 2015).

Water use is mainly dependent on residential population; however some basins are characterised by large seasonal population variations due to tourism. This can pose supply challenges in Mediterranean basins during the low flow season similar to those faced by irrigation. Drinking water supply is given the highest priority use during crisis. No restriction to drinking water use due to water shortage has been recorded in France yet; restrictions to water gardening are nevertheless regular.

The vast majority of the population use water delivered to their homes by public water suppliers (98%); however, an increasing number of households in detached or semidetached housing units have drilled private bore-wells since the 1990s for various economic, political and ethical reasons (Rinaudo et al., 2015). Typically, household use alternative water supplies for gardening and other non-consumptive uses in order to reduce their water bills. According to Montginoul and Rinaudo (2011), the presence of domestic tube wells and shallow wells is reported in a majority of French counties both in southern and northern France and is expected to significantly increase in the coming decade, as a result of increased water scarcity, higher tariffs from public water supplies, and the decreasing cost of alternative supply technologies. Furthermore, there is yet little regulation on private domestic drilling.

Overall the main challenge regarding groundwater abstraction for drinking water supply relates to water quality and the risks that pollution emission, mainly from agricultural activities.

3.2 Climate change challenge

This part is based on the BRGM report 61483-FR, Explore 2070 project (2012).

Climate change will not affect the water resources in the whole Europe the same way, depending on various factors, which are mostly related to climate, geology, pedology and land use (Figure 17 and Figure 18).

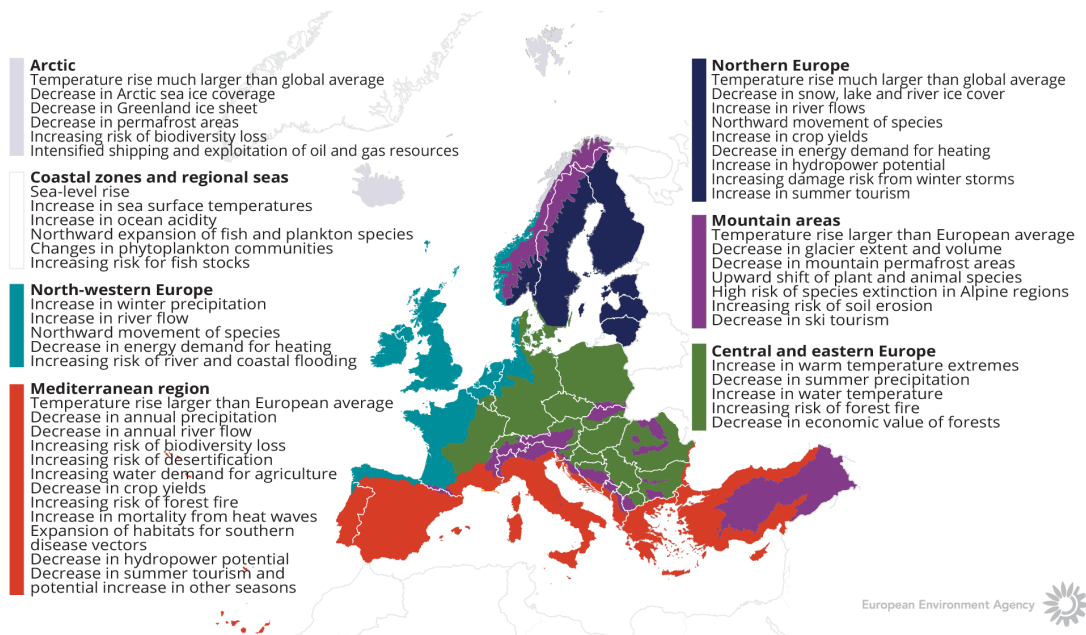


Figure 17: Observed and projected climate change and impacts for the main biogeographical regions in Europe (European Environmental Agency).

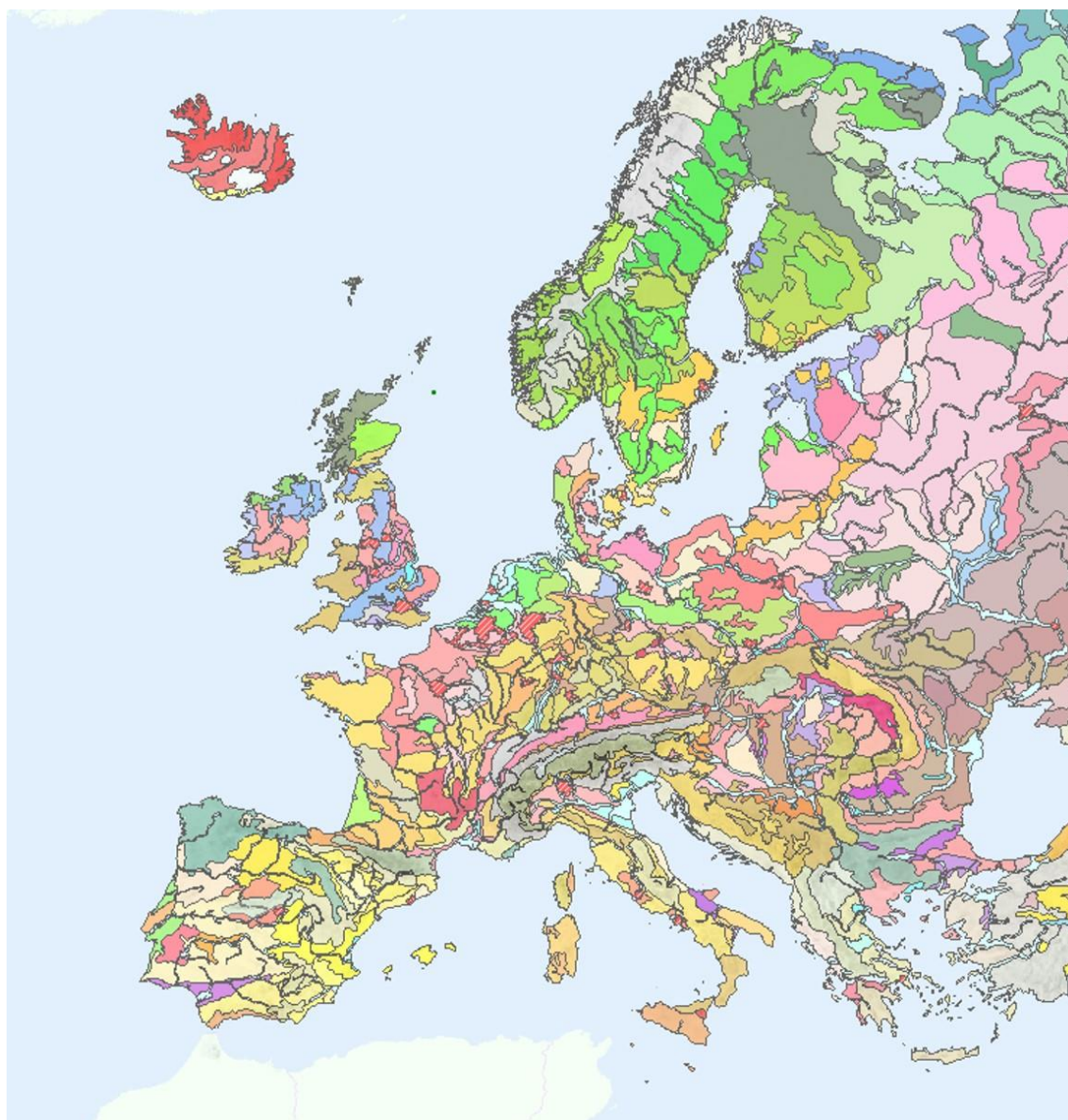


Figure 18: Soil map of Europe, from the EGD interactive maps
(map available at: <http://www.europe-geology.eu/soil/soil-map/>; legend available at:
<https://services.bgr.de/wms/boden/eusr5000/?request=GetLegendGraphic%26version=1.3.0%26format=image/png%26layer=2&lang=en>)

3.2.1 ***How is the climate expected to change in the area***

The effect of climate change on the water supply has already been the subject of a previous study, with quantifications of groundwater amounts estimations at present time and at the year 2070.

The method generally used in this type of project is:



- Greenhouse gas and aerosol emission scenario
- global climate model
- disaggregation (regionalization)
- regional hydro(geo)logical model
- impact analysis and uncertainty analysis.

Seven climate models from the IPCC Fourth Assessment Report (2007) have been used for every analysis (ARPEGE V3+, GISS-MODEL-ER, MRI-CGCM2.3.2, ECHAM5/MPI, GFDL-CM2.1, GFDL-CM2.0, CCCMA-CGCM3). The greenhouse-gas and aerosols emissions scenario used in the analysis is the median scenario proposed by the IPCC AR4 (scenario A1B). Abstraction and irrigation are assumed to be stable.

Regarding the general data, Figure 19 and Figure 20 show the main variations in annual thermometry and rainfall of the different models over the period (2045/2065), compared to their reference values (1961-1990). These graphs show that if the average value of temperatures is increasing (about 2 to 2.5 C) and the average rainfall is decreasing (about 6 to 8%), these values are very variable. From one climate model to another and extreme values can be very different. The variability of these results, obtained for all the climate models makes it possible to assess the uncertainties on the climate projections.

The temperature will have a significant influence on the potential evapotranspiration (PET). These few degrees of increase will thus generate an increase in PET of 10 to 15% or more depending on the regions and seasons. This increase in PET will directly increase actual evapotranspiration (AET) since the models used do not incorporate a possible adaptation of natural vegetation to climate change. This increase in AET associated with a decrease in rainfall, relatively low in percentage but significant in quantity, will thus lead to a significant reduction of effective rainfalls. This reduction is very variable depending on the regions and climate models, but it is rarely less than 20%.

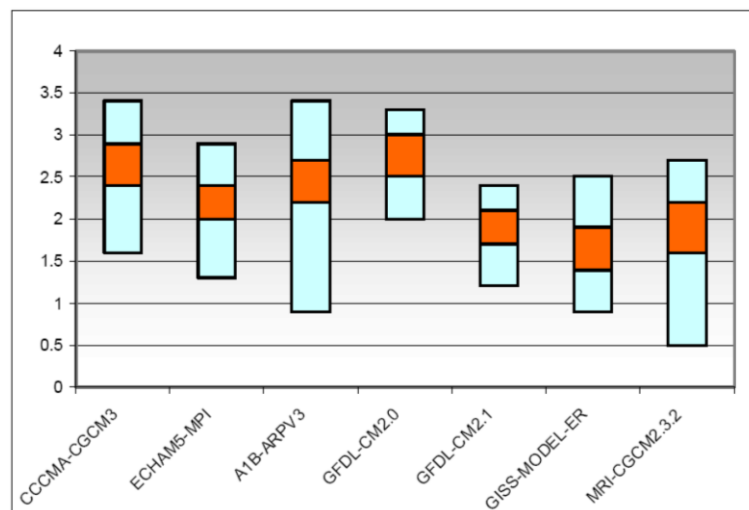


Figure 19: Deviation from the average annual temperature difference between current and predicted. Current: reference period (1961-1990); predicted: (2046-2065). Values presented in Celsius degrees, with confidence intervals (orange) and extremes values. Performed for the 7 climate models on scenario A1B (from Explore 2070, Lot3).

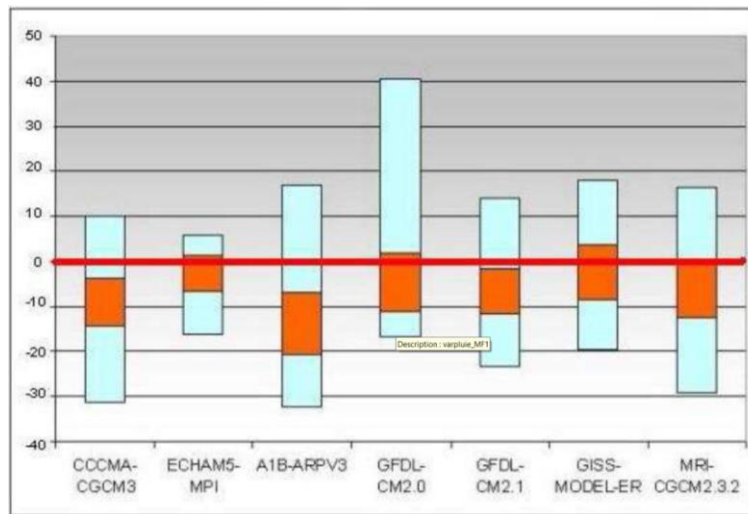


Figure 20: Average cumulative annual rainfall difference between current and predicted. Current: reference period (1961-1990); predicted: (2046-2065). Values presented in percentage of reference periods values, with confidence intervals (orange) and extremes values. Performed for the 7 climate models on scenario A1B (from Explore 2070, Lot3).

3.2.2 What are the challenges related to the expected climate change?

3.2.2.1 Almost universal decline in water recharge

The simulations performed with the seven climate models have produced three maps (minima, mean and maxima projections) indicating a virtually systematic 10 to 25% decline in water table recharge, with two areas more severely affected :

- the Loire basin with a 25 to 30% decline across half of the catchment area,
- and the south-west of France with a 30 to 50% decline.

In each modelling exercise, all of the piezometers show a decline in average monthly water table levels due to lower recharge. The optimistic scenarios show a slight 0.5 to 1.5 m drop in levels and even a possible slight rise in some zones (Aquitaine, Poitou), while the pessimistic scenarios show a very limited drop in piezometric levels beneath alluvial plains in particular, but levels dropping by as much as 10 m in lowland and foothill areas lying above sedimentary basins.

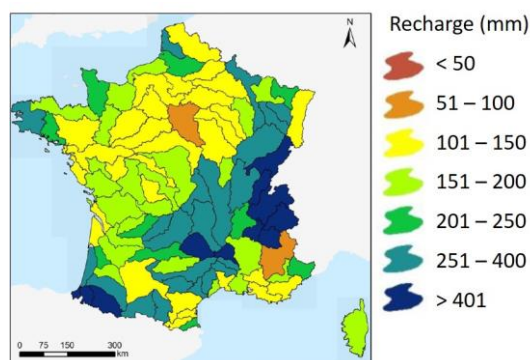


Figure 21: Average estimated recharge per year at present time

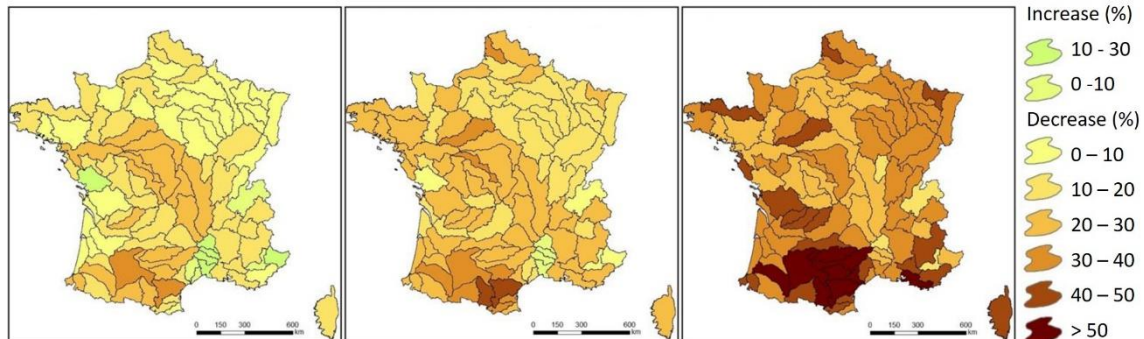


Figure 22: Difference between present day recharge and predicted recharge for the year 2070 (percent for minima projection, mean projection and maxima projection).

3.2.2.2 Decline in average river flow

All of the scenarios also show a decline in average river flow by 2065, which varies from 10 to 40% in the northern half of the country and from 30 to 50% in the southern half, with local extremes of up to 70%. Despite this relative decline in river flow, some models show that very high water levels are nevertheless possible during the winter in some catchment basins (e.g. Somme and Rhine), confirming the likelihood of lengthy periods of flooding.

3.2.2.3 30% potential loss of groundwater resources by 2070

Groundwater resources are therefore likely to decline significantly overall by 2070, with predicted variations of +10 to -30% in the optimistic scenarios and -20 to -55% in the pessimistic scenarios. This would cause a decline of similar proportions in low-water levels.

4.1 Methodology

The methodology applied to assess the potential groundwater recharge at the country scale combines a water budget approach and the use of an Effective Precipitation Infiltration Ratio (EPIR):

$$\text{Recharge} = \text{EPIR} * \text{Effective Precipitation.}$$

It is applied to evaluate both present and future groundwater recharge.

4.1.1 *Effective precipitation calculation*

A gridded water budget model was developed (with Matlab©) to compute the effective precipitation with a resolution of 8 km at a daily time step (see Figure 23). It relies on the water budget method proposed by Edijatno & Michel (1989). This method is implemented in several rainfall-runoff models (e.g. GR4J from Perrin et al., 2003).

4.1.2 *EPIR evaluation*

Assuming that the EPIR is constant over time, the France map of EPIR has been constructed taking advantage of the relationship established between two indices related to infiltration. These are the Indice de Développement et de Persistance des Réseaux (IDPR) and the baseflow index (BFI).

The IDPR is a GIS-built parameter that gives a qualitative indication on the infiltration coefficient. It has been developed by BRGM since 2004 (Mardhel et al., 2004). IDPR is constructed by comparing the theoretical river network computed from Digital Elevation Model to the real one. IDPR is available all over France with a 25 m spatial resolution (Mardhel et al. 2021). The IDPR values are comprised between 0 (only infiltration) and 2000 (only runoff), with a fixed value of 1000 along rivers.

The baseflow is defined as the delayed water contribution to river flow that is not related to direct runoff. It can be calculated from rivers discharge data by applying hydrograph separation algorithms, such as those proposed by the Wallingford Institute (see e.g. Gustard, 2008) or Lyne and Hollick (1979). The baseflow index (BFI) is the long-term ratio of the baseflow to the total stream flow. For undisturbed hydrogeological basins, with no inter-basins lateral exchanges nor vertical leakage and at an annual scale (negligible storage), the BFI appears to be a fair proxy of the EPIR. Obviously, the BFI is only available on gauged watersheds.

A survey was conducted over 357 gauged river basins distributed over France, for which discharges data are known to be undisturbed by pumping or dams. The mean inter-annual BFI values over the 1981 – 2010 period were computed with the Lyne and Hollick method. In parallel, the spatial average of the IDPR over the watersheds was calculated. Correlation between the two datasets were found after sorting the basins according to their lithology. These relationships allowed converting the IDPR map into an EPIR map, with a resolution equal to the hydrogeological unit scale.

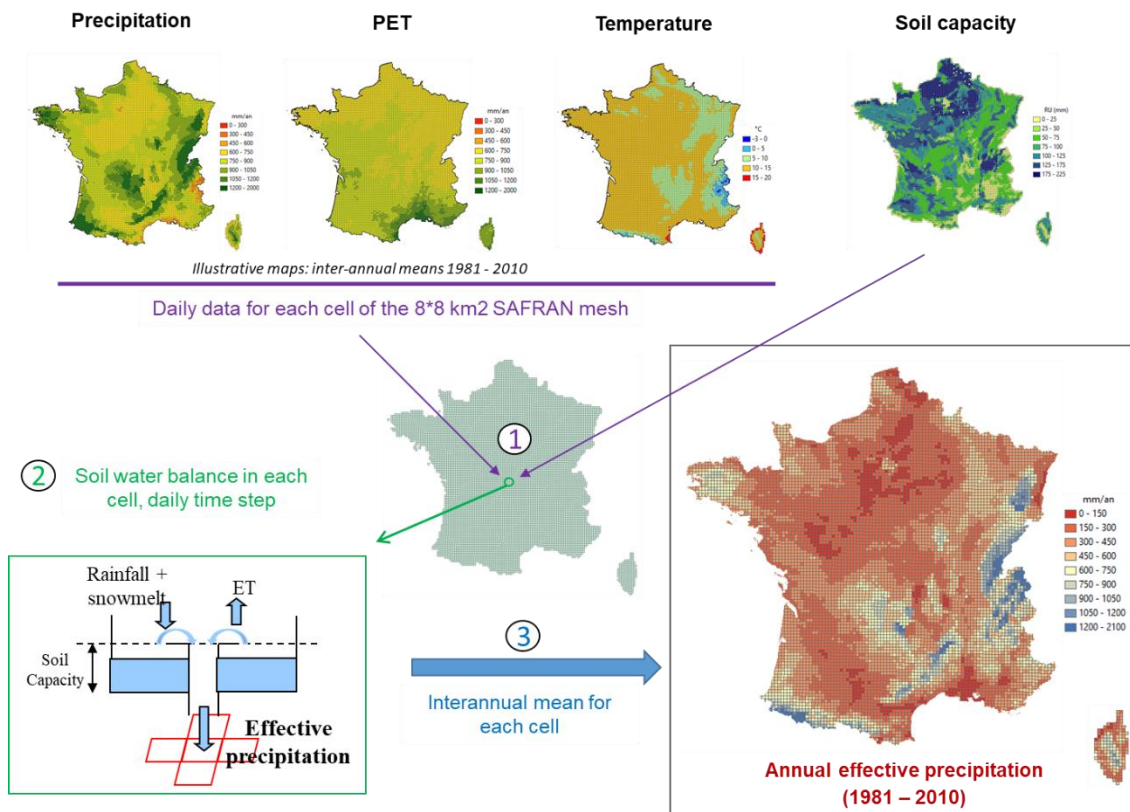


Figure 23: Sketch of the methodology applied to compute effective precipitation.

4.1.3 Climate data

4.1.3.1 Meteorological data

Meteorological data that are used to calculate effective recharge for the France pilot site are the SAFRAN reanalysis data (Vidal et al., 2010). They are available on a 8x8 km² mesh covering France, from 1958 to present day. For the modelling purpose, daily time-step rainfall, snow, temperature and Penman-Monteith PET are used. The chosen reference period, common to all pilot site, is the 30-years 1981-2010 period.

4.1.3.2 TACTIC standard Climate Change scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5° global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set were selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future



climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).

2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.

3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature were calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.

4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.

5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).

6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

Only the case of 3°C global warming is considered here (Table 2).

For the France pilot site, the change factors are calculated from the simulations RCP8.5 with the gfdl-esm2m GCM and RCP6.0 with the miroc-esm-chem GCM. The first one forecasts that 3°C warming will be reached (at a global scale) in 2057, and simulates a decrease of inter-annual precipitation for the 30-years period (2057-2086) of 9% (“lowest” impact on precipitation scenario). The second one forecasts that 3°C warming will be reached in 2042, and simulates an increase of inter-annual precipitation for the 30-years period (2042-2071) of 5% (“highest” impact on precipitation scenario).

Table 2 Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
3-degree	“Dry”	RCP8.5	gfdl-esm2m
	“Wet”	RCP6.0	miroc-esm-chem

Climate data are generated by applying these change factors to historical data used to run the hydrological model. The same reference period, 1981 – 2010, is used. Monthly change factors, which are provided on a 0.25° mesh, are first projected on the grid of reference data. Then temperature

change factors are added to reference time series, whereas precipitation and potential evaporation change factors are multiplied to reference time series.

4.1.3.3 Alternative climate change scenarios

Future effective precipitation and anomalies were calculated at the French national scale by BRGM in 2019. The methodology relies on ensemble simulations. For two contrasted emission scenario (RCP2.6 and RCP8.5), outputs of four General Circulation Model (BCC_CSM1-1-m, CanESM2, IPSL, NorESM1) combined with two statistical downscaling methods (DSCLIM described by Pagé et al. 2009, and the method proposed by Dayon, 2015) were used to run three different water budget models.

4.2 Results and conclusions

4.2.1 Climate data

Monthly change factors (given on a 0.5° grid) were projected on the SAFRAN mesh (8×8km cells). For illustration purpose, the monthly precipitation change factors corresponding to the ensemble simulation members that forecast the “lowest” impact on precipitation (i.e. 9% decrease) and the “highest” impact (i.e. 5% increase) are presented in Figure 24.

The annual mean change factors for precipitation, temperature, and potential evapo-transpiration maps are shown in Figure 25.

At the annual time scale, the “highest” impact scenario predicts a light decrease of precipitation around the Mediterranean sea, but a high increase (up to 10%) in the North-East and North-West parts of France (Figure 25a). Temperature increase are particularly important in the South-West part where they reach 2.7°C (Figure 25b). PET increase everywhere, between 4 and 10% (Figure 25c).

The “lowest” impact scenario actually shows also marked changes. Precipitation strongly decrease, especially in summer, with annual reduction showing a gradient pattern from 20% in South-West to 4% in North-East. Temperature increases remain under 2.5°C all over France (between 1.2°C in Bretagne to 2.16°C in Centre-East).

These change factors were applied to the SAFRAN daily data for the period 01/01/1981 – 31/12/2010, to produce climate data that can be used to simulate future effective precipitation. The resulting inter-annual means of meteorological data are presented in Figure 26, Figure 27 and Figure 28.

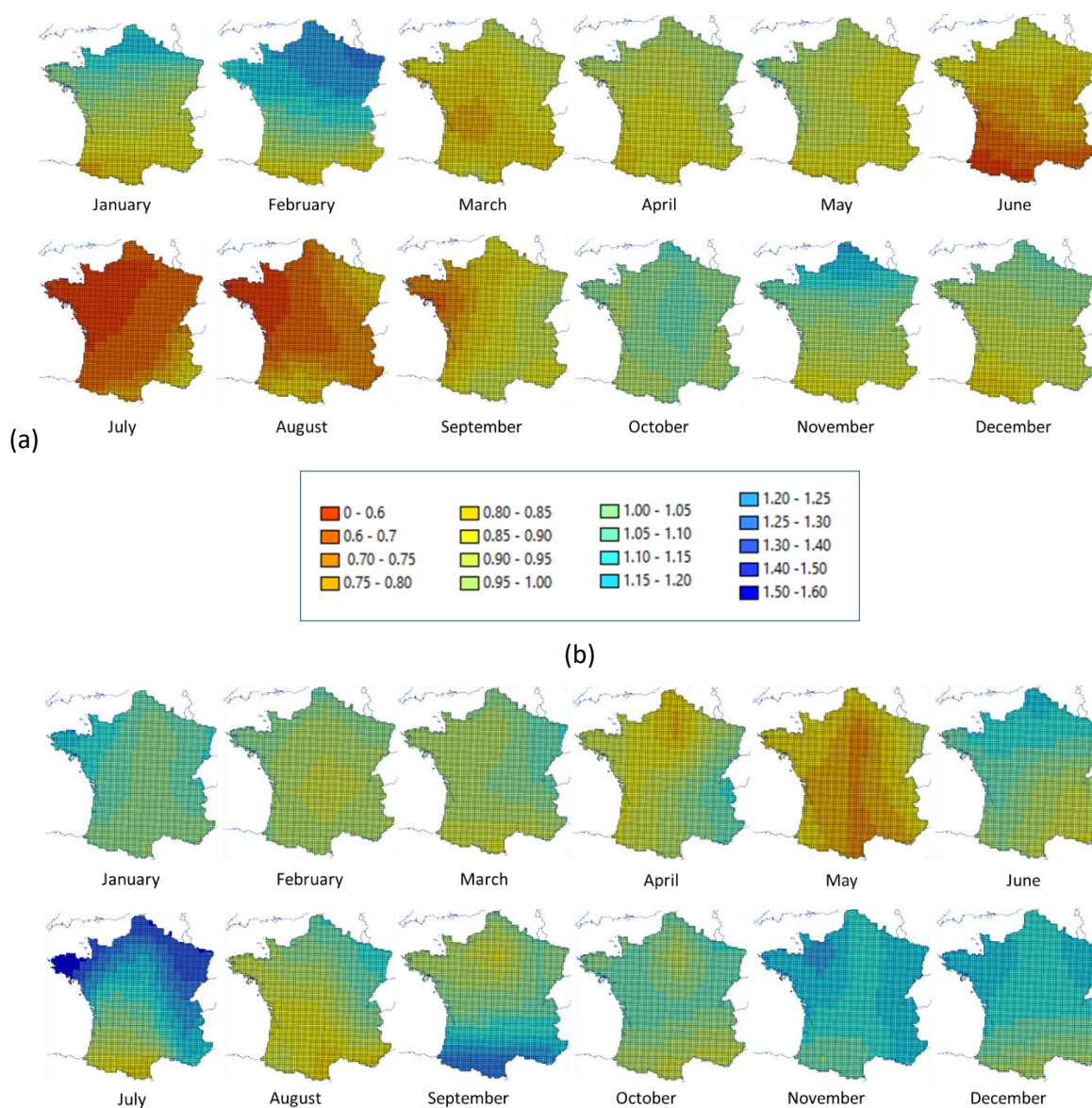


Figure 24: Monthly precipitation change factors (3°C warming)

Legend: (a) =Scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5 simulation, 2057-2086), values range from 0.428 to 1.269. (b)=Scenario with highest impact on precipitation (change factors given by miroc-esm-chem + RCP6.0 simulation, 2042-2071), values range from 0.729 to 1.6

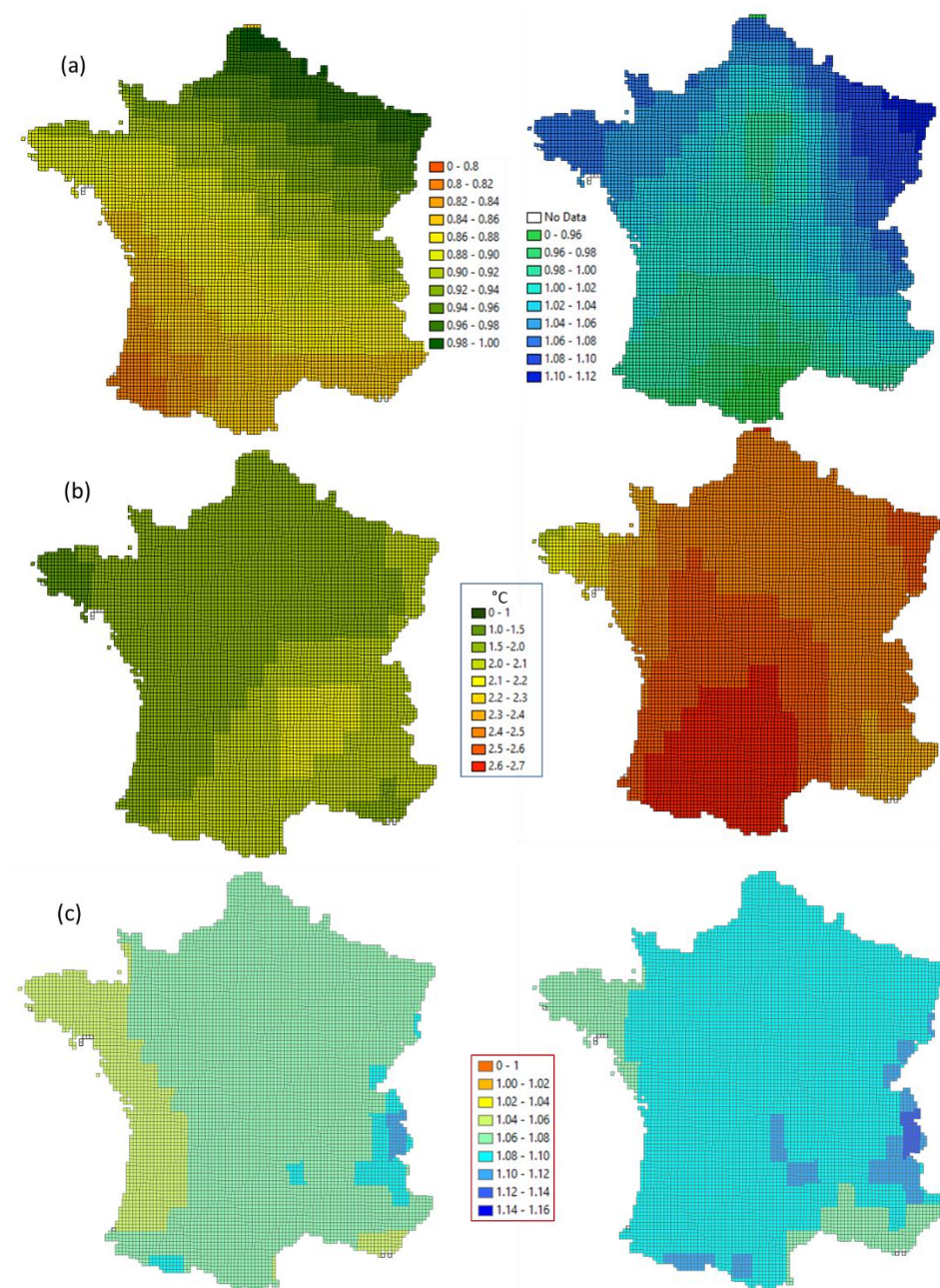


Figure 25: Mean annual change factors (3°C warming).

Legend: (a) Precipitation (b) Temperature (c) Potential evapotranspiration,

left= Scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5 simulation, 2057-2086), Right= Scenario with highest impact on precipitation (change factors given by miroc-esm-chem + RCP6.0 simulation, 2042-2071)

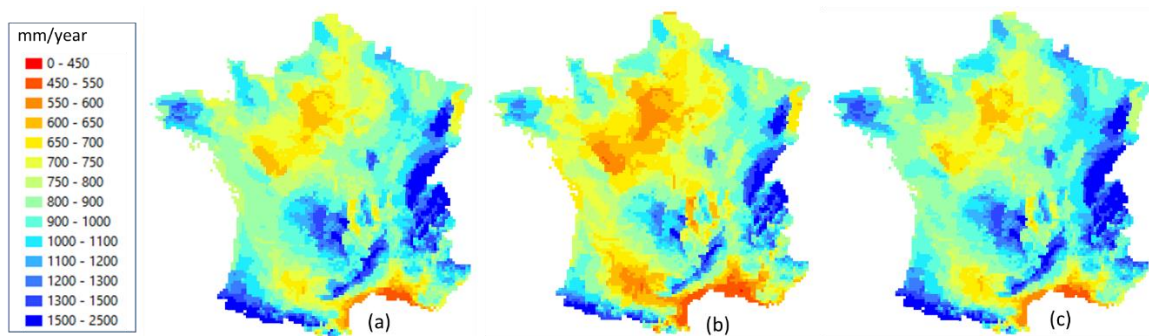


Figure 26: 30-years period interannual mean precipitation (3°C warming)

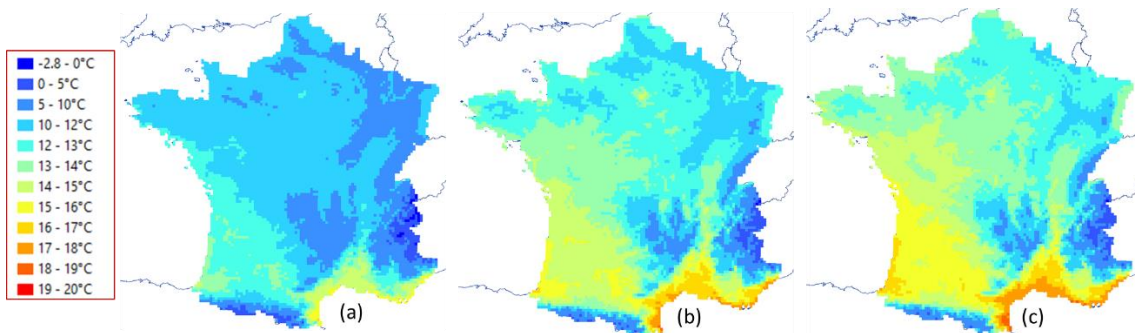


Figure 27: 30-years period interannual mean temperature (3°C warming)

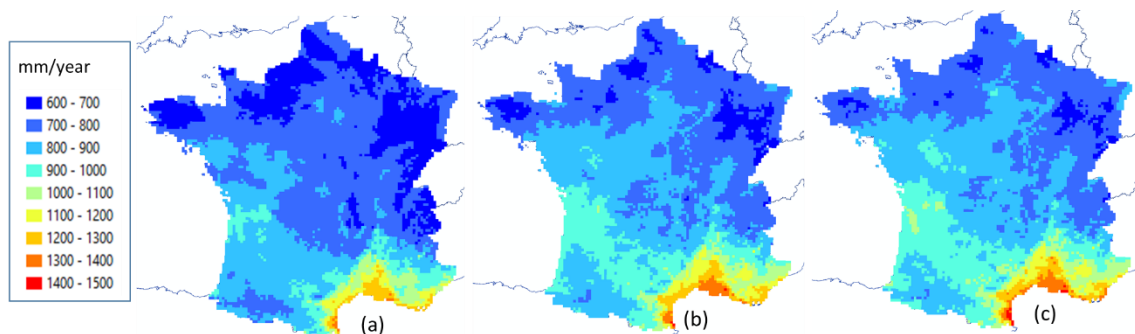


Figure 28: 30-years period interannual mean PET (3°C warming)

Legend: (a) reference, SAFRAN daily data, 1981-2010 (b) Scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5), 2057-2086 (c) scenario with highest impact on precipitation (change factors given by miroc-esm-chem + RCP6.0), 2042-2071

4.2.2 Effective precipitation

Daily effective precipitation for each 64km² cell were computed over the 30-years period by feeding the Matlab© model two SAFRAN datasets. The first consists of the historical climate data and the



second consists of the same data but altered with the change factors to represent future conditions. Maps of mean inter-annual effective precipitation over the 30 years-periods for each cases are shown in Figure 29. As it is difficult to compare these raw results, maps of anomalies are also produced (Figure 30). The anomalies are defined as the ratio, expressed in percentage, of the future effective precipitation minus the present ones related to present ones.

In the case of “lowest” impact scenario, effective precipitation anomalies are negative everywhere except along the North border where they are slightly positive. The effective precipitation reduction reaches 33% in the South-West, and gradually decreases northwards. The distribution of anomalies computed with the highest impact scenario shows an unexpected pattern, with a decrease of effective precipitation in the middle part of France (between 2.5 and 15%) and an increase elsewhere (up to 17% in Alsace). These results are strongly linked to the precipitation change factor maps.

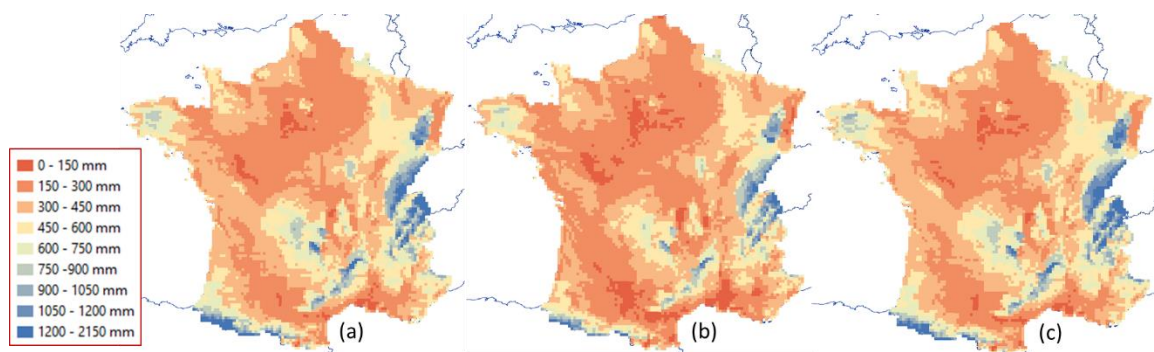


Figure 29: 30-years period interannual mean effective precipitation

Legend: (a) reference, SAFRAN daily data, 1981-2010 (b) Scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5), 2057-2086 (c) scenario with highest impact on precipitation (change factors given by miroc-esm-chem + RCP6.0), 2042-2071

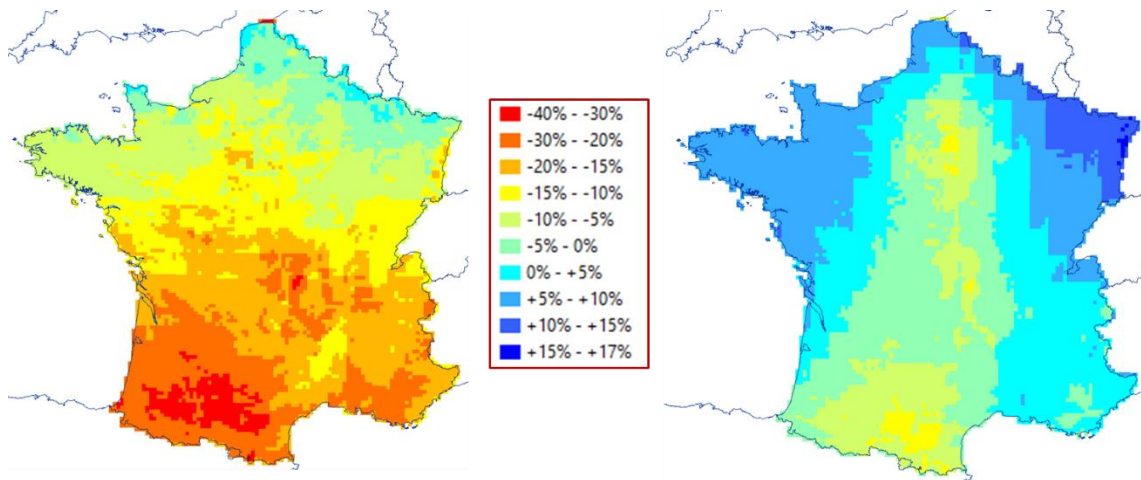


Figure 30: Effective precipitation anomalies

Legend: left=scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5), 2057-2086; right=scenario with highest impact on precipitation (change factors given by miroc-esm-chem + RCP6.0), 2042-2071

The “highest” impact scenario results are unexpected and far from other published results. On the other side, the “lowest” impact scenario results are in the same range and show comparable patterns as previous results obtained by BRGM with the same methodology but with different climate data (ensemble simulation with 4 GCM and 2 downscaling methods). The main differences concern the Paris basin and the North part of France (Figure 31). The important decrease of effective precipitation in the South-West region is of the same order of magnitude of the TACTIC results (-30 - -40%) as in the EXPLORE 2070 exercise¹ (Figure 22) but higher than in BRGM 2019 results (-20% - -30%).

¹ Assuming that the EPIR does not vary in the future, effective precipitation anomalies are equal to potential groundwater recharge anomalies.

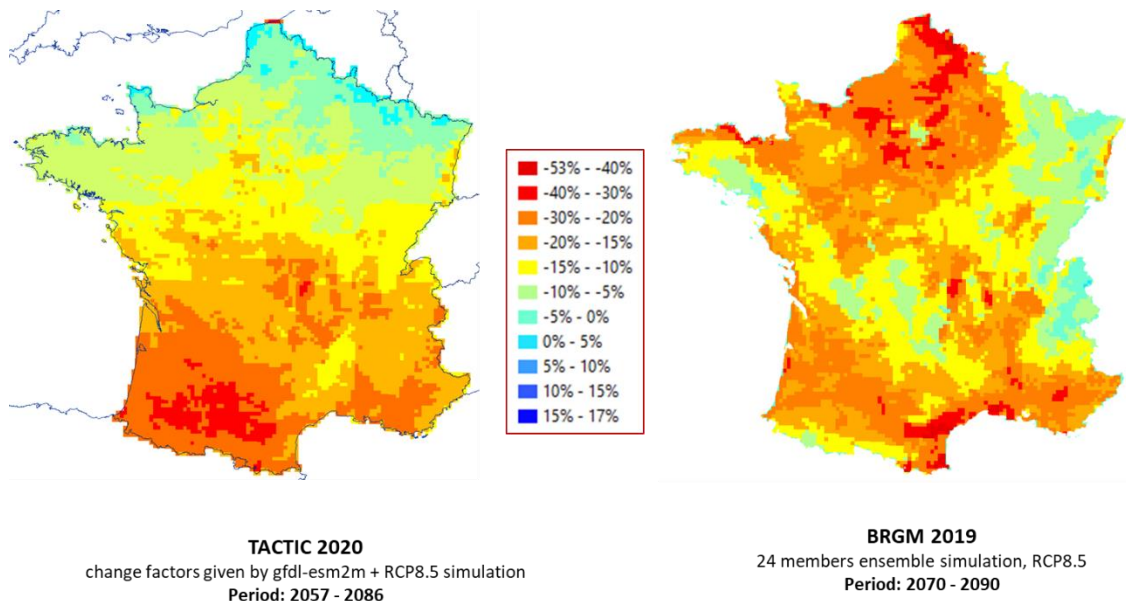


Figure 31: Comparison of effective precipitation anomalies maps.

Legend: left =scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5), 2057-2086 ; right = results of 24 members ensemble simulation, RCP8.5, 2070-2090

4.2.3 Groundwater potential recharge

According to the results of the analysis of IDPR and BFI on 357 gauged basins, the following relationships were applied to convert the France IDPR map into an EPIR map (Figure 32) taking into account the lithology of hydrogeological units (Caballero et al., 2020):

- Alluvial, sedimentary, volcanic formations:

$$\text{EPIR} = 0.9 \text{ if IDPR} < 100 \text{ and } \text{EPIR} = -0.0004 * \text{IDPR} + 0.9517 \text{ if } 100 \leq \text{IDPR} \leq 2000.$$

- Karstic formations:

$$\text{EPIR} = 0.9 \text{ if IDPR} < 100, \text{EPIR} = -0.0004 * \text{IDPR} + 0.9517 \text{ if } 100 \leq \text{IDPR} < 1200, \text{EPIR} = 0.5 \text{ if IDPR} \geq 1200$$

- Bedrock: EPIR = 0.55
- Folded formations: EPIR = 0.65

Finally, recharge maps are obtained multiplying EPIR map by effective precipitation maps (Figure 33).

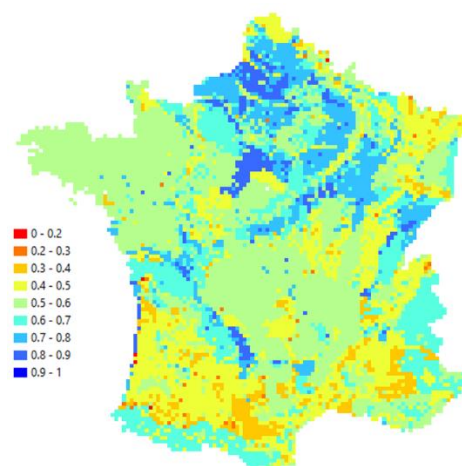


Figure 32: France map of EPIR (SAFRAN cells projection)

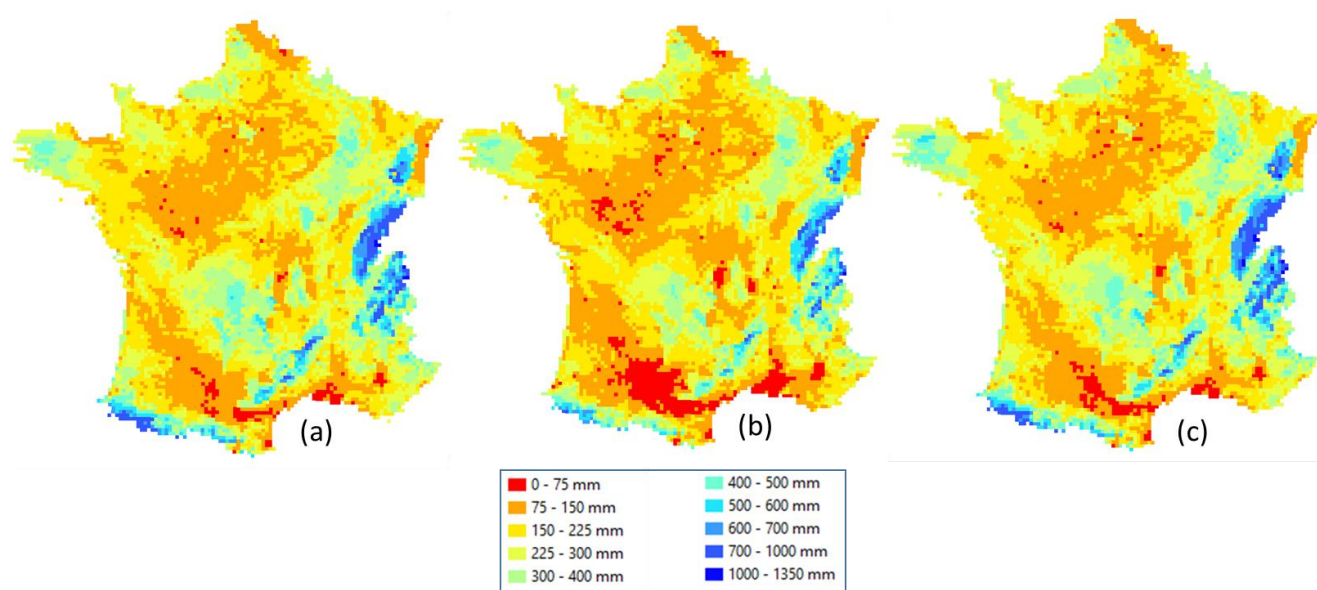


Figure 33: France map of present and future groundwater potential recharge

Legend: (a) reference, SAFRAN daily data, 1981-2010 (b) Scenario with lowest impact on precipitation (change factors given by gfdl-esm2m + RCP8.5), 2057-2086 (c) scenario with highest impact on precipitation (change factors given by miroc-esm-chem + RCP6.0), 2042-2071

5 VULNERABILITY TO CLIMATE CHANGE

5.1 Methodology

The vulnerability of aquifers to climate change will be assessed via monotonic and non-linear trend analyses. The monthly groundwater levels averages and monthly cumulative effective precipitation will be used to conduct it. Analyses will be performed on two reference periods (1996-2019 and 1976-2019) providing the best compromise between the length of groundwater time series and their spatial distribution through metropolitan France and northern France, respectively.

An effective precipitation time series is assigned to each groundwater time series via the development of an indicator (Manceau et al., 2020). Before using this indicator, we preselected all SAFRAN meshes within the catchment and a 50 km radius around each well. This limited area has been chosen to keep a reasonable computing time. These effective precipitation time series are then converted as a statistical indicator of groundwater recharge or discharge modulated by a time lag representing the memory effect of aquifers. The indicator time series (expressing the effective precipitation) allowing the maximization of the correlation coefficient with monthly groundwater levels is selected because considered as the most representative mesh of the groundwater level behaviour.

The following sections describe methodologies applied for trend detection and assessment of the influence of groundwater low-frequency variability on trends.

5.1.1 Groundwater and effective precipitation monotonic trend detection

The trend detection on monthly groundwater levels and cumulative precipitation is achieved on the two reference periods (1996-2019 and 1976-2019). The significance of detected monotonic trends was determined with a modified Mann-Kendall trend test for autocorrelated data (Hamed and Ramachandra Rao, 1998). Comparatively to the well-known Mann-Kendall trend test (Mann, 1945; Kendall et al., 1987), the modified Mann-Kendall trend test considers autocorrelation by correcting probability values (pvalues) after accounting for autocorrelation. The statistical significance threshold was set at 5%. Simultaneously, we assessed the magnitude of trends by estimating Sen's slope (Sen, 1968). This method is emphasized because it is less influenced by extreme values than a linear regression. Indeed, the slope is defined as the median of the set of slopes calculated between each pair of points.

In addition, we aimed to quantify groundwater level trends in relation to aquifer dynamic. For this purpose, we developed an indicator where Sen's slopes are normalised by the maximum water level fluctuation (WLF) with the following expression:

$$\text{Percentage of maximum WLF} = \left(\frac{\text{Sen's slope} * \text{duration}}{\text{Maximum WLF}} \right) * 100$$

The maximum water level fluctuation for each groundwater time series was determined using a boxplot that displays the scope of groundwater levels and avoids taking into account outliers.

Percentages of groundwater level loss/gain against maximum water level fluctuation were split into 5 classes according their magnitude:



- Negligible trend between -1% and +1% of maximum water level fluctuation.
- Moderate upward or downward trend between +1% and +10% or -1% and -10% of maximum water level fluctuation, respectively.
- Strong upward or downward trend between +10% and +100% or -10% and -100% of maximum water level fluctuation, respectively.

5.1.2 Non-linear trend estimation and linkage with effective precipitation

5.1.2.1 The Ensemble Empirical Mode Decomposition (EEMD)

To overcome the low-frequency variability induced by large-scale atmospheric/oceanic circulation and to extract the real and non-linear trends of monthly groundwater levels and effective precipitations, we applied an EEMD filtering (Wu and Huang, 2009). This method is widely applied to extract multi time-scale variability and/or get the not parametrically defined trend in environmental variables (e.g. Massei and Fournier, 2012; Bonnet *et al.*, 2020; Song *et al.*, 2020). Basically, it consists to extract the orthogonal intrinsic oscillatory modes (called IMFs: Intrinsic Mode Functions) constituting the signal $x(t)$ to analyse and a residue $r(t)$. Each IMF must satisfy two conditions: (i) numbers of extrema and zero crossings in the signal must equal or differ at most by one; (ii) the mean value of the envelope defined by local maxima and the envelope defined by local minima must be equal to zero at any point. The residue $r(t)$ represents the real trend existing in the signal and is not parametrically defined.

Compared to the Empirical Mode Decomposition (EMD) implemented by Huang *et al.* (1998), the EEMD has the benefit to be a noise-assisted data analysis method. It avoids intermittency problem in the decomposition by the EMD filter bank. In our analysis, the ensemble members was set to 100, and the added-noise was set to 10% of standard deviation for groundwater levels and 20% of standard deviation for precipitation.

The purpose being to get trends on large-scale climatic fluctuations filtered groundwater levels and effective precipitation, the following study was achieved on the EEMD residues $r(t)$ extracted on the 1976-2019 and 1996-2019 periods.

5.1.2.2 Estimation of monotonic trends on both groundwater and effective precipitation EEMD residues

From these EEMD residues, the same analysis of detecting monotonic trends will be repeated.

Firstly, modified Mann-Kendall and Sen's slope are recalculated on groundwater levels and effective precipitation EEMD residues. The purpose is to observe whether the filtering of low-frequency variability allows us to obtain similar trend directions between groundwater levels and effective precipitation. In this case, it would mean that effective precipitation trends explain groundwater levels trends.

Secondly, Sen's slopes calculated on groundwater EEMD residues will be normalised by the maximum WLF of unfiltered signal, to be compared to monotonic trends estimated on raw groundwater levels (section 5.1.1.). The aim is to check whether the filtering of quasi-periodic variabilities (especially low frequencies) in groundwater levels leads to similar or opposite trends (in magnitude and direction).

In order to better understand why detected opposite monotonic trends between filtered groundwater levels and filtered effective precipitation can be obtained, a visual check of non-linear trends (*i.e.* EEMD residues) is conducted simultaneously.

5.1.2.3 Clustering of groundwater and effective precipitation non-linear trends

One of the interests of EEMD method being to get the non-linear trends of signals, a clustering of groundwater and effective precipitation standardised EEMD residues is realised to identify their typical profiles and their geographical distribution. A partitioning using the k-medoids algorithm was preferred to conduct this analysis (Kaufman and Rousseeuw, 1990). Compared to the k-means algorithm, the k-medoids algorithm is stronger towards outliers. Briefly, it consists to search for k medoids among all time series of the dataset. These medoids represent the structure of data (*i.e.* time series). After finding the set of k medoids, k clusters are constructed by assigning each time series to the nearest medoid. The aim is to find k representative objects minimizing the sum of the dissimilarities of the observations to their closest representative object. The medoid of each cluster is the most central time series in the cluster, and therefore is the most representative of a given cluster. Nevertheless, the choice of number of clusters remains arbitrary. Therefore, an internal validation index is used to determine the optimal number of clusters. In our case, the Davies-Bouldin index is used (Davies and Bouldin, 1979). The clustering with a number of clusters minimizing the Davies-Bouldin index is considered as optimal. We also conducted a visual check between several clusterings minimizing the Davies-Bouldin index to select the one providing the best visual agreement.

By means of this clustering, typical profiles of non-linear trends (*i.e.* EEMD residues) are highlighted. Although shapes of non-linear trends within a cluster can be more or less various, the medoid represents their general shape within the cluster. However, medoids do not represent a mean or a median magnitude of change within clusters, they just describe the shape of non-linear trends.

5.1.2.4 Real non-linear trends or part of lower frequency variability?

The last issue remains to identify if the detected non-linear trends of groundwater levels and effective precipitation can be a part of a lower frequency variability. To answer this question, we compared the covariability of standardised non-linear trends (*i.e.* EEMD residues) extracted on a relatively short period with the standardised empirical modes (*i.e.* IMFs) extracted on a longer period. If non-linear trends display clear covariabilities (*i.e.* similar shapes) with the empirical modes extracted on longer periods, we can suggest that these non-linear trends are part of a lower frequency variability.

5.2 Results and conclusions

5.2.1 *Groundwater and effective precipitation monotonic trends in metropolitan France*

5.2.1.1 Groundwater trends in relation to water level fluctuation

Figure 34 displays the detected monotonic trends of groundwater levels (estimated with Sen's slope) normalised by their water level fluctuation over the 1976-2019 and 1996-2019 periods. The statistical significance of trends at the threshold of 5% are also indicated on these maps. For your information, ranges of normalised trends by hydrogeological entities are presented in Table 3 and Table 4.

Trends on groundwater monthly averages display heterogeneous behaviour through metropolitan France from an aquifer to another over the 1996-2019 period (Figure 34b). In similar hydrogeological entities, trends direction are rather consistent, while large discrepancies in the trend magnitude can appear (Figure 34b; Table 3). The Seno-Turonian chalk in the middle and northern part of Artois-Picardy basin is an example of this phenomenon. Groundwater levels in this entity are homogeneously upward, while their magnitude locally differ (Figure 34b). The Beauce calcareous aquifer (excepting northern part) also displays upward groundwater levels, as well as eastern part of Jurassic limestones from Sarthe to Bessin. Although these upward trends appear to be significant in relation to the water level fluctuation, there are very often not statistically significant.

Inversely, other aquifers exhibit consistent downward trends such as fluvio-glacial formations of Rhone valley (mainly statistically significant), the Jurassic limestones of Berry and Poitou (mainly statistically significant), the western bedrocks formations of Britain, the Upper Cretaceous chalk of Bourgogne, the Seno-Turonian chalk of Champagne, and northern part of volcanic formations of Central Massif. While the Seno-Turonian chalk of Normandy/Picardy mainly present downward trends in the western part, discrepancies appear in the eastern part with upward and downward trends. Other entities also display a heterogeneous trend behaviour such as alluvial formations of the Alsace plain, alluvial formations of mediterranean region, or southern bedrocks of Armorican Massif. These trends are very often statistically significant in the two firsts entities, even if they present opposite directions.

Finally, one of the studied entities exhibits rather homogeneous negligible trends on this short period, the fissured Jurassic limestone of northern Aquitaine Basin.

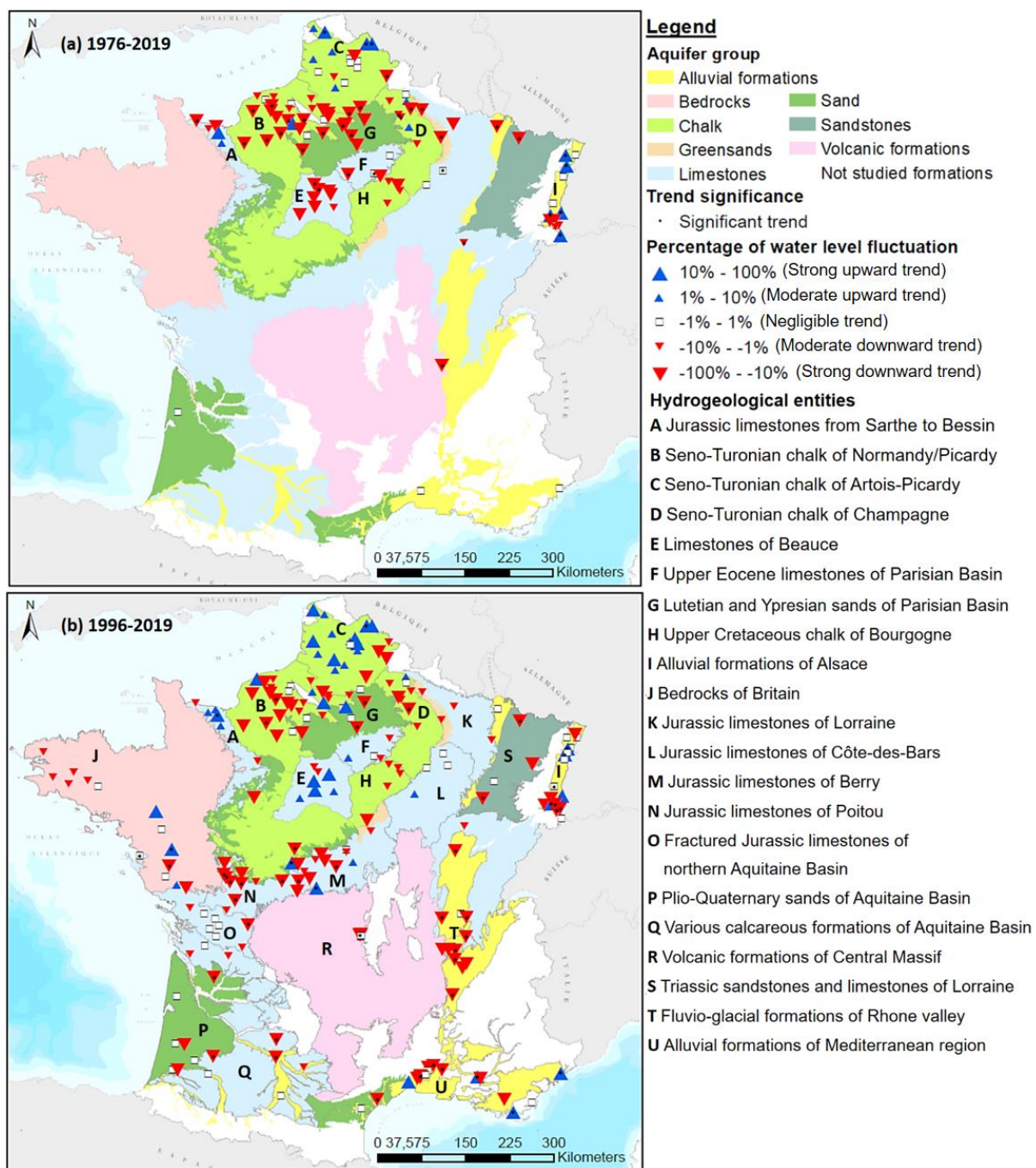


Figure 34: Trends magnitude normalised by the maximum water level fluctuation and their statistical significance (threshold of 5%) of monthly groundwater levels averages over the 1976-2019 and 1996-2019 periods.

Table 3 *Normalised groundwater trends ranges for the main hydrogeological entities over the 1996-2019 period.*

Hydrogeological entities	Lower bound - Slope (% of WLF)	Upper bound - Slope (% of WLF)	Number of boreholes
Seno-Turonian chalk of Artois-Picardy	-22	25	18
Seno-Turonian chalk of Normandy/Picardy	-52	16	30
Seno-Turonian chalk of Champagne	-13	3	8
Jurassic limestones from Sarthe to Bessin	-6	26	5
Lutetian and Ypresian sands of Paris Basin	-57	0	3
Jurassic limestones of Lorraine and Côte-des-Bars	-7	3	4
Triassic sandstones of Lorraine	-76	-16	2
Upper Eocene limestones of Paris Basin	-5	9	4
Alluvial formations of Alsace	-34	40	18
Limestones of Beauce	-8	35	8
Chalk of Bourgogne and Gâtinais	-12	-1	4
Triassic limestones of Lorraine	0	0	1
Bedrocks of Britain	-19	42	10
Jurassic limestones of Berry	-13	0	9
Jurassic limestones of Poitou	-32	-13	6
Fractured Jurassic limestones of northern Aquitaine Basin	-9	0	7
Alluvial and fluvio-glacial formations of Rhone valley	-47	0	11
Volcanic formations of Central Massif	-21	0	5
Various calcareous formations of Aquitaine Basin	-39	-14	3
Plio-Quaternary sands of Aquitaine Basin	-10	0	3
Alluvial formations of Mediterranean region	-35	31	12

Table 4 *Normalised groundwater trends ranges for the main hydrogeological entities over the 1976-2019 period.*

Hydrogeological entities	Lower bound - Slope (% of WLF)	Upper bound - Slope (% of WLF)	Number of boreholes
Seno-Turonian chalk of Artois-Picardy	-31	34	15
Seno-Turonian chalk of Normandy/Picardy	-48	12	29
Seno-Turonian and Turonian chalk of Champagne	-30	5	8
Jurassic limestones from Sarthe to Bessin	-21	13	4
Lutetian and Ypresian sands of Paris Basin	-30	-17	3
Upper Eocene limestones of Paris Basin	-53	0	4
Alluvial formations of Alsace	-11	47	13
Limestones of Beauce	-55	-9	8
Upper Cretaceous chalk of Bourgogne	-13	-3	3

Trends on groundwater levels monthly averages on the 1976-2019 period, become spatially more homogeneous with mostly downward trends in the northern part of metropolitan France (Fig. 4a). Groundwater levels in the limestones of Beauce are homogeneously downward with mostly strong magnitudes (Tab. 2). These downward trends are also noticeable in the Seno-Turonian chalk of Picardy and Normandy with various magnitudes, whether in this last region, some wells do not display trends, and one of them an upward trend. In this hydrogeological entity, strong downward trends are very often statistically significant. In the southern and middle part of Seno-Turonian chalk of Artois-Picardy, groundwater levels do not exhibit homogenous trend direction; while the extreme northern part of Seno-Turonian chalk (near to North sea) is submitted to the increase of its monthly groundwater levels with statistically significant strong upward trends. On smaller hydrogeological entities, many of them display various trend directions: the Seno-Turonian chalk of Champagne exhibits various moderate upward and downward trends, and the Alsace plain alluvial formations exhibit all types of trends. Downward trends in the Seno-Turonian chalk of Champagne are very often statistically significant, while upward trends in alluvial formations of Alsace are all statistically significant. The chalk of Bourgogne still displays downward groundwater levels. Finally, groundwater levels in southern part of Jurassic limestones from Sarthe to Bessin are upward, while they are declining in the border of the English Channel.

5.2.1.2 Comparison between groundwater and effective precipitation detected monotonic trends

A comparison between groundwater (red) and effective precipitation (blue) trends magnitude and direction is established in Figure 35 and Figure 36 by means of Sen's slope over the 1996-2019 and 1976-2019, respectively. A downward stick indicates a negative Sen's slope, and an upward stick indicates a positive Sen's slope, while the stick length indicates the magnitude of trends. The statistical significance at a threshold of 5% is indicated with hatchings.

First of all, we observe on the entire territory consistent downward trends in effective precipitation, even if not statistically significant, over the 1996-2019 period (Figure 35). Very few statistical significant trends in effective precipitation are observed at the scale of metropolitan France. Only the eastern part of France (near the Alsace region) and the Central Massif exhibit consistent statistically significant downward trends. Locally, specific sectors show upward trends but they present very often weak magnitudes and are not statistically significant (e.g. southern Jurassic limestones from Sarthe to Bessin, southern Seno-Turonian chalk of Normandy/Picardy, southern part of fractured Jurassic limestones of northern Aquitaine Basin).

When comparing trends direction of groundwater levels and effective precipitation, major discrepancies appear in the Seno-Turonian chalk of Artois-Picardy (upward groundwater levels vs downward effective precipitation), or in the southern Seno-Turonian chalk of Normandy/Picardy (downward groundwater levels vs upward effective precipitation). In these cases, trends in effective precipitation cannot explain trends in groundwater levels. Many reasons could explain these opposite trends between effective precipitation and groundwater levels such as: a possible anthropogenic influence, a strong influence of low-frequency variability in groundwater levels that could modify the trend, a delay in the long-term evolution of groundwater levels compared to effective precipitation due to memory effects, an error in the choice of effective precipitation SAFRAN mesh.

Otherwise, we observe generally downward trends or stable trends in groundwater levels when effective precipitation exhibit downward trends.

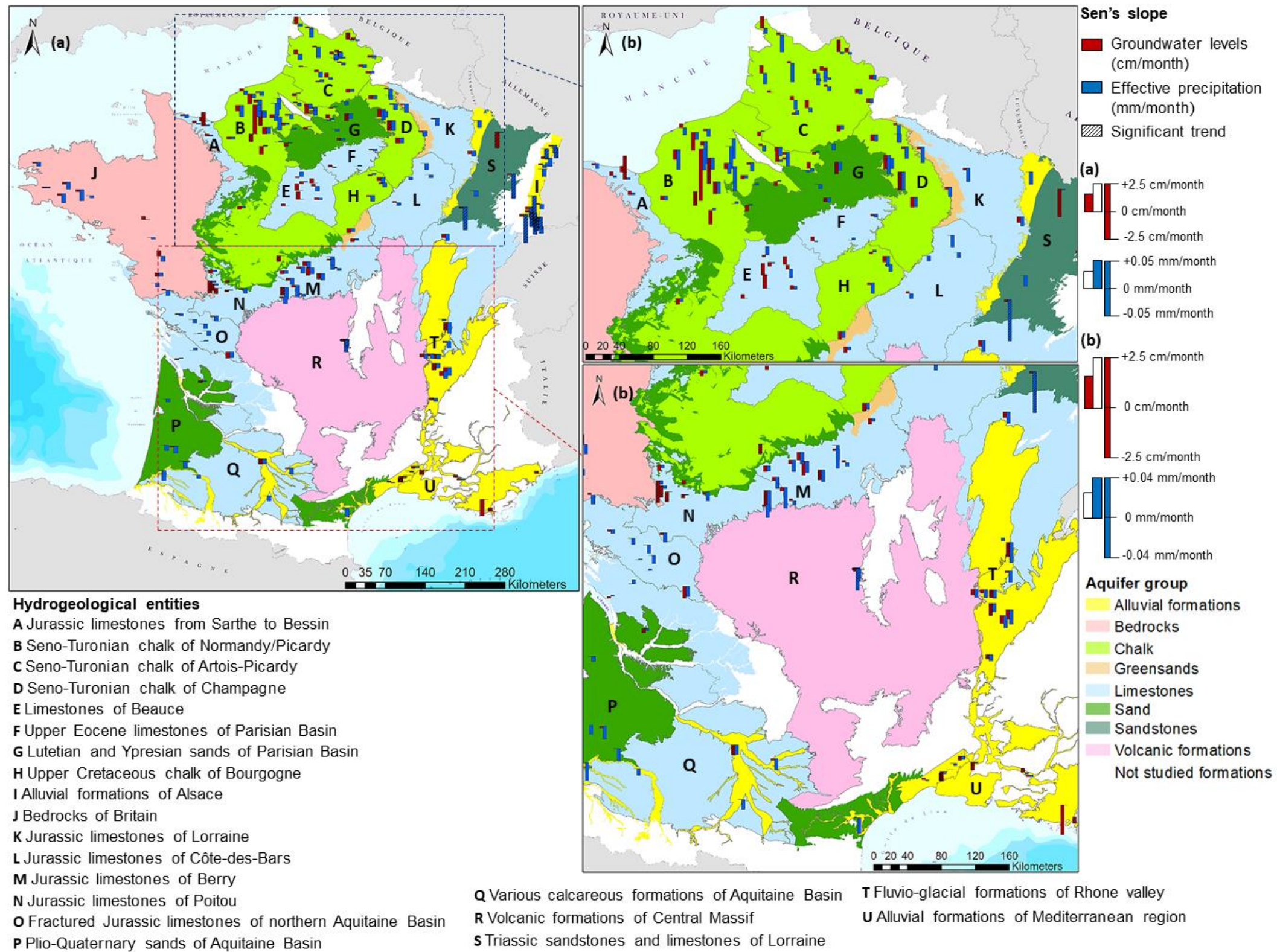


Figure 35: Comparison between Sen's slope of groundwater levels and effective precipitation over the 1996-2019 period. The statistical significance of trends is tested at a threshold of 5%.



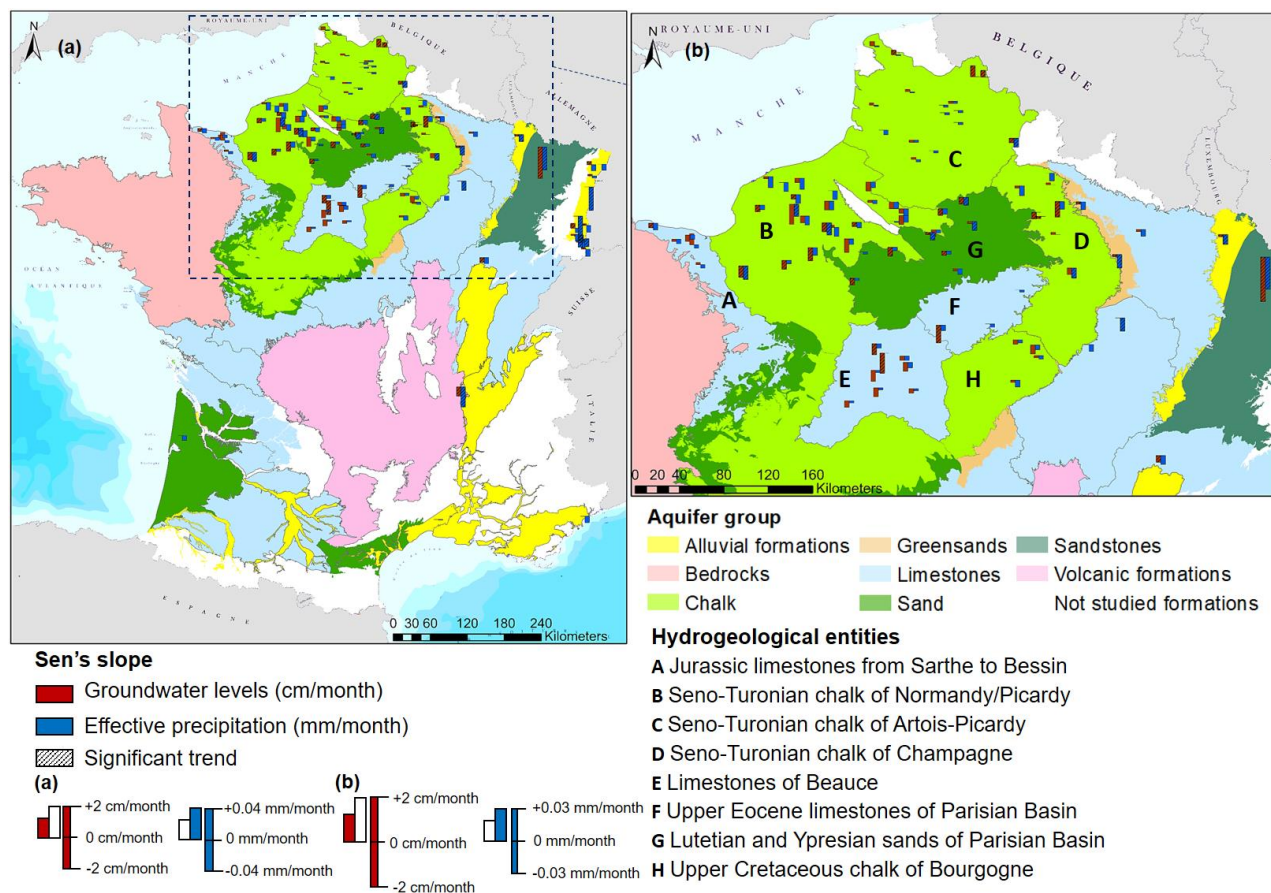


Figure 36: Comparison between Sen's slope of groundwater levels and effective precipitation over the 1976-2019 period. The statistical significance of trends is tested at a threshold of 5%.



Over the 1976-2019 period, trends exhibited by effective precipitation are consistently downward (Figure 36). In contrast, their statistical significance is rather sporadic and not homogeneous at the scale of northern metropolitan France. We still observe on this longer period opposite trends between effective precipitation and groundwater levels in the Seno-Turonian chalk of Artois-Picardy but trends magnitude appear rather weak (upward groundwater levels and downward effective precipitation). On this period, the same phenomenon of opposite trends appears this time for southern Jurassic limestones from Sarthe to Bessin and remains for specific sectors of alluvial formations of Alsace. As explained in the previous paragraph, multiple causes may lead to opposite trends. Inversely, opposite trends between effective precipitation and groundwater levels that appeared over the 1996-2019 period in the southern Seno-Turonian chalk are in the same direction this time (downward) (Figure 35 and Figure 36). In other cases, when effective precipitation display downward trends, groundwater levels also display downward trends or at least no trends, meaning that trends in effective precipitation may explain trends in groundwater levels.

5.2.1.3 Conclusion on the evolution of groundwater levels and effective precipitation in metropolitan France

In metropolitan France, we mainly observe downward groundwater levels on the two studied periods. This pattern is also observed in effective precipitation. Nevertheless, some hydrogeological entities display consistent upward trends in groundwater levels such as the limestones of Beauce (but only on the 1996-2019 period), the Seno-Turonian chalk of Artois-Picardy and the southern Jurassic limestones from Sarthe to Bessin. More locally, we also observe these upward trends in alluvial formations of Alsace (both periods), or in alluvial formations of Mediterranean region (1996-2019 period). Overall, we notice a decrease of the number of upward trends in groundwater levels on the 1976-2019 period compared to the 1996-2019 period.

In hydrogeological entities displaying homogeneous upward trends in groundwater levels, particularly in the Seno-Turonian chalk of Artois-Picardy, effective precipitation exhibit very often downward trends apart from Beauce region. It means that the decrease of groundwater recharge is not reflected in groundwater levels. One of the most probable hypothesis to explain this phenomenon would be relative to the influence of low-frequency variability on trends. Indeed, catchment and aquifers have the ability to smooth out rapid fluctuations from precipitation, and even to exacerbate the large-scale atmospheric/oceanic circulation induced low-frequency variabilities, due to their memory effect. Many researches addressed the influence of low-frequency variability on trends in surface hydrology and concluded to its heavy impact on streamflow or rainfall trends (*e.g.* Hannaford et al., 2013; Peña-Angulo et al., 2020). Therefore, the groundwater low-frequency variability could easily mask real trends induced by the decrease of recharge.

Secondly, the hydrogeological response to trends or to low-frequency variabilities is delayed in comparison to precipitation and effective precipitation, particularly when the characteristic time of aquifers is long. Therefore, this delayed response time could easily lead to opposite trends between effective precipitation and groundwater levels on similar periods.

In view of the influence of low-frequency variability on streamflow or rainfall trends, the investigation of the potential influence of groundwater low-frequency variability on trends was realised and a publication about this subject in our study area has been submitted to the Journal of Hydrology (Baulon et al., submitted). Conclusions about this study are provided in the following section.



5.2.2 Conclusions on the sensitivity of groundwater trends to low-frequency variability (Baulon et al., submitted)

Results of this study highlight the heavy influence of groundwater low-frequency variability (from multiannual to decadal) on trends estimation. The multi-temporal analysis of trends proves that upward trends displayed in the Seno-Turonian chalk of Artois-Picardy, the limestones of Beauce, and the Jurassic limestones from Sarthe to Bessin, either on one reference period or both, are not stable over time meaning that downward trends are detected on other time periods. Therefore, these upward trends are not necessarily indicative of the real evolution of groundwater levels.

Generally, aquifers displaying inertial (i.e. a predominant low-frequency variability) or combined behaviours (i.e. a well-pronounced low-frequency variability superimposed by annual variability) display unstable trends (i.e. regular changes of direction according study period). These alternative trend directions on decreasing periods (e.g. from 1976-2019 to 2000-2019) arise because the trend estimation can be started during either a multiannual high-level or a multiannual low-level, which highly influence trend direction.

Sometimes, in such contexts, stable trends can be detected (i.e. no changes of direction according study period) when an underlying trend is present. These underlying trends are very often segments of slower fluctuations that cannot be highlighted by the length of the study window. Then, the weakening of low-frequency variability observed over last decades is the second factor to get stable trends in some hydrogeological entities.

This study also indicates that multiannual (~7-yr) and decadal (~17-yr) variabilities affect the general trend in groundwater levels by driving upward or downward levels. Indeed, the multiannual variability drives upward groundwater levels in northern inertial aquifers with accentuated upward trends and attenuated downward trends; while in southern aquifers it drives downward groundwater levels with attenuated upward trends and accentuated downward trends. This north/south discrepancy may be directly related to ETP and/or aquifer properties of northern hydrogeological inertial system to interfere and reverse the influence of multiannual variability on trends (from a downward influence in precipitation to an upward influence in groundwater). Finally, the decadal variability drives downward groundwater levels in northern aquifers with attenuated upward trends and accentuated downward trends. No conclusion have been attained for southern aquifers due to the lack of data.

The degree of influence of multiannual and decadal variabilities on trends appears to be related to (i) the proportion of variance that they explain in groundwater levels, (ii) the length of the study period. Thus, the more they explain a large proportion of variance, the greater their influence on trend, and the shorter the study duration, the greater their influence on trend.

Hence, the main issues of trend studies in surface hydrology due to low-frequency variability are also perfectly highlighted in groundwater levels. Therefore, groundwater trend studies must be consider with caution to avoid misleading interpretation, including ours in the section 5.2.1., especially because the low-frequency variability can be exacerbated in aquifers compared to precipitation. It ensues that estimated monotonic trends cannot be extrapolated on other periods, nor used to predict future evolutions.

To overcome issues of the influence of low-frequency variability on trends and detect “real” trends in groundwater levels, we need to remove these variabilities from groundwater levels and effective

precipitation. Therefore, in the next section, we will use the EEMD filtering technique to identify “real” and non-linear trends in groundwater levels.

5.2.3 *Evolution of the filtered groundwater levels and effective precipitation of large-scale atmospheric circulation induced low-frequency variability*

5.2.3.1 Monotonic trend detection of filtered groundwater levels (EEMD residue) in relation to water level fluctuation

Figure 37 displays the detected monotonic trends of filtered groundwater levels (estimated with Sen’s slope) normalised by their water level fluctuation over the 1976-2019 and 1996-2019 periods. The statistical significance of trends at the threshold of 5% are also indicated on these maps. For your information, ranges of normalised trends by hydrogeological entities are presented in Table 5 and Table 6.

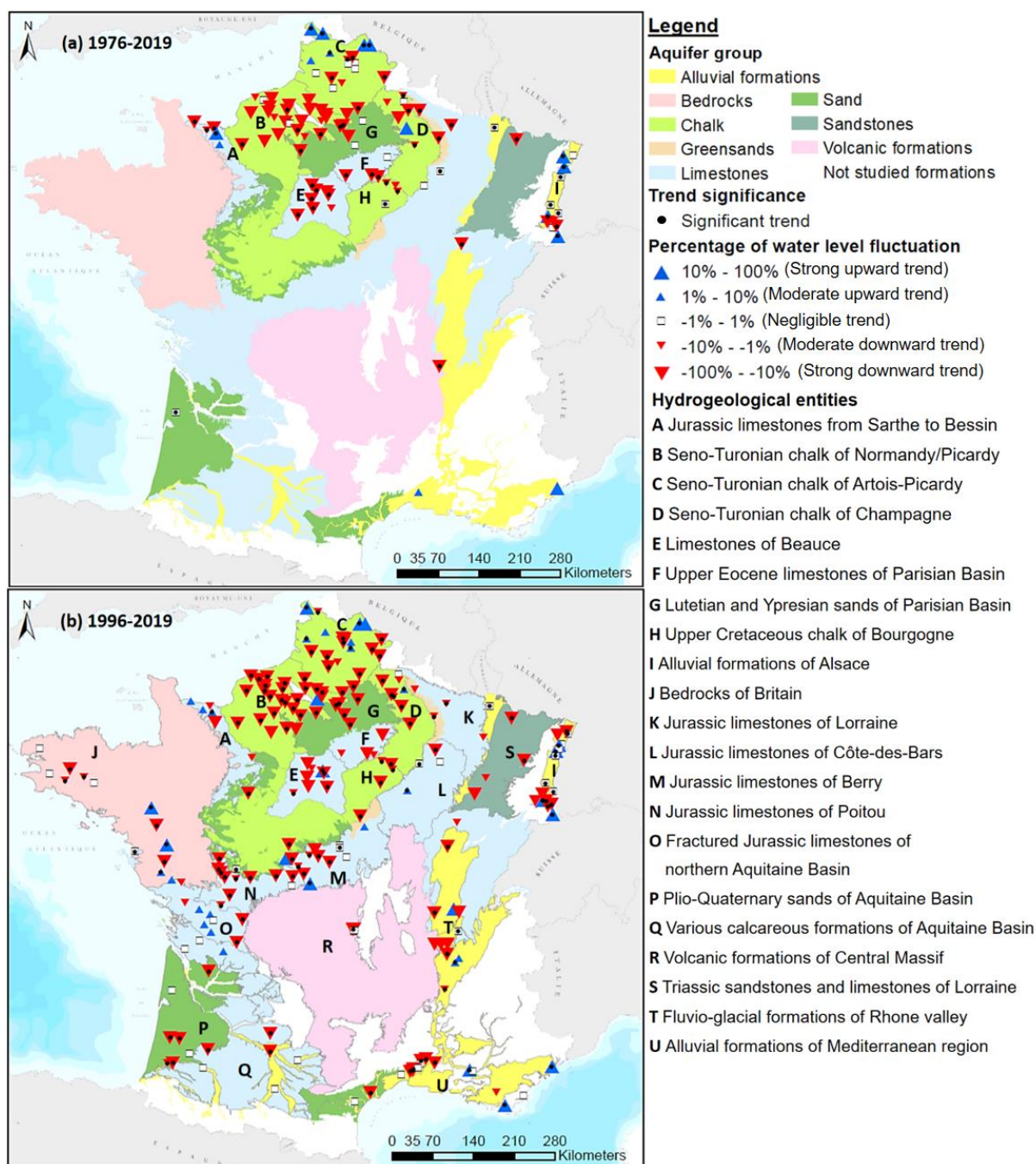


Figure 37: Trends magnitude normalised by the maximum water level fluctuation and their statistical significance (threshold of 5%) of filtered monthly groundwater levels (EEMD residue) over the 1976-2019 and 1996-2019 periods.

The overall picture of filtered groundwater levels trends at the scale of northern metropolitan France over the 1976-2019 period mainly shows downward trends (Figure 37a). Consistent statistically significant downward trends are observed in the northern part of Jurassic limestones from Sarthe to Bessin, the limestones of Beauce and the Upper Cretaceous chalk of Bourgogne. Downward trends are



also displayed in the Seno-Turonian chalk of Normandy/Picardy but they are not statistically significant excepting in the southern part of the entity. The chalk of Champagne also presents downward trends, even if there is a borehole displaying an upward trend not statistically significant. Hydrogeological entities that exhibited upward trends of raw groundwater levels also display such trends in their filtered groundwater levels as the southern Jurassic limestones from Bessin to Sarthe and the northern Seno-Turonian chalk of Artois-Picardy. Lastly, alluvial formations of Alsace still display various trends (from upward to downward).

Monotonic trends detected on the filtered groundwater levels are heavily similar in direction than those exhibited in raw groundwater levels (unfiltered) on the 1976-2019 period (Figure 37a and Figure 34a). Magnitudes of filtered groundwater trends ranges in relation to water level fluctuation remain rather similar than those of raw groundwater levels, excepting in three entities: the Lutetian and Ypresian sands of Paris Basin (reduction), the alluvial formations of Alsace (accentuation), the limestones of Beauce (reduction) (Table 5 and Table 6).

Table 5 *Normalised groundwater trends ranges on EEMD residue for the main hydrogeological entities over the 1976-2019 period.*

Hydrogeological entities	Lower bound - Slope (% of WLF)	Upper bound - Slope (% of WLF)	Number of boreholes
Seno-Turonian chalk of Artois-Picardy	-31	34	15
Seno-Turonian chalk of Normandy/Picardy	-48	0	29
Seno-Turonian and Turonian chalk of Champagne	-34	12	8
Jurassic limestones from Sarthe to Bessin	-21	16	4
Lutetian and Ypresian sands of ParisBasin	-15	0	3
Upper Eocene limestones of Paris Basin	-59	0	4
Alluvial formations of Alsace	-19	70	13
Limestones of Beauce	-37	-4	8
Upper Cretaceous chalk of Bourgogne	-7	-3	3

More discrepancies in trend direction between raw groundwater levels and filtered groundwater levels appear on the 1996-2019 period at the scale of metropolitan France (Figure 37b and Figure 34b). In the Seno-Turonian chalk of Artois-Picardy, the southern Jurassic limestones from Sarthe to Bessin or the fluvio-glacial formations of Rhone valley, filtering the low-frequency variability from groundwater levels leads to a heterogeneity of trend direction while homogeneous trends were observed on raw groundwater levels. Inversely, a consistency in trend direction is reached in the Seno-Turonian chalk of Normandy/Picardy with homogeneous statistically significant downward trends in filtered groundwater levels. A major switch of trend direction is observed in the limestones of Beauce exhibiting downward trends of filtered groundwater levels instead of upward trends in raw groundwater levels. This change of direction is also noticeable in the fractured Jurassic limestones of northern Aquitaine Basin with filtered groundwater levels displaying upward trends while insignificant trends in relation to water level fluctuation were identified in raw groundwater levels.



Filtering the groundwater low-frequency variabilities highlights a homogeneity of statistically significant downward trends in entities of Parisian Basin (the Seno-Turian chalk of Normandy/Picardy and southern Artois-Picardy Basin, the Lutetian and Ypresian sands, the chalk of Champagne and Bourgogne), the Jurassic limestones of Berry and Poitou, and even in western alluvial formations of Mediterranean region (Figure 37b).

Compared to the trend analysis on raw groundwater levels, we can observe a large number of statistically significant trends on filtered groundwater levels (Figure 34b and Figure 37b). This is certainly due to the absence of variability in groundwater EEMD residue. Indeed, a large variability in groundwater levels often leads to non-significant trends, even if their magnitude is considerable.

Filtering the low-frequency variabilities of groundwater levels can have various effects on magnitude of trends in relation to water level fluctuation: accentuation (*e.g.* the Seno-Turonian chalk of Normandy/Picardy), reduction (*e.g.* alluvial and fluvio-glacial formations of Rhone valley), little impact (*e.g.* volcanic formations of Central Massif) (Table 6 and Table 3).

Table 6 *Normalised groundwater trends ranges on EEMD residue for the main hydrogeological entities over the 1996-2019 period.*

Hydrogeological entities	Lower bound - Slope (% of WLF)	Upper bound - Slope (% of WLF)	Number of boreholes
Seno-Turonian chalk of Artois-Picardy	-44	22	18
Seno-Turonian chalk of Normandy/Picardy	-99	11	30
Seno-Turonian and Turonian chalk of Champagne	-19	7	8
Jurassic limestones from Sarthe to Bessin	-13	9	5
Lutetian and Ypresian sands of Paris Basin	-71	-47	3
Jurassic limestones of Lorraine and Côte-des-Bars	-7	10	4
Triassic sandstones of Lorraine	-81	-16	2
Upper Eocene limestones of Paris Basin	-22	-5	4
Alluvial formations of Alsace	-37	40	18
Limestones of Beauce	-24	44	8
Chalk of Bourgogne and Gâtinais	-15	-3	4
Triassic limestones of Lorraine	-2	-2	1
Bedrocks of Britain	-19	34	10
Jurassic limestones of Berry	-17	2	9
Jurassic limestones of Poitou	-40	-7	6
Fractured Jurassic limestones of northern Aquitaine Basin	-9	5	7
Alluvial and fluvio-glacial formations of Rhone valley	-24	16	11
Volcanic formations of Central Massif	-21	0	5
Various calcareous formations of Aquitaine Basin	-39	-14	3
Plio-Quaternary sands of Aquitaine Basin	-13	0	3
Alluvial formations of Mediterranean region	-35	41	12

5.2.3.2 Comparison between the detected monotonic trends of filtered groundwater levels and effective precipitation

A comparison between filtered groundwater levels (red) and effective precipitation (blue) trends magnitude and direction is established in Figure 38 and Figure 39 by means of Sen's slope over the 1996-2019 and 1976-2019, respectively. A downward stick indicates a negative Sen's slope, and an upward stick indicates a positive Sen's slope, while the stick length indicates the magnitude of trends. The statistical significance at a threshold of 5% is indicated with hatchings.

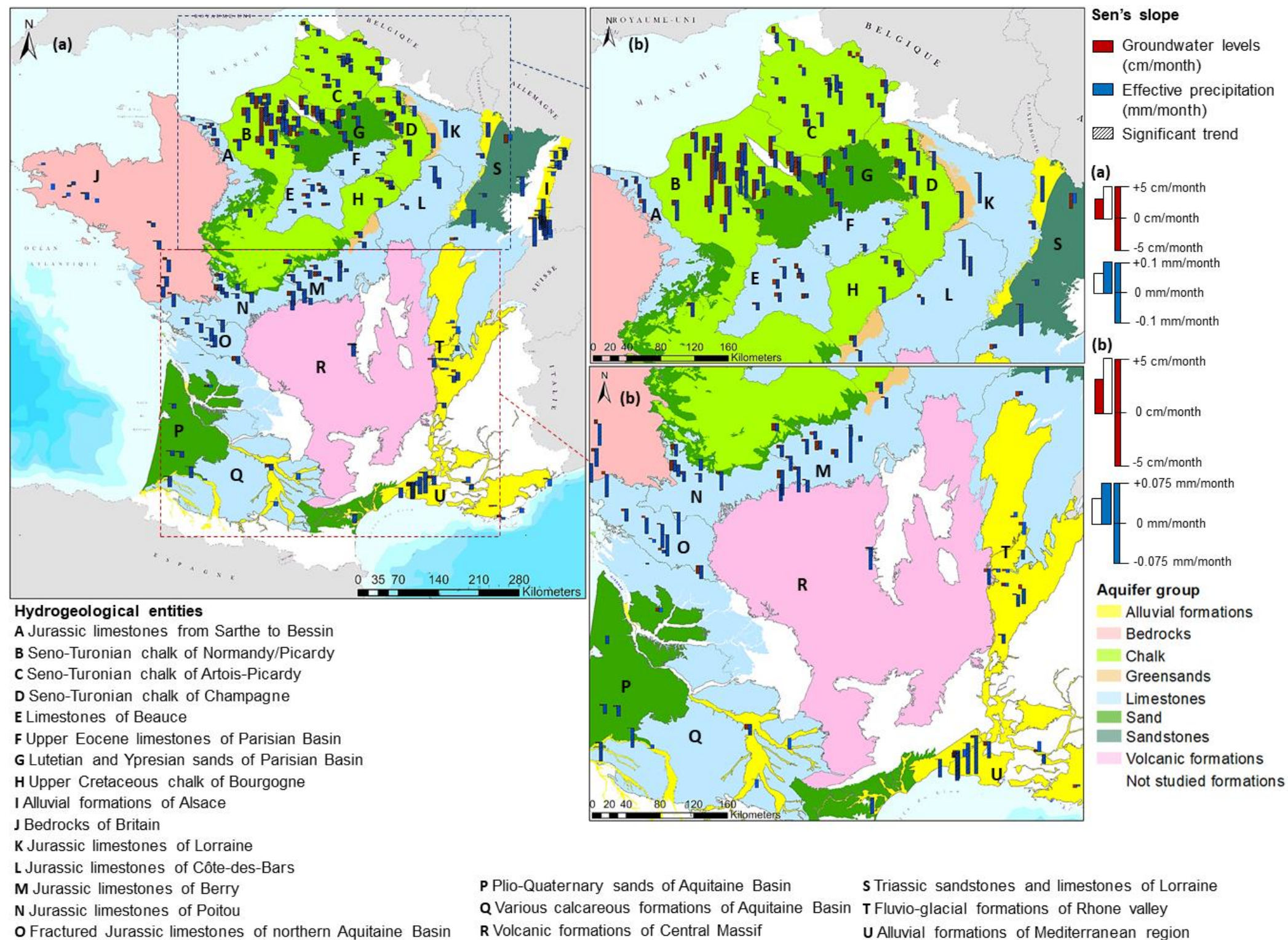


Figure 38: Comparison between Sen's slope of filtered groundwater levels and effective precipitation over the 1996-2019 period. The statistical significance of trends is tested at a threshold of 5%.



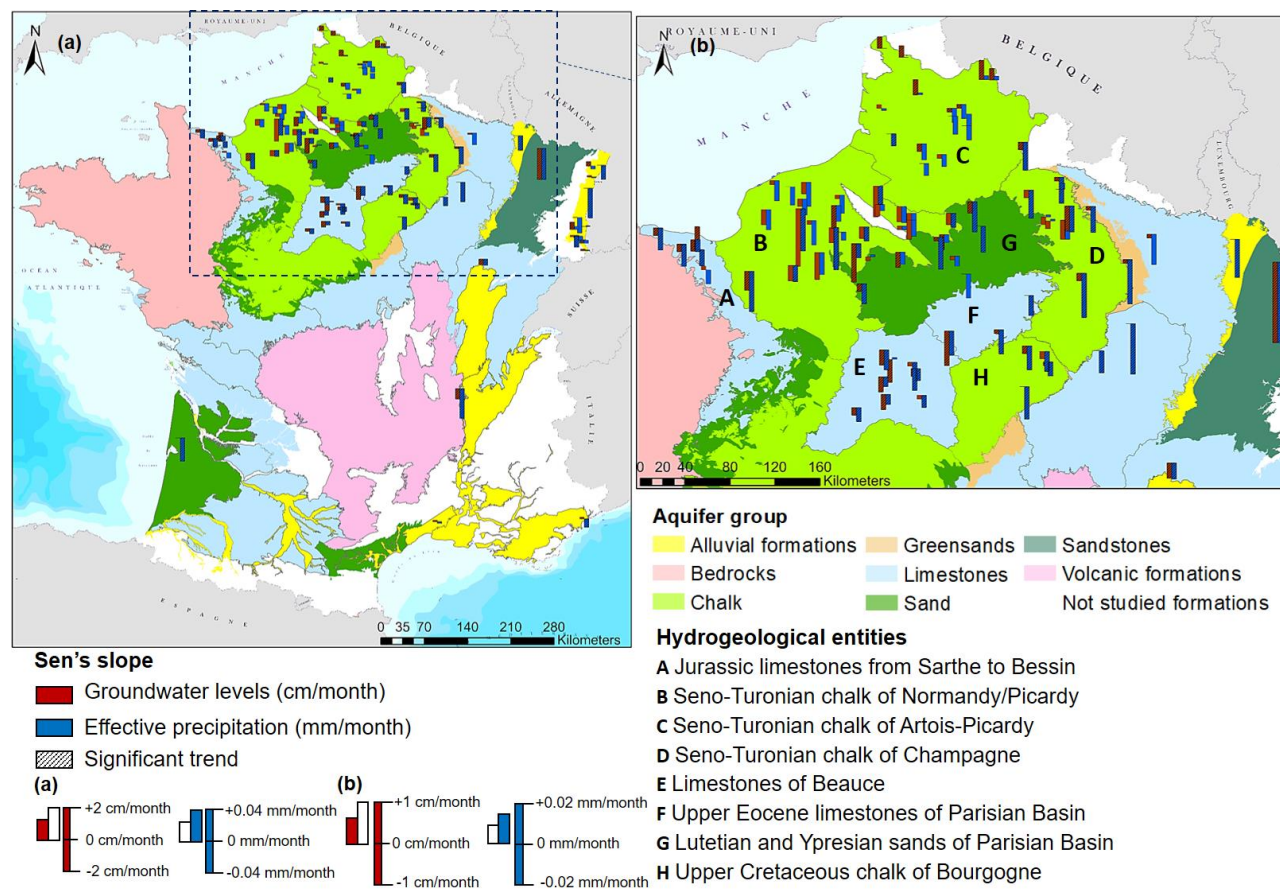


Figure 39: Comparison between Sen's slope of filtered groundwater levels and effective precipitation over the 1976-2019 period. The statistical significance of trends is tested at a threshold of 5%.



As was the case for raw effective precipitation, the filtered effective precipitation exhibit predominantly downward trends at the scale of metropolitan France over 1996-2019, which are this time widely statistically significant (Figure 38). Locally, upward trends can be displayed by filtered effective precipitation particularly in Britain.

Discrepancies that appeared when comparing trends direction of raw groundwater levels and effective precipitation remain for filtered data in northern Seno-Turonian chalk of Artois-Picardy, especially because in this part of the entity, filtered groundwater levels are still upward. Other opposite trends between filtered groundwater levels and effective precipitation appear in the fractured Jurassic limestones of northern Aquitaine Basin (upward filtered groundwater levels and downward filtered effective precipitation), some boreholes of fluvio-glacial formations of Rhone valley (upward filtered groundwater levels and downward filtered effective precipitation), bedrocks of Britain (both sides) and a few boreholes in other hydrogeological entities locally. Inversely in the southern Seno-Turonian chalk of Normandy/Picardy, the filtering of low-frequency variability in effective precipitation allows for highlighting downward trends that matches with the exhibited trends of filtered groundwater levels.

Otherwise, downward trends in filtered effective precipitation lead to downward trends in filtered groundwater levels in most cases (*e.g.* Jurassic limestones of Poitou and Berry, Plio-Quaternary sands of Aquitaine Basin, chalk of Champagne and Bourgogne).

On the longer period (1976-2019), filtered effective precipitation exhibit mainly downward trends through northern metropolitan France (Figure 39). In the northern part of the study area (*i.e.* Seno-Turonian chalk of Normandy/Picardy and southern part of Artois-Picardy basin), there are less downward trends which are statistically significant than in southern-eastern part of the study area. Locally, a few upward trends can be observed but they are marginal.

While opposite trends were exhibited on the shorter period (1996-2019) between filtered effective precipitation and groundwater levels in the northern Seno-Turonian chalk of Artois-Picardy, similar upward trends (or no trend in filtered effective precipitation) are displayed this time, which is more consistent. Opposite trends, with upward filtered groundwater levels and downward filtered effective precipitation, are noticeable sporadically in southern Jurassic limestones from Sarthe to Bessin, the alluvial formations of Alsace or the Seno-Turonian chalk of Artois-Picardy. Inversely, downward filtered groundwater levels and upward filtered effective precipitation are noticeable sporadically in the limestones of Beauce, the Seno-Turonian chalk of Champagne and Normandy/Picardy.

Overall, these opposite trends remain on this period very local meaning the good adequacy between trends in filtered groundwater levels and effective precipitation.

To better understand why such discrepancies and opposite trends are displayed between filtered groundwater levels and effective precipitation; next section will aim to describe the non-linear trends exhibited by EEMD residues of groundwater levels and effective precipitation.

5.2.3.3 Understanding the detected opposite monotonic trends between filtered effective precipitation and groundwater levels

To understand why discrepancies are observed in the detected monotonic trend direction of filtered groundwater levels and their respective filtered effective precipitation time series, a visual analysis of EEMD residues is realised (Figure 40 and Figure 41).

Thanks to this viewing, several phenomena explaining the detected opposite monotonic trends are highlighted. Firstly, we observe cases where the non-linear trend in effective precipitation does not explain the non-linear trend in groundwater levels (*i.e.* the EEMD residues display divergent shapes). In this case, several explanations may be raised:

- a wrong selection of effective precipitation mesh, and the non-linear trend in the selected effective precipitation does not explain the non-linear trend in groundwater levels.
- a long term pumping of groundwater, which may explain why the non-linear trend in groundwater levels does not reflect the non-linear trend observed in effective precipitation, the long term groundwater trend being influenced by anthropogenic activities. However, it may be a complicated task to identify boreholes and aquifers submitted to such phenomenon in view of scarcity of database describing long-term pumpings.
- a distortion of non-linear trend by the physical properties of catchment, vadose zone and aquifers. However, the use of a numerical model should be interesting to test and approve such hypothesis.

Figure 40 displays an example of the first case with detected opposite monotonic trends related to a wrong selection of effective precipitation time series for a borehole monitoring the limestones of Beauce. In this case, the shape of effective precipitation non-linear trend differs than the one exhibited in groundwater levels, meaning that the trend in effective precipitation does not explain the trend in groundwater levels (Figure 40a). Looking at other meshes and effective precipitation time series within the catchment and a 50 km radius around the well allows for identifying effective precipitation time series displaying the same type of non-linear trend than groundwater levels (Figure 40b). Therefore, it means that the indicator allowing us to select the best effective precipitation time series in relation to groundwater recharge/discharge, does not always reflect a good accordance between non-linear trends of effective precipitation and groundwater levels. Further investigations should be conducted to assign to each borehole a mesh of effective precipitation describing the best the dynamic of groundwater levels but also displaying the best agreement between long-term non-linear trends.

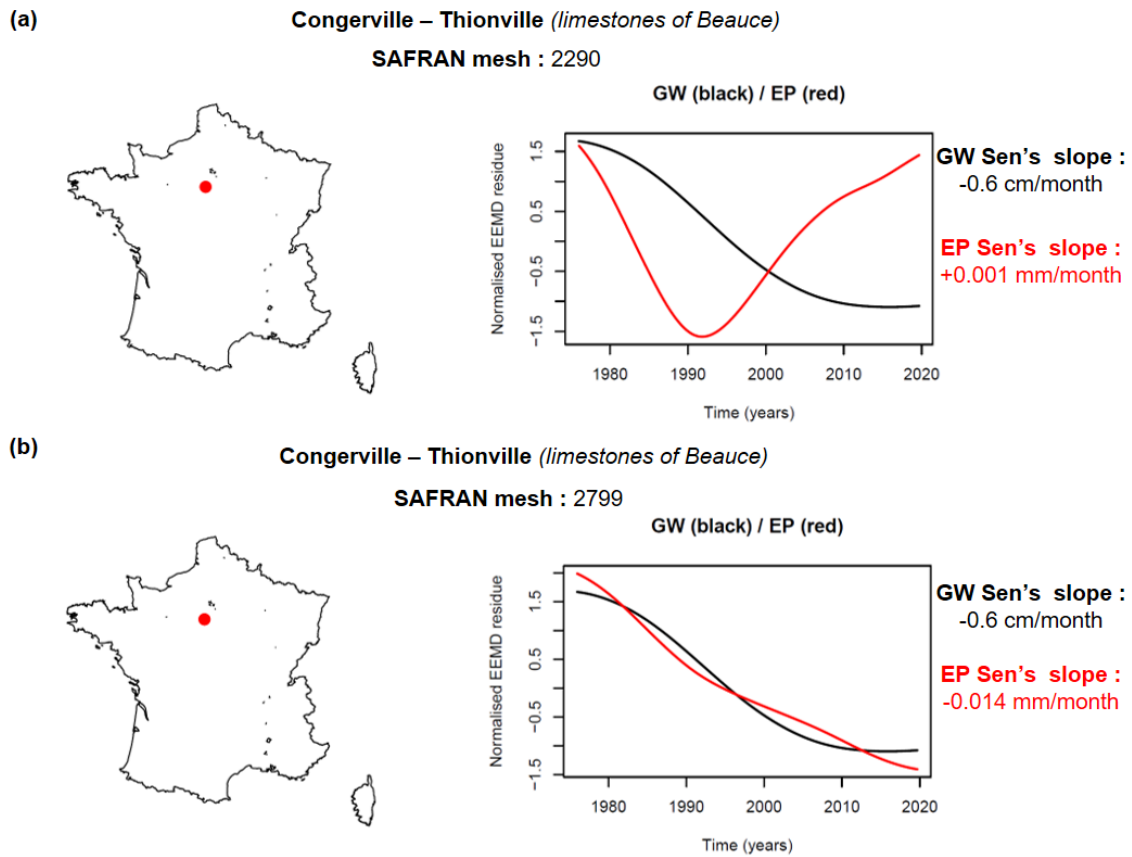


Figure 40: Standardised EEMD residues (i.e. non-linear trends) of groundwater levels (GW) for the borehole of Congerville-Thionville monitoring the limestones of Beauce and effective precipitation (EP) for (a) the selected SAFRAN mesh with the methodology presented in 5.1. to conduct the present study and (b) another SAFRAN mesh within the catchment and a 50 km radius around the well. Sen's slopes estimated on non-standardised EEMD residues of GW and EP are indicated on the right side.

Secondly, we observe cases where the non-linear trend in effective precipitation explains the non-linear trend in groundwater levels (i.e. the EEMD residues display similar shapes) (Figure 41). In this case, several explanations may be raised to justify the detected opposite monotonic trends:

- a dephasing between the two non-linear trends that may be related to the response time of aquifers to effective precipitation input.
- an amplitude modification of the non-linear trend "oscillation" by the intrinsic properties of aquifers and vadose zone.
- a discrepancy in skewness of non-linear trends that may be also related to a modification of signal by aquifers and vadose zone.

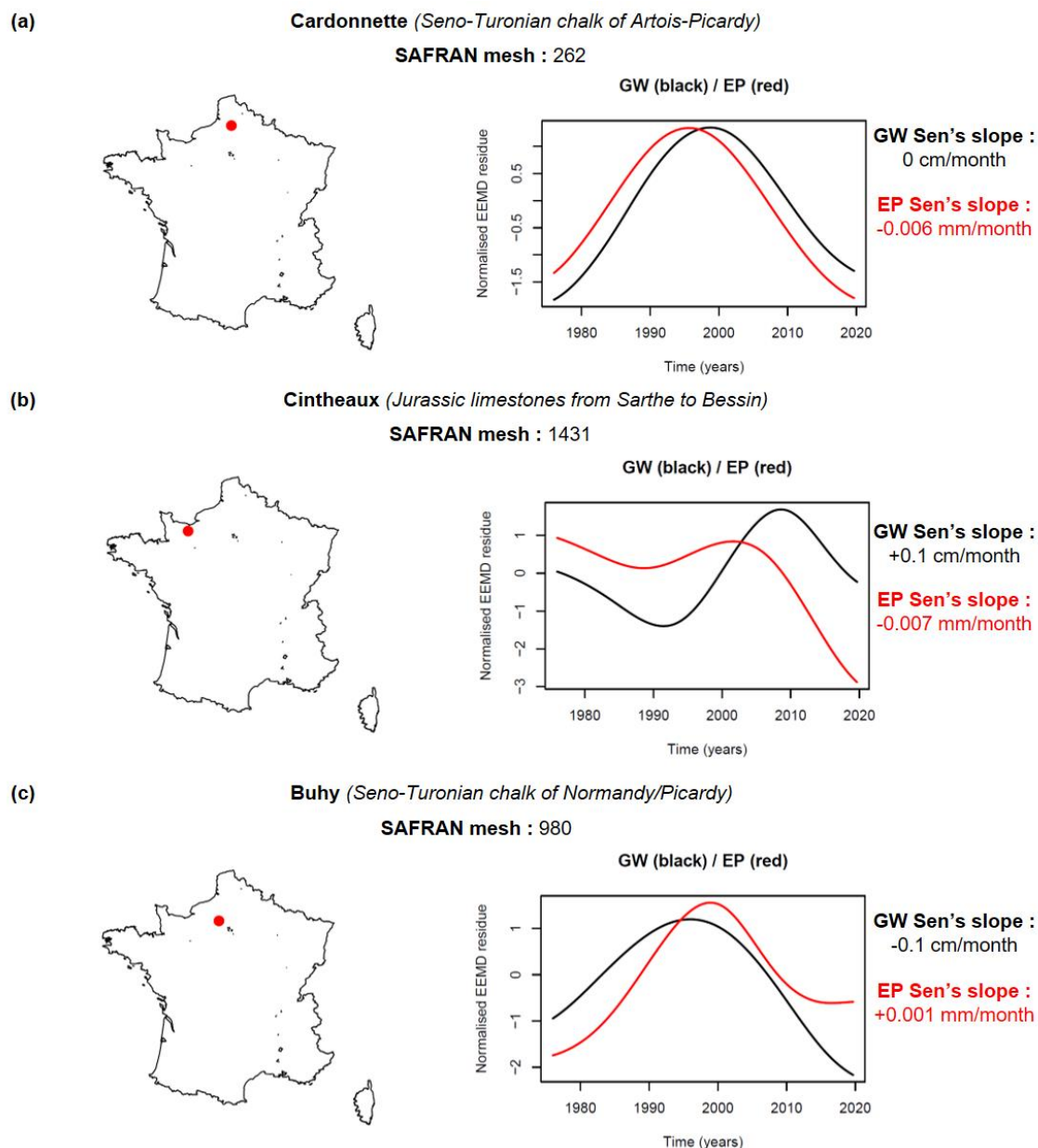


Figure 41: Standardised EEMD residues (i.e. non-linear trends) of effective precipitation (EP) and groundwater levels (GW) for the boreholes of (a) Cardonnette monitoring the Seno-Turonian chalk of Artois-Picardy, (b) Cintheaux monitoring the Jurassic limestones from Sarthe to Bessin, (c) Buhy monitoring the Seno-Turonian chalk of Normandy/Picardy. Sen's slopes estimated on non-standardised EEMD residues of GW and EP are indicated on the right side.

For instance, Figure 41 displays these three phenomena through three boreholes monitoring different hydrogeological entities. The borehole of Cardonnelle in the Seno-Turonian chalk of Artois-Picardy exhibits a typical dephasing between non-linear trends of effective precipitation and groundwater levels (Figure 41a). While the effective precipitation display a downward detected monotonic trend, the groundwater levels does not display trend due to this dephasing. In the same way, groundwater levels of Cintheaux in the Jurassic limestones from Sarthe to Bessin also display a dephasing of its non-linear trend compared to effective precipitation (Figure 41b). In addition, oscillations in groundwater levels are exacerbated compared to effective precipitation, which may be related to the physical properties of aquifers and vadose zone modulating the variance of such oscillation. These two combined phenomena explain why opposite monotonic trends are detected between groundwater levels and effective precipitation. Finally, groundwater levels of Buhy in the Seno-Turonian chalk of Normandy/Picardy and effective precipitation non-linear trends display a quite similar shape (Figure 41c). However, the discrepancy of skewness (probably related to the modulation by system properties) of EEMD residues may affect the detected monotonic trend direction and generate opposite trends.

5.2.3.4 Typical patterns of non-linear trends in groundwater levels and effective precipitation through metropolitan France

1996-2019 period

To identify typical patterns of non-linear trends of groundwater levels and effective precipitation through metropolitan France, a k-medoids clustering is conducted on EEMD residues for the two reference periods (Figure 42Figure 43Figure 44Figure 45). Figure 42 displays for each cluster all non-linear trends belonging to the cluster and the cluster medoid (*i.e.* the most representative non-linear trend within each cluster) on the 1996-2019 period. Figure 43 displays the cluster distribution through metropolitan France on the same period.

Groundwater levels can be clustered in 4 classes (medoids displaying the most central behaviour within the cluster) (Figure 42a):

- a parabolic decrease (cluster 1)
- a steady increase (cluster 2)
- a steady decrease (cluster 3)
- a serpentine shape with a decreasing trend (cluster 4)

The first cluster with non-linear trends showing parabolic decreases appears rather locally but is well represented in the limestones of Beauce, the alluvial formations of Alsace, the Triassic limestones of Lorraine, the Jurassic limestones of Berry, the bedrocks of Britain, or the Jurassic limestones from Sarthe to Bessin (Figure 43a). The second cluster with steady increases is particularly present in northern Seno-Turonian chalk of Artois-Picardy, and more locally in other hydrogeological entities such as the bedrocks of Britain, the Jurassic limestones from Sarthe to Bessin, the alluvial formations of Alsace. The third cluster with steady decreases is largely predominant in the Seno-Turonian chalk of Normandy/Picardy, the southern Seno-Turonian chalk of Artois-Picardy, the chalk of Bourgogne and Champagne, the Lutetian and Ypresian sands of the Paris Basin, the Jurassic limestones of Berry and Poitou, the Plio-Quaternary sands of



Aquitaine Basin, the Triassic sandstones of Lorraine. This pattern is present more locally in the fluvio-glacial formations of Rhone valley, the alluvial formations of Mediterranean region and Alsace, or in the bedrocks of Britain. Finally, the fourth cluster showing non-linear trends with a serpentine shape is predominant in the fractured Jurassic limestones of northern Aquitaine Basin, the Upper Eocene limestones of Paris Basin, specific sectors of fluvio-glacial formations of Rhone valley, and locally present in alluvial formations of mediterranean region.

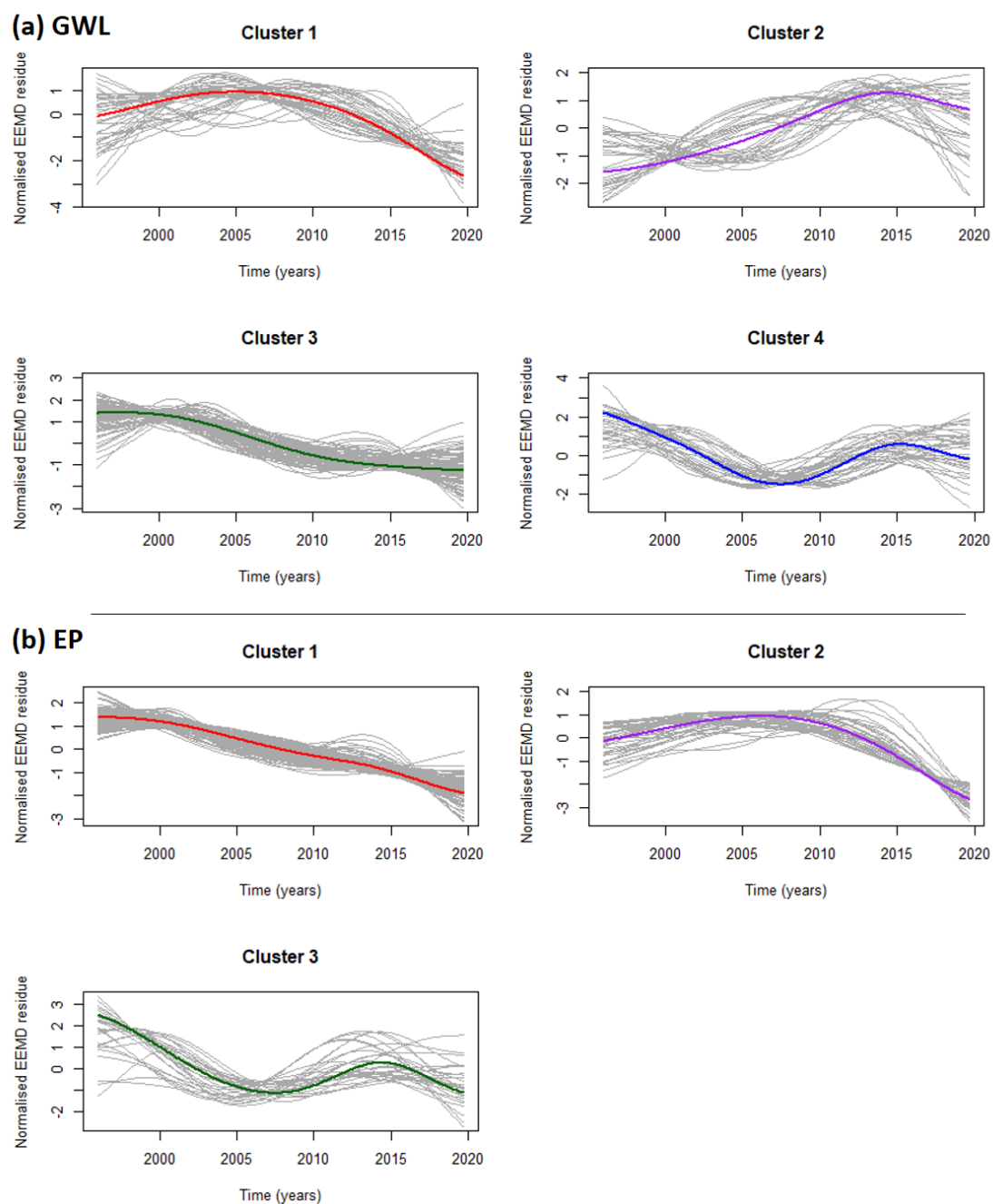


Figure 42: K-medoids clustering on non-linear trends (i.e. standardised EEMD residues) over the 1996-2019 period for (a) groundwater levels and (b) effective precipitation. Grey lines are all non-linear trends belonging to the cluster and color lines are cluster medoids (i.e. the most representative non-linear trend within each cluster).

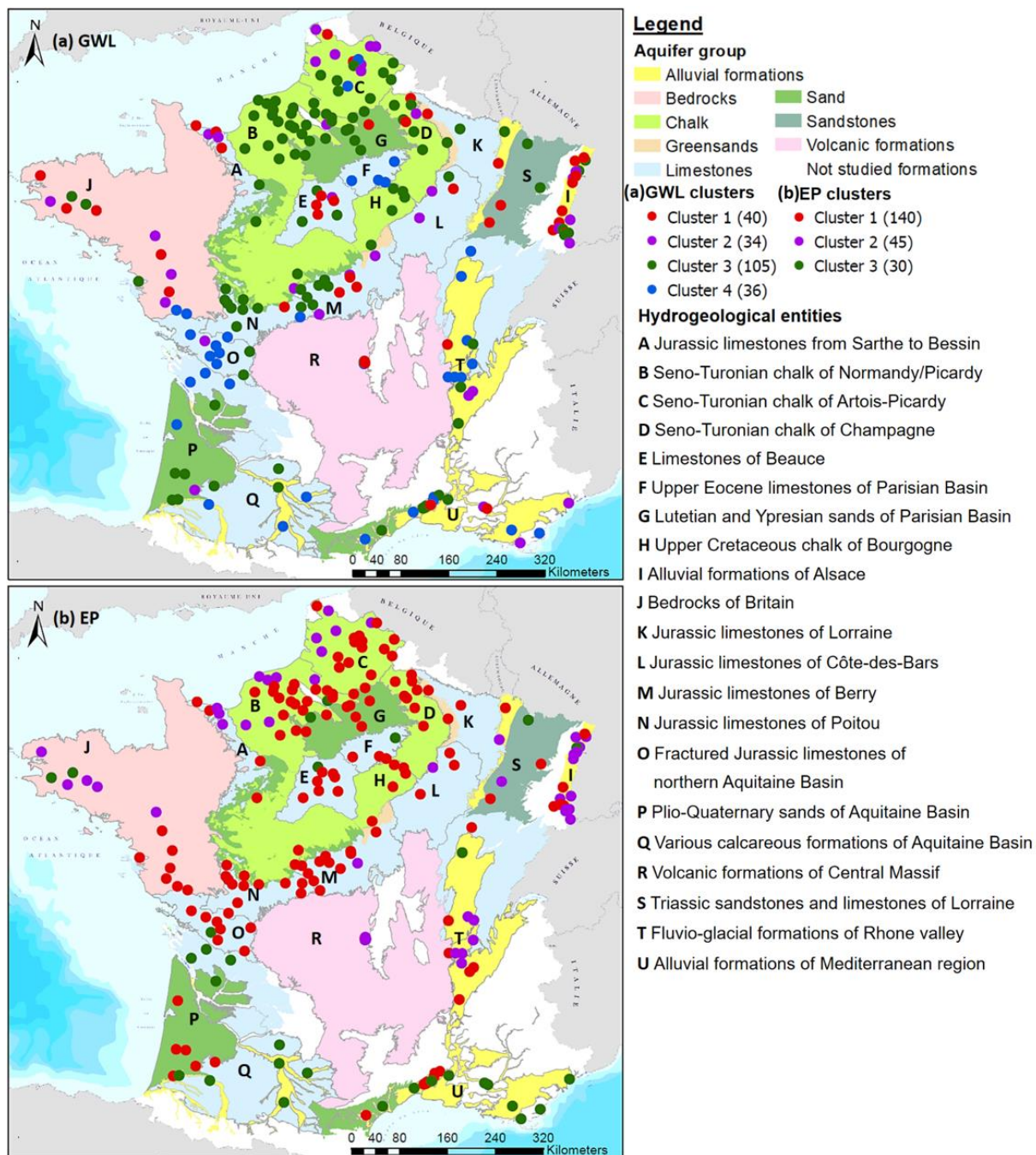


Figure 43: Spatial distribution of clustered non-linear trends over the 1996-2019 period for (a) groundwater levels and (b) effective precipitation.

Simultaneously, effective precipitation can be clustered in 3 classes (medoids displaying the most central behaviour within the cluster) (Figure 42b):

- a steady decrease (cluster 1)
- a parabolic decrease (cluster 2)
- a serpentine shape with a decreasing tendency (cluster 3)

The steady increase displaying by groundwater levels, particularly in northern Seno-Turonian chalk of Artois-Picardy, does not exist in the dataset of effective precipitation.

The first cluster displaying steady decreases of non-linear trends of effective precipitation is largely predominant in hydrogeological entities of Parisian Basin and its borders from the Jurassic limestones of Lorraine to the northern Jurassic limestones of Aquitaine Basin (Figure 43b). This type of non-linear trends are also detected importantly in southern bedrocks of Britain, the Plio-Quaternary sands of Aquitaine Basin, and specific sectors of fluvio-glacial formations of Rhone valley, alluvial formations of Alsace and Mediterranean region, and in the northern part of Jurassic limestones from Sarthe to Bessin. The second cluster with parabolic decreases is predominant in coastal watershed of Seno-Turonian chalk from Normandy to Artois-Picardy, southern Jurassic limestones from Sarthe to Bessin, northern-western bedrocks of Britain, alluvial formations of Alsace and a specific sector of fluvio-glacial formations of Rhone valley. Finally, the third cluster with non-linear trends displaying serpentine shapes is mainly present for southern hydrogeological entities such as the various calcareous formations of Aquitaine Basin, or the alluvial formations of Mediterranean region.

1976-2019 period

The same analysis is conducted on the 1976-2019 period for northern metropolitan France (Figure 44 and Figure 45). Groundwater levels non-linear trends were clustered into 3 classes (Figure 44a):

- a steady increase (cluster 1)
- a parabolic decrease (cluster 2)
- a steady decrease (cluster 3)

The first cluster with non-linear trends displaying steady increase is largely predominant in northern Seno-Turonian chalk of Artois-Picardy, southern Jurassic limestones from Sarthe to Bessin, and alluvial formations of Alsace (Figure 45a). The second cluster showing parabolic decrease of non-linear trends is largely predominant in the Seno-Turonian chalk of Normandy/Picardy, southern Seno-Turonian chalk of Artois-Picardy, the Lutetian and Ypresian sands of Paris Basin and the Seno-Turonian chalk of Champagne. This pattern of non-linear trends is also well represented in the chalk of Bourgogne. Finally, the third cluster displaying steady decrease of non-linear trends is predominant in the limestones of Beauce, the northern Jurassic limestones from Sarthe to Bessin, the eastern Seno-Turonian chalk of Artois-Picardy. This pattern is also well represented in southern Seno-Turonian chalk of Normandy/Picardy, the chalk of Bourgogne and in the various formations of Lorraine region.



Simultaneously, effective precipitation non-linear trends were clustered into 3 classes as well (Figure 44b):

- a parabolic trend (cluster 1)
- a weak increase followed by a significant decrease (cluster 2)
- a steady decrease (cluster 3)

The pattern of the first cluster with a parabolic trend is largely predominant in the Seno-Turonian chalk of Artois-Picardy or the southern alluvial formations of Alsace (Figure 45b). Locally, it appears in southern Seno-Turonian chalk of Normandy/Picardy and the chalk of Champagne. The second cluster, with non-linear trends displaying a weak increase followed by a significant decrease, is predominant in the Jurassic limestones from Sarthe to Bessin, the Seno-Turonian chalk of Normandy/Picardy, the Lutetian and Ypresian sands of Paris Basin. This pattern is also well represented in the chalk of Champagne and locally in the alluvial formations of Alsace. Finally, the third cluster with non-linear trends displaying steady decreases is predominant for southern hydrogeological entities such as the limestones of Beauce, the Upper Eocene limestones of Parisian Basin, the chalk of Bourgogne.

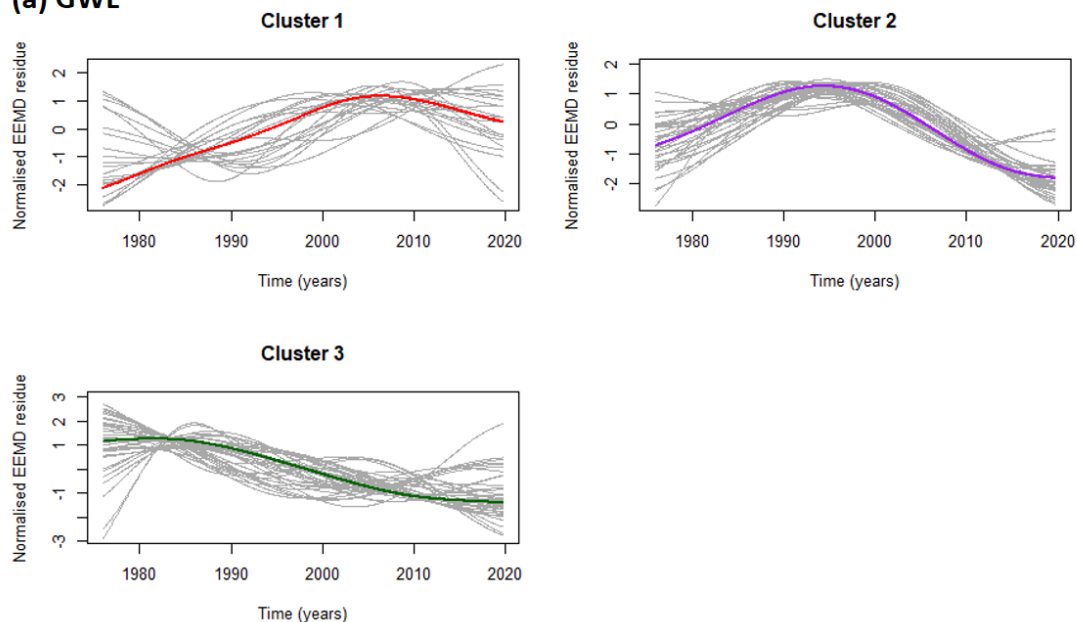
Without considering the Alsace region, the spatial distribution of effective precipitation non-linear trends clusters is rather spread according a north-south axis, with cluster 1 farthest north, cluster 2 at the middle, and cluster 3 farthest south.

Overall, this analysis highlights two different types of spatial distribution of clusters through metropolitan France and northern France between non-linear trends of groundwater levels and effective precipitation. Clusters of effective precipitation non-linear trends are spread rather according the geographical situation indicating the probable climatological influence on the detected trends (Figure 43b and Figure 45b). This is the case for the 1976-2019 period with the north-south spreading of clusters through northern France, but also on the 1996-2019 period through metropolitan France:

- the cluster 1 is predominantly spread rather on northern and western France,
- the cluster 2 is predominantly spread on coastal catchments at the border of English Channel but also on eastern France,
- the cluster 3 is predominantly spread on southern France.

For clusters of groundwater non-linear trends, their spatial distribution seems to be function of hydrogeological entities and their physical properties, even if it can differ locally due to the local variability of them (Figure 43a and Figure 45a).

(a) GWL



(b) EP

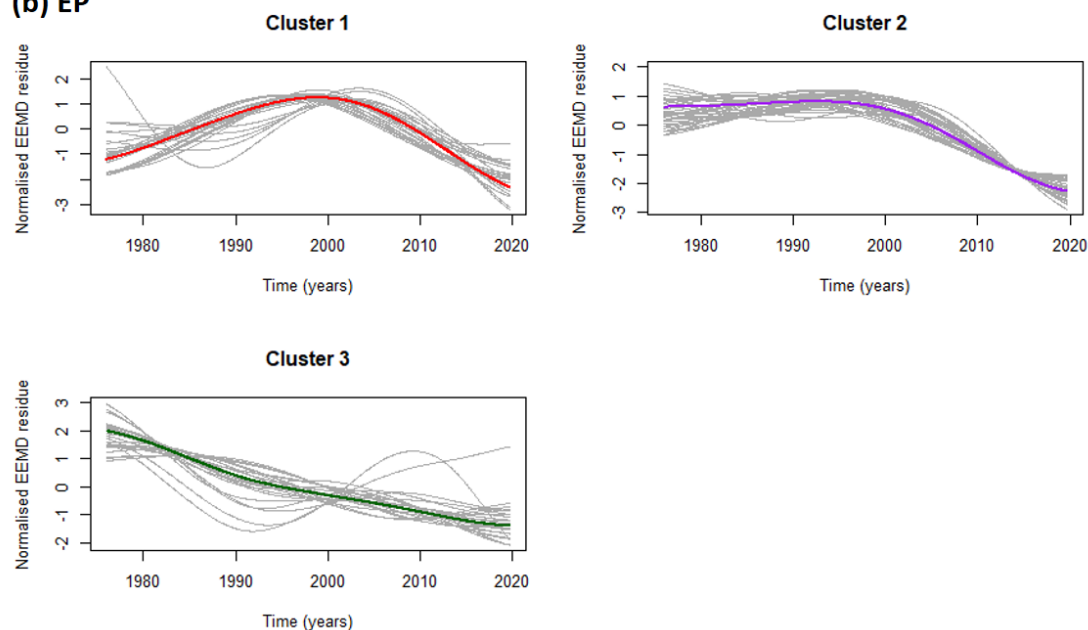


Figure 44: K-medoids clustering on non-linear trends (i.e. standardised EEMD residues) over the 1976-2019 period for (a) groundwater levels and (b) effective precipitation. Grey lines are all non-linear trends belonging to the cluster and color lines are cluster medoids (i.e. the most representative non-linear trend within each cluster).

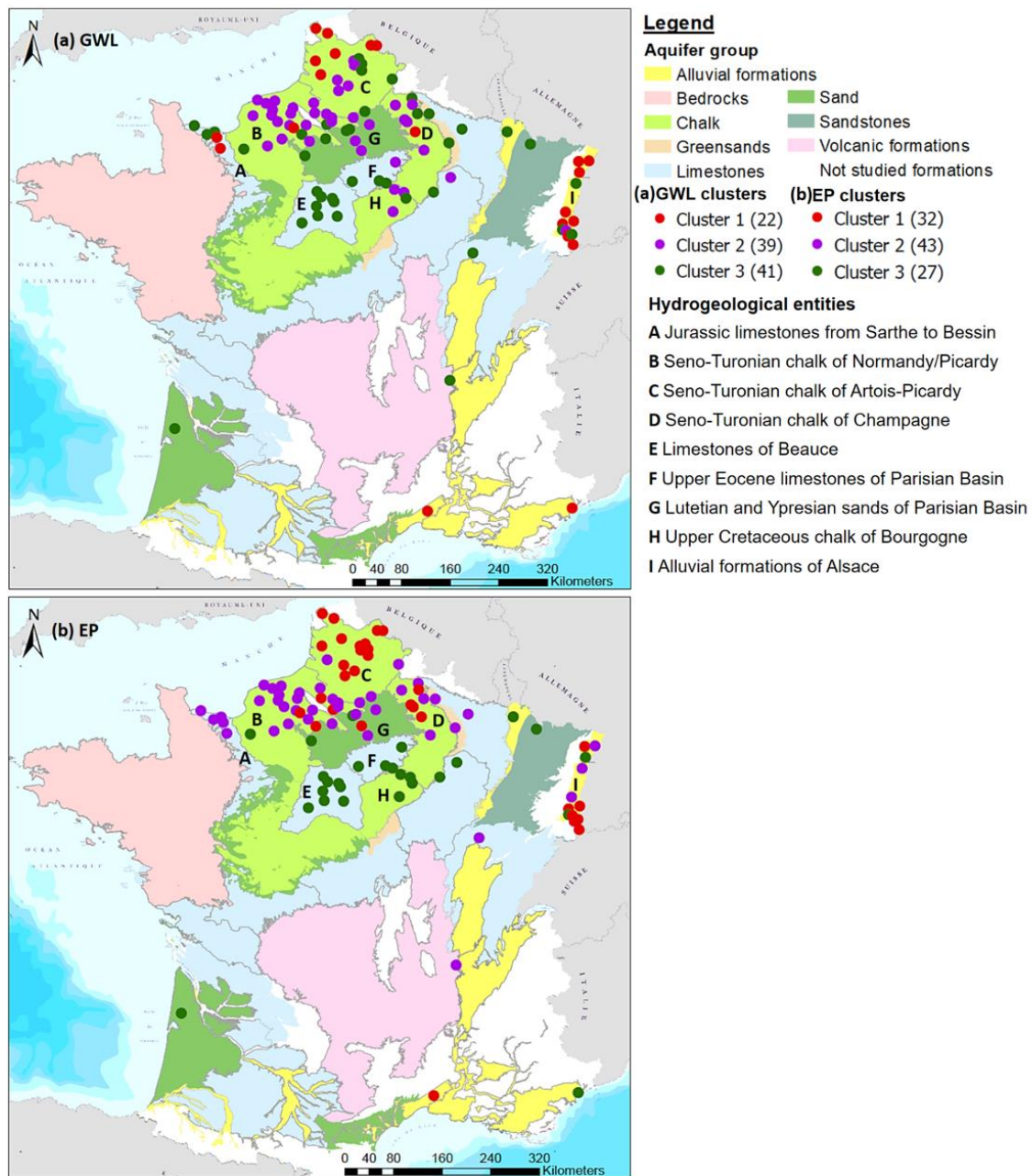


Figure 45: Spatial distribution of clustered non-linear trends over the 1976-2019 period for (a) groundwater levels and (b) effective precipitation.

Findings over the two periods

It can arise discrepancies in the accordance of non-linear trends clusters of groundwater levels and effective precipitation (Figure 42Figure 43Figure 44 Figure 45). Indeed for the 1996-2019 period, cluster 1 of groundwater levels should correspond to cluster 2 of effective precipitation, cluster 3 of groundwater levels to cluster 1 of effective precipitation, and cluster 4 of groundwater levels to cluster 3 of effective precipitation (Figure 42). However, for specific points, there is a discrepancy in this theoretical accordance. This is the case for numerous boreholes monitoring the limestones of Beauce for instance (Figure 43). While their non-linear trends display parabolic decreases (cluster 1), the non-linear trends of their corresponding effective precipitation time series display steady decreases (cluster 1). In this case, this discrepancy may be related to the dephasing between non-linear trends of effective precipitation and groundwater levels (Figure 46a). The capability of aquifers and catchment to dampen or accentuate oscillation amplitude may be also a factor to get non-corresponding clusters between groundwater levels and effective precipitation. This is what happening in the fractured Jurassic limestones of northern Aquitaine Basin, with an accentuated oscillation in groundwater levels providing a serpentine shape with a decreasing tendency to the non-linear trend (cluster 4) (Figure 46b). These oscillations are less pronounced in the non-linear trends of effective precipitation and consequently the non-linear trend belongs to the cluster with a steady decrease (cluster 1). Moreover within a cluster, it may be possible to get a large diversity of non-linear trends shape. Therefore, non-linear trends of a given borehole and its corresponding effective precipitation mesh with quite similar shape, but a bit different due to a dephasing or oscillation modulation by catchment and aquifers, can be spread in different clusters depicting by medoids with quite different shape. For instance, this is the case for the borehole of Nort-Leulinghem in the Seno-Turonian chalk of Artois-Picardy (Figure 46c). The non-linear trends of groundwater levels and its corresponding effective precipitation mesh are quite similar in terms of shape on the 1976-2019 period, but signals are lagged with an opposite asymmetry. Consequently, the groundwater levels non-linear trend is classified into the cluster for which the medoid displays steady increase (cluster 1), while effective precipitation non-linear trend is classified into the cluster for which the medoid displays a parabolic shape (cluster 1).

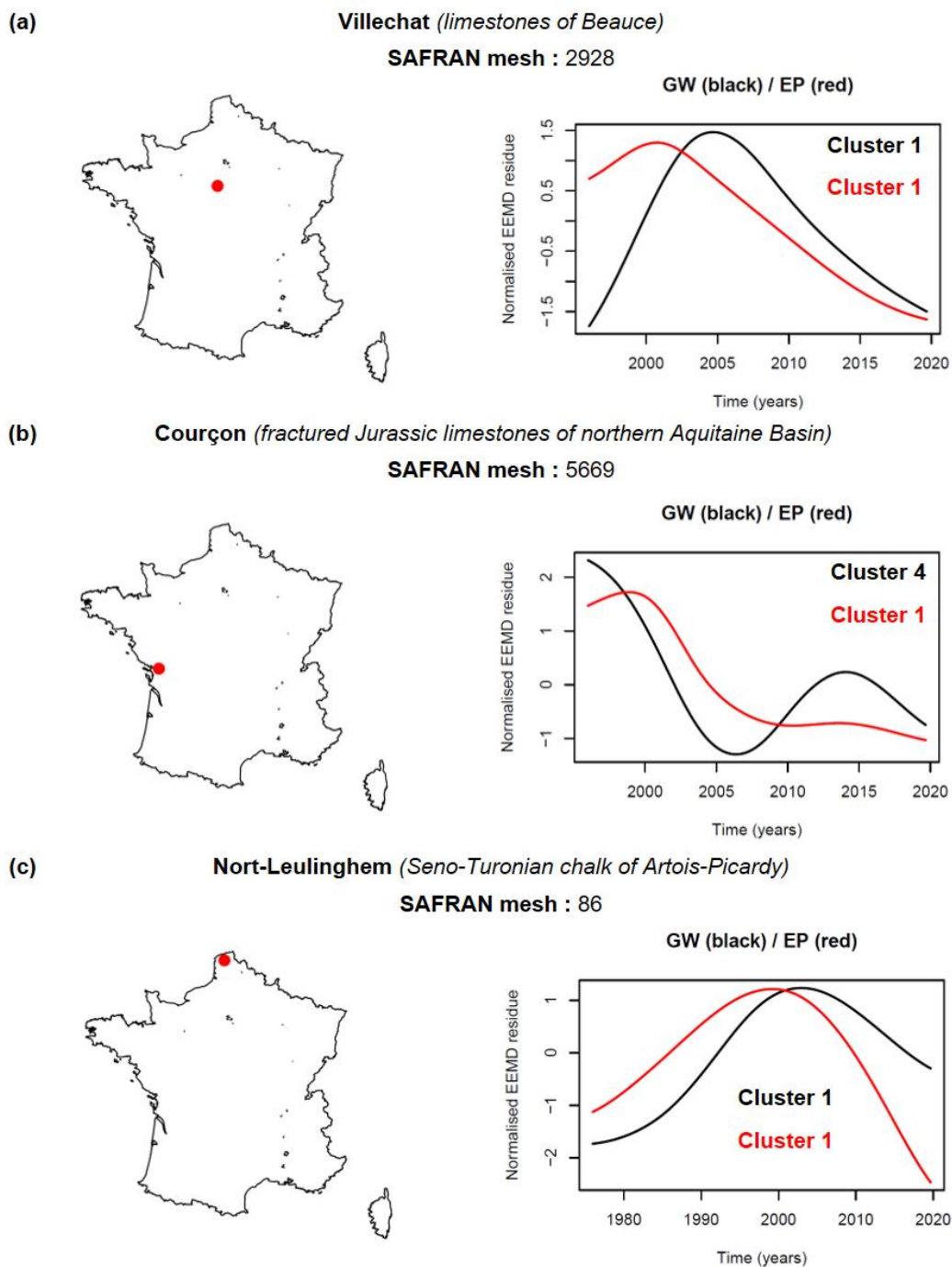


Figure 46: Examples of non-linear trends showing discrepancies in their cluster membership between effective precipitation and groundwater levels.

5.2.3.5 Non-linear trends or low-frequency variability?

The non-linear trends exhibited by groundwater levels or effective precipitation display different patterns and some of them could remind us of long-term oscillation (*i.e.* to a low-frequency variability). To determine if these non-linear trends are “trends” or a low-frequency variability that the study window does not allow us to identify as such, the non-linear trends (*i.e.* the EEMD residues) can be compared to the intrinsic oscillatory modes (*i.e.* IMF’s) extracted on a longer period. This work is realised for 3 boreholes (one per cluster). The chosen groundwater time series to achieve this work display non-linear trends that are quite explained by the non-linear trends of effective precipitation (Figure 47).

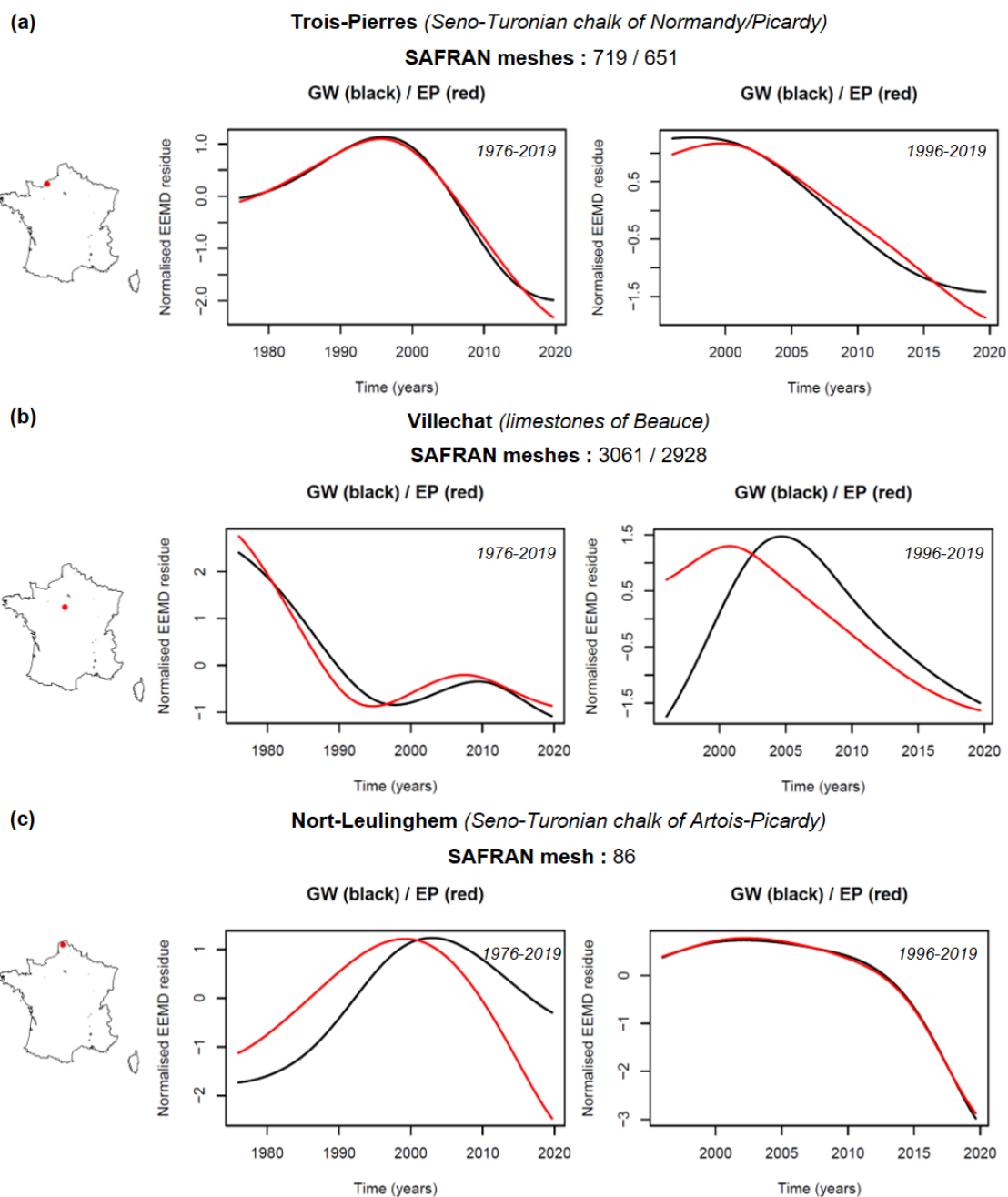


Figure 47: Boreholes chosen to determine if non-linear trends are “trends” or low-frequency variability. This figure displays groundwater non-linear trends (black) on the two reference period and the non-linear trend of their corresponding effective precipitation timeseries (red).



The comparison between EEMD residues extracted on “short periods” and IMFs (*i.e.* empirical modes) extracted on longer periods highlights the similarity between the non-linear trends and low-frequency variabilities (Figure 48). In these three cases, each non-linear trend appears to be a segment of a lower-frequency fluctuation. This is particularly striking for the borehole of Villechat in the limestones of Beauce with a non-linear trend over the 1996-2019 period exhibiting a similar behaviour than the ~24 years empirical mode over the 1976-2019 period (Figure 48b). Although the covariability of non-linear trends and the last empirical modes (IMF) extracted on longer periods is less pronounced for boreholes of Trois-Pierres and Nort-Leulinghem in the Seno-Turonian chalk of Normandy and Artois-Picardy, respectively, than the borehole of Villechat, they still display quite similar shape (Figure 48a and Figure 48c). This result means that although EEMD methods may be a good approach to filter redundant oscillations, they do not have the capacity to filter oscillations at a larger scale than the study window. Therefore in our case, the detected non-linear trends are still trends generated by low-frequency variability, but over our short study periods they are not considered as low-frequency variabilities. Such conclusions are reached also on other variables such as streamflows by Massei and Fournier (2012) or Palmer Drought Severity Index by Song et al. (2020), with non-linear trends that may be related to large-scale atmospheric and oceanic circulation low-frequency variabilities or well-known climate indices meaning the potential reversibility of such trends.

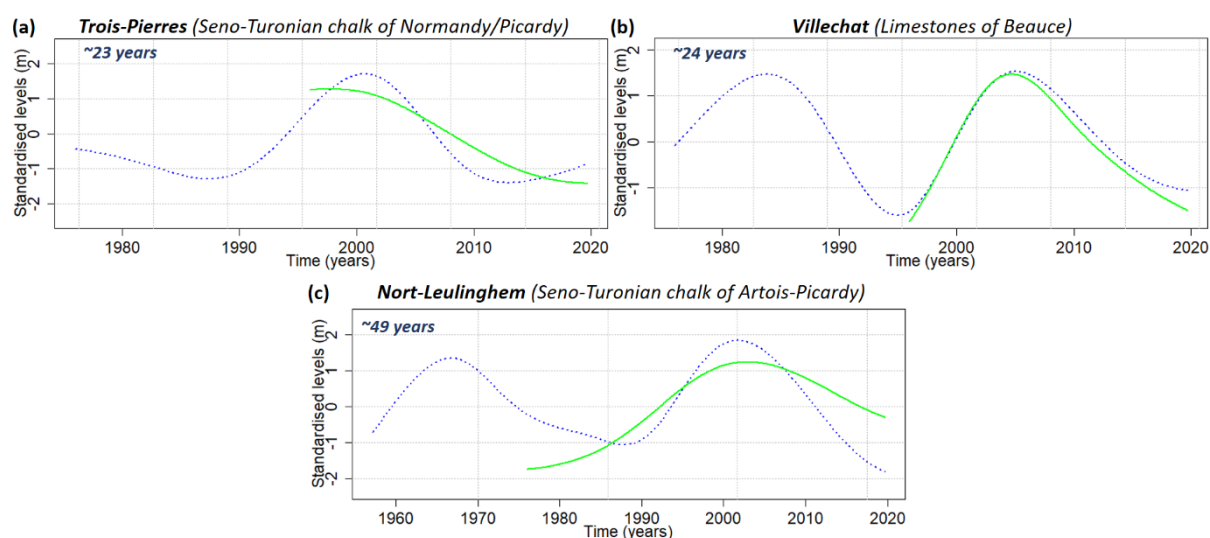


Figure 48: EEMD residues (solid green) extracted on shorter periods superimposed to the last IMFs (dashed blue) extracted on a longer period.

5.2.3.6 Conclusion on the evolution of the filtered groundwater levels and effective precipitation

The study of filtered groundwater levels and effective precipitation has been done via several approaches: (i) the estimation of monotonic trends on these filtered data (*i.e.* EEMD residues or



non-linear trends), (ii) the clustering of these non-linear trends, (iii) the questioning of if these non-linear trends are “trends” or only segments of lower frequency variabilities.

The monotonic trends detected on filtered data reveal few differences with monotonic trends estimated on raw data (*i.e.* unfiltered data) on the longest reference period (1976-2019), particularly for groundwater levels. However on shorter period (1996-2019), greater discrepancies appear with monotonic trends estimated on raw data: magnitudes of trends are very often accentuated and even trend direction can be impacted. The filtering of low-frequency variability widely impacts the significance of trends, with lots of non-significant trend on raw data becoming significant on filtered data. This phenomenon may be related to data variability that is considerably reduced in filtered data and consequently no longer affects the significance of trends. Therefore, filtering low-frequency variability or not from data can lead to different results in terms of trend magnitude, direction and significance inducing different interpretations.

The opposite detected monotonic trends between filtered groundwater levels and effective precipitation may be related to several phenomena: (i) a wrong selection of effective precipitation mesh at the beginning of the analysis leading to a non-linear trend in effective precipitation that does not represent the non-linear trend in groundwater levels, (ii) a long-term anthropogenic influence on aquifers (*e.g.* long-term pumping) and the non-linear trend of groundwater levels no longer represents the one of effective precipitation, (iii) a dephasing between the non-linear trend of groundwater levels and effective precipitation due to the response time of aquifers, (iv) a distortion or modulation of oscillation amplitude induced by catchment and aquifers properties, (v) asymmetry discrepancies between non-linear trends of groundwater levels and effective precipitation also induced by catchment and aquifer properties.

The clustering of groundwater and effective precipitation non-linear trends exhibits a heavy predominance of decreasing patterns for both variables. Increasing patterns of non-linear trends are only displayed by groundwater levels, particularly in the Seno-Turonian chalk of Artois-Picardy, and more locally in other hydrogeological entities. Overall, spatial distribution maps of effective precipitation non-linear trends patterns reveals a spread according to geographical location, with a good spatial homogeneity of clusters. For groundwater levels non-linear trends, the spread of clusters seems to be more as a function of hydrogeological entities, and their physical properties at local or regional scale.

Generally, we expect a well accordance between groundwater levels and effective precipitation clusters for a given borehole and its corresponding precipitation mesh, because non-linear trends are quite similar. In many cases, this assumption is true, but sometimes this is not the case and several explanations can be arised involving the capability of catchment, vadose zone and aquifers to modulate and delay oscillations from effective precipitation.

Finally, the non-linear trends detected in groundwater levels appear to be part of lower frequency variabilities. Although EEMD method is a usefulness tool to filter the low-frequency variability, and therefore to limit its influence on the trend estimation, it does not have the capacity to filter an oscillation at a larger scale than the study window. Therefore, monotonic trends that were estimated on EEMD residues are still impacted by low-frequency variability and



underline it. Since large-scale atmospheric and oceanic oscillations are expressed over a wide range of timescales, any groundwater trend could be the result of a slower fluctuation (Rossi et al., 2011). For instance, the Atlantic Multidecadal Oscillation (AMO) oscillates on ~60 years timescales (Kerr, 2000; Enfield et al., 2001). Thus, the youth of French piezometric networks does not, in most cases, allow us to grasp such low-frequency timescale as a fluctuation, but it can grasp it as a trend. Therefore, it highlights the complexity to define whether trends in hydroclimate variables can be related to climate change or simply being part of a lower-frequency oscillation originating from large-scale atmospheric or oceanic circulation. It can be even more complicated when working on groundwater levels that are also subjected to significant long-term anthropogenic pressures (*e.g.* pumping) not necessarily well referenced.

In summary, multiple interpretations of groundwater level trends can be made. These trends may be linked to (i) anthropogenic impacts (*e.g.* groundwater pumping, changes in land cover that may generate a decrease in groundwater recharge), (ii) climate change that may result in a decrease in groundwater recharge, (iii) a segment of low-frequency oscillations which could appear as a trend on the short-term. Without taking into account the anthropogenic impacts (which data are often poorly referenced), the most limiting factor to make the distinction between points (ii) and (iii) remains the availability of groundwater levels data and the length of time series. Works on groundwater levels reconstruction might overcome this constraint via, for instance, deep learning approaches or tree-ring-based reconstruction (Vu et al., 2020; Tegel et al., 2020). However, differentiate between climate change or variability associated to large-scale atmospheric or oceanic circulation could remain difficult, even with longer timeseries, because anthropogenic forcing may also impact these large-scale patterns (*e.g.* Dong et al., 2011; Caesar et al., 2018).

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