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Version of Record: https://www.sciencedirect.com/science/article/pii/S0022169422000117
Manuscript_3745665b4fec66e2a36a7865a812f472

Influence of low-frequency variability on groundwater level trends

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Abstract

Estimating groundwater level evolution is a major issue in the context of climate change. Groundwater is a key resource and can even account in some countries for more than half of the water supply. Groundwater trend estimates are often used for describing this evolution. However, the estimated trend obviously strongly depends on available time series length, which may be caused by the existence of long-term variability of groundwater resources. In this paper, using a groundwater level database in Metropolitan France as an example, we address this issue by exploring how much trend estimates are sensitive to low-frequency variability of groundwater levels. Database consists of relatively undisturbed groundwater level time series regarding anthropogenic influence (water abstraction by either continuous or periodic pumping). Frequent changes in trend direction and magnitude are detected according to time series length, which can eventually lead to contradictory interpretations of the groundwater resource evolution, as presented in first part of this article. To assess whether low-frequency variability – known to originate from climate variability – can induce such modifications of trends, we explored in a second step the multi-time scale variability of groundwater levels using a methodology based on discrete wavelet transform. Most of the time series displaying changing trends depending on time series length corresponded to aquifers with high-amplitude low-frequency variability of groundwater levels. Two

predominant low-frequency components were detected: multi-annual (~7 years) and decadal (~17 years). We finally examined how much those two low-frequency components may affect trend estimates on the longer time period available. For this purpose, we individually removed each of both components from the original times series by discrete wavelet filtering and re-estimated trends in the filtered groundwater level time series. The results showed that the groundwater level trends were highly sensitive to the presence of any of these low-frequency components, which may then strongly influence the estimated trends either by exaggerating or mitigating them. These results emphasize that i) attributing the estimated trends only to climate change would be hazardous given the large influence of low-frequency variability on groundwater level trends, ii) estimation of trends in hydrological projections resulting from GCM outputs in which low-frequency variability is not well represented would be subject to strong uncertainty, iii) a potential change in the amplitude of internal climate variability – e.g. increasing or decreasing low-frequency variability – in the next decades may lead to substantial changes in groundwater level trends.

Keywords

Low-frequency variability; Groundwater level trends; Metropolitan France; Maximum overlap discrete wavelet transform

1. Introduction

According to Iliopoulou and Koutsoyiannis (2020), the number of scientific publications using the word "trend" has steadily increased over the past two decades, especially in relation to hydroclimatological variables. Various scientific questions and aims can lead scientists to search for trends in hydrological processes. The assessment or forecasting of the qualitative and quantitative evolution of environmental variables – such as detecting short- to long-term increases or decreases – are part of this (Visser et al., 2009; Giuntoli et al., 2013; Sakizadeh et al., 2019; Caporali et al., 2020; Dudley et al., 2020). These questions are related to resource preservation issues in the context of global change. For instance, the

European Union's Water Framework Directive is based on this philosophy: detect negative trends in water resources (streamflow and groundwater levels) with the aim of their protection (European Commission, 2009); deterioration of a resource can cause restrictions on freshwater withdrawals.

In the context of climate change, assessing the long-term evolution of hydrological variables and associated extremes is a major issue, particularly for identifying which parts of this evolution can be attributed to climate change and to anthropogenic forcing (Massei et al., 2020). For groundwater, this issue is even more relevant when considering pumping; for instance, groundwater provides 65% of the water supply in France (Chataigner et al., 2019). Hence, the study of long-term groundwater level evolution is especially relevant for management purposes and the knowledge of groundwater resource capacity. Methods for identifying linear or monotonic trends are commonly used for describing changes in hydrological variables (Stahl et al., 2010; Lorenzo-Lacruz et al., 2012; Blöschl et al., 2019; Pathak and Dodamani, 2019; Vicente‐Serrano et al., 2019; Mohanavelu et al., 2020; Peña-Angulo et al., 2020).

Although the detection of monotonic trends is a widely used tool for quantifying evolution of hydrological variables, its use may still raise questions. First, they cannot be extrapolated to other study periods, and longer or shorter periods, regardless of the type of variable considered (Koutsoyiannis, 2006; Burn and Whitfield, 2018). For a given region, authors commonly find contradictory or varying results as trends are often not estimated over the same periods, a point that is often discussed as a major issue (Hannaford et al., 2013; Degefu et al., 2019). Therefore, their "non-extrapolability" makes them poor predictors and unsuitable for forecasting (Iliopoulou and Koutsoyiannis, 2020). Second, trends commonly reflect long-range dependence/autocorrelations, because of low-frequency variability in the hydroclimatic variables of interest (Iliopoulou and Koutsoyiannis, 2020). Such variability generated by large-scale atmospheric and oceanic circulation patterns is the primary source of a "misperceived" trend, as short-term periods affected by a trend may actually be part of longer-term fluctuations. Multi-temporal trend-definition methods have been developed to highlight this dependence of trend assessment on low-frequency variability (multi-annual–multidecadal) in hydroclimatic variables and to

avoid trend "misperceptions" (McCabe and Wolock, 2002; Schmocker-Fackel and Naef, 2010; Hannaford et al., 2013; Stojković et al., 2014; Peña-Angulo et al., 2020). For instance, Hannaford et al. (2013) demonstrated that trend direction and magnitude are highly influenced by interdecadal variability.

Given the influence of interdecadal variability, and more generally low-frequency variability, on the hydrological trends, it is crucial to better understand the large-scale origin of these fluctuations and how catchments can filter and modify them. In this regard, Gudmunsson et al. (2011) indicated that the low-frequency variability of runoff directly originates from the large-scale atmospheric circulation, while the catchments properties control the proportion of variance of low-frequency variability in hydrological variables. Simultaneously, a large amount of studies addressed the large-scale origins of such variabilities in hydroclimatic variables (streamflow, precipitation, groundwater, temperature), using climate indices and atmospheric fields (Massei et al., 2010; Boé and Habets, 2014; Dieppois et al., 2013; Dieppois et al., 2016; Massei et al., 2017; Neves et al., 2019; Liesch and Wunsch, 2019).

Across the whole metropolitan France area, Fossa et al. (2021) detected ~3-yr and ~7-yr variabilities in streamflow, precipitation and temperature but with fluctuating amplitudes depending on the region. At a smaller regional scale, particularly in the Seine watershed, many studies previously highlighted these same two low-frequency variabilities in precipitation and streamflow as well as a ~17-yr variability (Massei et al., 2007; Massei et al., 2010; Fritier et al., 2012; Massei and Fournier, 2012; Dieppois et al., 2013; Massei et al., 2017). The North Atlantic Oscillation (NAO) was described as one significant driver of such temporal signature (~7-yr and ~17-yr) in precipitation and streamflow (Massei et al., 2007; Massei et al., 2010). Later, Massei et al. (2017) highlighted using a composite analysis with Sea Level Pressure (SLP) that the atmospheric pattern associated to the ~7-yr variability was not exactly reminiscent of the NAO, with centers of action actually shifted to the North. Similarly, the pattern associated to ~17-yr variability was a spatially extended pattern across the Atlantic ocean with lower SLP roughly following the Gulf Stream front. This result highlighted that atmospheric patterns

107 associated to ~7-yr and ~17-yr variabilities are not similar and these atmospheric patterns exhibit centers
108 of action that are not necessarily corresponding to those of established climate indices such as the NAO.
109
110 Aquifers very often act as rather strong low-pass filters, leading to high-amplitude low-frequency
111 variability in groundwater levels. In other words, aquifers filter out high-frequency (short-term)
112 variations of the precipitation input more or less significantly, letting only low-frequency (longer-term)
113 variations dominate the overall variability of the groundwater level signal. Some studies also
114 investigated the role played by geological characteristics in controlling the magnitude of these
115 fluctuations in groundwater levels: thickness of superficial formations, of the vadose zone, hydraulic
116 properties of aquifers (Slimani et al., 2009; El Janyani et al., 2012; Velasco et al., 2017). In Normandy,
117 Slimani et al. (2009) and El Janyani et al. (2012) identified a significant ~7-yr variability in groundwater
118 levels of chalk aquifer consistent with many previous works that had already documented the presence
119 of both ~7-yr and ~17-yr variabilities, and their link to the NAO in northern France on precipitation
120 (Massei et al., 2007) or river flow (Massei et al., 2010, 2012, 2017). Later, the exact same multi-annual
121 and decadal fluctuations were also identified in groundwater levels in Great Britain (Rust et al., 2019)
122 and on the western European continent (Liesch and Wunsch, 2019; Neves et al., 2019).
123
124 In this article, we specifically addressed the issue of the influence of low-frequency variability on
125 groundwater level trend estimates. In metropolitan France, for instance, many changes in trend direction
126 and magnitude were observed depending on the length of time series considered, thus leading to
127 completely contradictory conclusions on groundwater level evolutions, as exposed in section 3.1. In
128 some surface hydrology studies (e.g. Hannaford et al., 2013, as mentioned previously), such
129 contradictory conclusions were related to low-frequency variability. Therefore as a second step, we
130 aimed to determine whether French aquifers concerned by these regular changes in trend direction and
131 magnitude, exhibited a significant low-frequency variability in groundwater levels. In section 3.2., we
132 thus broke down groundwater level signals using discrete wavelet transform and quantified the variance
133 percentage of total signal explained by each time scale of variability. Finally, in a third step, we
134 examined if and how low-frequency variability influenced trend estimates by filtering out each low-

frequency component from the original time series using discrete wavelet transform and re-estimating trends on filtered time series (Section 3.3.). This last point is particularly important because if the low-frequency variability significantly influences the estimated groundwater level trends, this has several implications:

(i) First, regarding the identification of traces of climate change in groundwater levels. Indeed, if the low-frequency variability in groundwater levels significantly affects trend estimates, it is hazardous to conclude that, for instance, a decreasing evolution of groundwater levels is directly the result of climate change. Indeed, such trends would then be primarily the result of internal climate variability instead of anthropogenic climate change.

(ii) Second, regarding future projections. Indeed, trend estimates in hydrological projections resulting from GCM outputs in which low-frequency variability is not well represented would be subject to strong uncertainty.

(iii) Third, regarding future evolutions. Indeed, a potential change in the amplitude of internal climate variability – e.g. increasing or decreasing low-frequency variability – in the next decades may lead to substantial changes in groundwater level trends.

2. Data and methods

2.1. Data

2.1.1. Groundwater data

For this study, we used 215 boreholes in continental France, with groundwater level time series being little or not affected by pumping (Fig. 1). They were selected from a BRGM database on boreholes not influenced by human activities (Baulon et al., 2020) that was constituted in three steps:

(i) a selection of boreholes with time series satisfying criteria of duration, minimum amount of data per month, maximum length of gaps;

(ii) the crossing of pre-selected boreholes with other BRGM databases on known anthropogenic influences;

(iii) numerous visualisations of time series with the hydrogeologists responsible for piezometric networks, in order to retain only non-influenced boreholes.

Time series of boreholes in this database were initially gathered in the ADES database that contains all groundwater data (quantity and quality) across continental France (*https://ades.eaufrance.fr/*).

Figure 1. *Spatial distribution of the 215 little- or non-influenced groundwater boreholes in continental France*

The criteria satisfied for selecting groundwater level time series in the database, and thus for the present study, were:

- The duration of the groundwater level time series must be >30 yr for regions where monitoring history is sufficiently long, and >20 yr for regions where monitoring history is shorter.
- The time series must contain a minimum amount of data in a month. This minimum amount is divided into two parts. A date of sampling-frequency change is identified in each time series, and the minimum sampling frequency must be at least one datum per month before this date and three data per month after this date.
- The length of consecutive gaps must be <3 yr for time series starting after 1950 and <10 yr for time series starting before 1950. This allows time series in the new database to preserve low-frequency variability in the data. Several gaps in the time series can be allowed if these criteria are respected, and if the number of gaps and their lengths are small.

Before data analysis, a visual check of the groundwater level time series served to remove or correct erroneous data. Wishing to qualify the behaviour of water tables by including annual variability, we decided to work on monthly averages. Any missing months in these time series were then filled by linear interpolation, before spectral analyses.

In continental France, groundwater level time series in some regions span on a limited historical time period, especially in western and southern France. Hence, we decided to focus on two different time spans: 1996–2019 and 1976–2019. For all French aquifers, the analyses cover the 1996–2019 period,

ensuring a good trade-off between time series length and spatial coverage (215 time series available). The longer period, spanning 43 years between 1976 and 2019, covered 102 time series in northern France. These two periods are referred to as “reference periods”.

In our study, the selected wells are representative of the various French hydrogeological contexts: alluvial, sedimentary, volcanic, and bedrock aquifers, but most wells are in sedimentary aquifers, primarily in the Paris Basin, and some in the Aquitaine Basin. Each well is attached to a hydrogeological area based on the groundwater bodies.

In the resulting database, the Seno–Turonian chalk aquifer of the Paris Basin is the best represented (60 boreholes), followed by Jurassic limestone aquifers in Lorraine, Berry, and Poitou on the rim of the Paris Basin (19 boreholes), and the Eocene Beauce limestones aquifer (8 boreholes). Wells in the Aquitaine Basin mainly capture the Jurassic limestone aquifer of the northern part of the Basin (7 boreholes) and multiple sedimentary hydrogeological formations in the southern part (sand, limestone: 10 boreholes). Finally, most of the wells selected in the Rhône valley monitor alluvial and fluvio-glacial formations (11 boreholes).

Alluvial aquifers are also well represented in the dataset, especially the Rhine/Vosges alluvium (18 boreholes) in Alsace, the Garonne alluvium in the Toulouse region (3 boreholes), and recent alluvium in the Mediterranean region (11 boreholes).

Some wells in the Central Massif are located in volcanic aquifers in various formations with different behaviour of groundwater levels (5 boreholes). Finally, bedrock aquifers are monitored by a few selected wells in the Armorican Massif (10 boreholes).

2.1.2. Precipitation data

Precipitation data used in this study come from the SAFRAN reanalysis (Vidal et al., 2010), which provides daily data on an 8×8 km^2 mesh covering France from 1958 to 2019. In addition, based on

meteorological data (precipitation (P), snow, temperature, and Penman-Monteith potential evapotranspiration (PET)) from the SAFRAN reanalysis, effective precipitation (EP = P – PET) data were computed using a gridded water-budget model with 8 km resolution at a daily time step, relying on the water-budget method of Edijatno and Michel (1989). The water-bugdet method considers that in the water cycle, the soil acts as a reservoir caracterized by its water storage capacity. Edijatno and Michel (1989) introduced a quadratic law to progressively empty the soil water reserves and to distribute the positive difference between P and PET between EP and soil storage. In the present study, the temporal resolution of both precipitation and effective precipitation was set at a monthly time step by using monthly cumulated data.

2.2. Methods

2.2.1. Trends over multiple time series lengths

We first estimated groundwater level trends over multiple time series lengths. We then determined whether changes in the length of time series affected trend estimates, by assessing the stability of trends when comparing the direction and magnitude of trends over decreasing periods. The procedure is illustrated in Fig. 2a. As explained above, we split the trend stability analysis into two reference periods, 1976–2019 and 1996–2019, corresponding to the best agreements between the spatial distribution of wells and groundwater level time series lengths over northern aquifers (102 boreholes) and all of continental France (215 boreholes), respectively. The 1996–2019 reference period provided an image of the stability of groundwater level trends through whole continental France, though over a relatively short period. To improve the consistency of the study, the 1976–2019 reference period was used for obtaining a longer historical hindsight, but covering only northern aquifers due to the data availability.

Figure 2. *Workflow of (a) trend stability analysis over decreasing time periods and (b) assessment of groundwater low-frequency influence on trend direction and magnitude. "WLF" is "water level fluctuation".*

To complete the stability analysis, we first evaluated the magnitude of trends and their statistical significance over different study periods (Fig. 2a; Step 1). Within the 1976–2019 reference period, trends were estimated for all groundwater level time series over six periods: 1976–2019, 1981–2019, 1986–2019, 1991–2019, 1996–2019 and 2000–2019. Within the 1996–2019 reference period, groundwater level trends were estimated over two study periods: 1996–2019 and 2000–2019. The significance of monotonic trends was determined with a modified Mann–Kendall trend test for autocorrelated data (Hamed and Ramachandra Rao, 1998). Compared 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 (p-values) after accounting for autocorrelation. The threshold for statistical significance was set at 5%. As we primarily aimed at quantifying changes in groundwater level trends in relation to groundwater stock variation over decreasing time periods – which cannot be estimated by the significance value of the modified Mann–Kendall trend test – we developed an indicator describing this phenomenon. Therefore, although the statistical significance of trends was also tested in the present study, we decided to present only the afore-mentioned indicator.

To develop this indicator, we first assessed the magnitude of trends by estimating Sen's slope (Sen, 1968), this method was selected as it is less sensitive to outliers than linear regression. The slope is defined as the median of the set of slopes calculated between pairs of points. To evaluate the relative importance of trends, compared to the groundwater stock variation, the percentage of decrease or increase in groundwater levels compared to the maximum water level fluctuation (WLF) was calculated using the following equation:

$$Percentage\ of\ maximum\ WLF = \left(\frac{Sen's\ slope * duration}{Maximum\ WLF}\right) * 100 \quad (1)$$

where maximum WLF is the difference between the highest and the lowest groundwater levels measured for a given time series. This normalisation of Sen's slope by the maximum WLF allowed comparing the magnitude of groundwater trends between aquifers with various water table behaviours and significant differences in their water stock variations.

The percentages of groundwater level loss/gain against maximum WLF were split into five classes according to their magnitude:

- Negligible trends between -1% and +1% of maximum WLF;
- Moderate upward or downward trends between +1% and +10%, or -1% and -10%, of the maximum WLF, respectively;
- Strong upward or downward trends between +10% and +100%, or -10% and -100%, of the maximum WLF, respectively.

This normalisation was applied to every well for each period analysed. The maximum WLF adopted, i.e. that of the two reference periods, remained constant from one period to the next, as it is a parameter that we used for characterising the groundwater stock variation.

For each well, the trend stability was evaluated by comparing the trend direction and belonging to the above classification for all studied periods (Fig. 2a; Step 2). For a given borehole, the groundwater trend can be stable or unstable in direction. We considered a trend direction "stable" if its direction was constantly upward, downward, or negligible from one period to another. Conversely, a trend was "unstable" when its direction fluctuated depending on the study period, or whether a trend emerged, such as a negligible trend for a given period followed by an upward or downward trend for the next period. Moreover, a "direction-stable" trend can be stable or unstable in magnitude; it is stable when the magnitude class does not change between periods and unstable if it does change.

2.2.2. Groundwater multi-timescale variability analysis

To determine the importance of low-frequency variability in groundwater levels, we identified and extracted high- to low-frequency wavelet components by multiresolution analysis, using the maximum overlap discrete wavelet transform (MODWT) algorithm. Like the more common discrete wavelet transform (DWT) method, MODWT is an iterative filtering of time series using a series of low- and high-pass filters, producing one high-frequency component, or "wavelet detail", and one lower frequency component called "approximation" or "smooth" at each scale. The smooth component is then

297 further decomposed into a wavelet detail and a smooth component, the latter being decomposed again
298 until it can no longer be decomposed. The original signal can be reconstructed by summing up all the
299 wavelet details and the last smooth. The original signal is then separated into a relatively small number
300 of wavelet components from high to low frequencies, which together explain the total variability of the
301 signal. For this study, the maximum decomposition level used in the MODWT was *log2(N)* where *N* is
302 the length of the time series. The least-asymmetric (symmlet) wavelet "s20" was used in order to better
303 capture variability at all time scales of sometimes relatively smooth groundwater level time series.
304
305 However, unlike DWT, MODWT was essentially designed to prevent phase shifts in the transform
306 coefficients at all scales by avoiding downsampling – reducing by a factor 2 the number of coefficients
307 – the signal with increasing scales. It results that the computed wavelet and scaling coefficients at each
308 scale remain aligned with the original time series; that is, the variance explained by these coefficients is
309 located where it truly lies in the time series analysed (Percival and Walden, 2000; Cornish et al., 2003;
310 Cornish et al., 2006). While not necessarily essential for signal or image processing or numerical
311 compression, this property is fundamental for physical interpretation of the wavelet details in
312 multiresolution analysis, and has already been used to that purpose in several studies such as Percival
313 and Mofjeld (1997), Massei et al. (2017) and Pérez Ciria et al. (2019).
314
315 The dominant frequency associated with each MODWT wavelet detail was calculated by Fourier
316 transform of each wavelet detail. The MODWT also provides the amount of variance (or energy)
317 explained by each wavelet detail and frequency level. The energy percentage of a given wavelet detail
318 expresses the relative importance of this variability in the total signal variability. As a result, the energy
319 distribution between wavelet details for each well in the database can be extracted and mapped.
320
321 Continuous global wavelet spectra were also calculated by averaging the spectral power from the
322 continuous wavelet spectra over time (Torrence and Compo, 1998). These analyses used R packages
323 wmtsa (Constantine and Percival, 2016) and biwavelet (Gouhier and Grinsted, 2012). They were
324 conducted for both reference periods: 1976–2019 and 1996–2019.

2.2.3. Influence of low-frequency variability of groundwater levels on trend direction and magnitude

The influence of groundwater low-frequency variabilities on the trend direction and magnitude was estimated using the MODWT method. As described in Section 2.2.2., summing up all wavelet details and the last smooth rebuilds the original signal. Based on this assessment, we first subtracted the wavelet detail of interest (or component) corresponding to a specific variability from the original signal (i.e., groundwater level monthly averages) (Fig. 2b; Step 1). We then calculated the Sen's slope (Section 2.2.1.) of the filtered signal and normalised it to the maximum WLF of the original signal (i.e., without filtering) (Fig. 2b; Step 2). The interest in keeping a fixed maximum WLF to normalise Sen's slopes is to assess only the influence of the removal of the component on the slope, and not to assess the influence of the removal of the component combined to variance modification linked to the removal of the component. Finally, we compared the magnitude and direction of the trends between the original and filtered signals to assess the influence of the component on the trend of the original signal. This analysis covered both reference periods: 1976–2019 and 1996–2019.

3. Results

3.1. Stability of trend directions and magnitudes of groundwater levels

In this section, we investigate the stability of groundwater level trends, that is, we aim at determining if trend direction and magnitude change according to the length of time series used for the trend analysis. To this end, we introduce the notions of "trend stability" (no change in direction or magnitude) and "instability" (changes in direction or magnitude) over decreasing time periods. If trend direction is stable, we consider that the length of time series has a minor influence on trend estimate, then a conclusion about groundwater level evolution may be drawn. Conversely, if it is unstable, the time series length has a significant influence on such estimate, then any conclusion regarding groundwater level

evolution may not be drawn. The trend-stability maps for the reference periods (1976–2019 and 1996–2019) used to verify this hypothesis, are shown on Figure 3.

Figure 3. *Trend-stability maps from the two reference periods (a) 1976–2019 to 2000–2019 and (b) 1996–2019 to 2000–2019. These maps show for a given reference period to what extent groundwater level trends are susceptible to changes of direction and magnitude according to the time series length. If the change of time series length does not affect trend direction (stable trend in direction), a triangle or a square is drawn for the borehole. If the change of time series length affects trend direction (unstable trend in direction), a diamond or a crossed-out circle is drawn according the type of trend instability. Finally, if the change of time series length does not affect trend magnitude (stable trend in magnitude), a dot is added in the symbol.*

From the 1996–2019 reference period, some hydrogeological formations show an instability in trend direction (positive and negative trend; Fig. 3b). These instabilities in trend direction are represented on maps either with a diamond in case of change of sign from a period to another period (alterning positive and negative trend) or a crossed-out circle in case of emerging trend (insignificant trend and positive or negative trend). These entities are the Eocene Beauce limestones, the Seno–Turonian chalk of Artois–Picardy (Fig. 4; Beauval), and the Jurassic limestones from Sarthe to Bessin. For these entities, no conclusions regarding the evolution of groundwater levels can be drawn, given the reccurrent change in trend direction according to the length of time series taken into account for the trend analysis.

Figure 4. *Example of trends over multiple time series lengths (1996–2019 and 2000–2019) on monthly groundwater levels at Beauval (Seno-Turonian chalk of Artois-Picardy), Goupillières (Seno-Turonian chalk of Normandy/Picardy) and Penol (fluvio-glacial formations in Rhône valley).*

Conversely, the Seno–Turonian chalk of Normandy/Picardy (Fig. 4; Goupillières), the Jurassic limestones of Poitou and Berry, the fluvio-glacial formations of the Rhône valley (Fig. 4; Penol), the Brittany bedrock, Champagne and Bourgogne chalk exhibit stable trend directions (Fig. 3b). For these

entities, conclusions regarding groundwater level evolution may be drawn: they are still downward regardless the study period.

However, if the analysis is conducted over longer periods for hydrogeological entities of northern France (particularly for the Normandy/Picardy, Champagne and Bourgogne chalk), changes in trend direction or a trend emergence can be detected when changing the time series length (Fig. 3a). Consequently, conclusions regarding the groundwater level evolution drawn for the 1996–2019 reference period are no longer valid for the 1976–2019 reference period since instabilities in trend direction are detected. Naturally, boreholes with trend direction instability between 1996–2019 and 2000–2019 periods are also subject to this instability over longer periods. Overall, the result is not homogeneous within the same hydrogeological unit as we can detect both boreholes with stable and unstable trend directions.

Most boreholes with stable (upward or downward) trend directions from the shorter reference period (1996–2019) are also stable in magnitude, meaning that the importance of slope in relation to groundwater level amplitude does not change class (Fig. 3b – dot in the symbol). This is the same for the longer reference period (1976–2019) in the western Seno-Turonian chalk of Normandy and the Lutetian/Ypresian sands of the Paris Basin (Fig. 3a).

Overall, when stable trend directions are detected, from the reference period 1976–2019 for northern France and 1996–2019 for the other regions of France, and that conclusions on groundwater level evolutions can be drawn, the levels are in the majority decreasing (Fig. 3). The existence of unstable trend directions raises the following question: are there low-frequency variabilities in groundwater levels that could induce these changes in trend directions and thus influence the trend estimates? Consequently, next section aims to identify the existence and significance of low-frequency variability in groundwater level signals.

3.2. Groundwater level fluctuations across multiple timescales: significance and spatial distribution over France

In this section, we assess the existence, significance and spatial distribution of low-frequency variability in groundwater level signals over France. We aim at determining if the unstable trend directions previously identified, could be potentially induced by the existence of low-frequency variability in groundwater level signals.

The energy percentage (i.e., the proportion of the total variance) at each timescale of variability can be extracted via MODWT and mapped for each groundwater time series. Figure 5 shows the spatial distribution of the energy contained in each spectral component, as a function of the hydrogeological entity. Multi-annual (5–12 yr) and decadal (12–24 yr) variabilities dominate over much of the Paris Basin (from Beauce limestones to the Seno–Turonian chalk farther north). Elsewhere, low-frequency variability can also prevail over a short period (1996–2019), such as in the fluvio-glacial formations of the Rhône basin, the Jurassic limestones of Poitou, and the alluvial formations of the Garonne River. Increasing the length of the studied period (1976–2019) highlights the prevalence of decadal variability (12–24 yr) in groundwater levels in the Beauce limestones and in the southern Seno–Turonian chalk of Normandy. This decadal variability also occurs in significant proportions farther north in the Seno–Turonian chalk of Normandy, but there its proportion is rather similar to that of the multi-annual variability (5–12 yr). These observations highlight the inertial nature of water tables in Normandy chalk and Beauce limestones aquifers (Fig. 6a and 6b) due to their highly capacitive nature, particularly in plateau areas (Roux, 2006). In these hydrogeological units, groundwater levels depend essentially on recharge from past winters. They are particularly sensitive to a succession of dry or wet winters, due to the memory effect linked to the regulation power of the water table. Regeneration of the water table stock spans several successive years with excess winter recharges.

Figure 5. *Proportion of the total variance explained by each timescale of variability (energy associated to each timescale, expressed as the percentage of total energy of each groundwater time series).*

Figure 6. *Examples of groundwater level time series representative of each major water tables behaviour.*

Although these low-frequency variabilities (multi-annual and decadal) are substantial components of the total groundwater variability in the Seno–Turonian chalk of the Artois–Picardy region, the annual variability explains a larger part of the total groundwater variability than in Normandy and Picardy (Fig. 5). The groundwater levels on the borders of the Seno–Turonian chalk (Champagne and Bourgogne) also display this type of variability, but here the annual variability dominates. Jurassic limestones on the edge of the Paris Basin from the Lorraine region to the Berry region also show this predominant annual variability with only a small part of the total variability explained by multi-annual and decadal variabilities. Overall, the water tables in these hydrogeological units show a combined behaviour: variously significant multi-annual to decadal variability is superimposed by prominent annual variability (Fig. 6c and 6d). In these aquifers, the annual variability is all the more important as their storage capacity decreases, with increasing fracturing, permeability, and proximity to the outlet (Roux, 2006). Here, groundwater levels strongly depend on infiltrated rainfall during the previous winter, while having a memory effect linked to the regulation power of water table.

Annual variability generally becomes predominant in compact highly fractured and low capacitive sedimentary aquifers (Roux, 2006), such as the fissured Jurassic limestones of the northern Aquitaine Basin or in fractured bedrock of Brittany (Fig. 5b and 6e). In such settings, groundwater levels rapidly rise in response to winter rainfall, but drop as rapidly as soon as water input stops.

No typical pattern in the energy distribution is noticeable for alluvial aquifers in France, and the dominance of one variability compared to another strongly depends upon the local geological and

hydrological context (Fig. 5). Boreholes monitoring alluvial formations commonly also monitor the underlying water body in the absence of an impermeable layer. Consequently, the borehole captures the behaviours exhibited by both groundwater bodies. Hence, water tables in alluvial formations can exhibit either an annual, multi-annual, or combined behaviour.

Hydrogeological entities previously described as susceptible to trend direction instabilities, are essentially entities for which the water tables display inertial or combined behaviour, which means that the existence of a low-frequency variability in groundwater levels and in significant proportions could be partly responsible for these instabilities (Fig. 3 and 5). These entities are: the Normandy/Picardy chalk, the Artois-Picardy chalk, the Bourgogne and Champagne chalk, the Beauce limestones, and the southern Jurassic limestones from Sarthe to Bessin.

The superposition of all the global wavelet spectra calculated for each groundwater level time series gives us a synthetic view of the predominant variabilities in groundwater levels of French aquifers (Fig. 7). The three preeminent variabilities in monthly groundwater levels are: ~1 yr, 5–8 yr (~7-yr), and >12 yr (~17-yr). The ~7-yr and ~17-yr variabilities show larger spectral powers and carry the largest part of the low-frequency variability in monthly groundwater levels. Such characteristic variabilities are known to be induced by large-scale climatic circulation, including the NAO, and was earlier observed in Normandy groundwater levels by Slimani et al. (2009) and El Janyani et al. (2012), and in streamflow of the Seine River (Massei et al., 2010). Later, studies highlighted these variabilities in groundwater levels in other countries (Rust et al., 2019; Liesch and Wunsch, 2019; Neves et al., 2019).

Figure 7. *Global wavelet spectra of (a) 102 monthly groundwater levels over 1976–2019, covering northern France and (b) 215 monthly groundwater levels over 1996–2019, covering all of France. Leading variabilities are highlighted.*

Since the low-frequency variabilities significantly explain groundwater level variability, the next section seeks to determine if, how and to what extent they influence the estimated trends on the reference

485 periods. As the ~7-yr and ~17-yr variabilities appear to be the predominant low frequencies in
486 groundwater level signals, hereafter, we provide details on the influence of these two variabilities on
487 groundwater level trends.
488
489 ## 3.3. Influence of groundwater level low-frequency variability on trend direction and
490 magnitude
491 In this section, we aim at determining the influence of groundwater multi-annual (~7-yr) and decadal
492 (~17-yr) variabilities on the estimated trends. In other words, we want to determine whether these low-
493 frequency variabilities affect trend estimates, and if so, whether they aggravate or mitigate the estimated
494 trends on the reference periods. To this end, we individually removed the detected low-frequency
495 components corresponding to multi-annual and decadal variabilities and recomputed the trends for the
496 resulting filtered groundwater level signals, to assess the effect of such low-frequency components on
497 trend magnitude and direction. Low-frequency components to be filtered were chosen based on global
498 wavelet spectra (Fig. 7). For the 1996–2019 reference period, only the ~7-yr component was filtered
499 from monthly groundwater levels, while for the 1976–2019 reference period, both ~7-yr and ~17-yr
500 components were individually filtered (Fig. 8 and 9).
501
502 ***Figure 8.*** *Comparison of groundwater trend magnitude between monthly groundwater levels and ~7-*
503 *yr filtered groundwater levels over 1996–2019.*
504
505 ***Figure 9.*** *Comparison of groundwater trend magnitude between monthly groundwater levels, ~7-yr*
506 *filtered groundwater levels, and ~17-yr filtered groundwater levels over 1976–2019. The legend of*
507 *hydrogeological entities can be found on Fig. 8.*
508
509 Figures 8 and 9 show the magnitude of the trend (Sen's slope/maximum WLF ratio) of each groundwater
510 time series analysed. Monthly groundwater levels are in red, the ~7-yr filtered monthly groundwater
511 levels in grey, and the ~17-yr filtered groundwater levels in blue (only for the 1976–2019 period). Both

figures show the impact of removing a given variability (~7-yr or ~17-yr) on the trend, compared to the unfiltered groundwater levels; they also show the influence of a given low-frequency variability on unfiltered groundwater level trends by considering the sign of the subtraction between unfiltered (red) and filtered (grey or blue) groundwater levels. Nevertheless, quantifying the exact contribution of a given variability to unfiltered groundwater level trends is difficult because other (low- or high-frequency) variabilities can modulate this contribution.

For the shorter period (1996–2019), the effect of the ~7-yr variability on trends shows a well-established spatial pattern throughout France (Fig. 8). In the North, for aquifers with inertial or combined behaviour of water tables, the ~7-yr variability drives levels up. In contrast, in various southern French aquifers, this variability drives groundwater levels down.

In northern France in chalk, sands, and Eocene limestones of the Paris Basin, we see an accentuation of downward trends (Fig. 10b; Goupillières), a mitigation of upward trends, and reversals in direction from upward to downward trends when the ~7-yr variability is filtered from monthly groundwater levels (Fig. 8b1). This effect of removing the ~7-yr variability means that in unfiltered original groundwater levels, this variability drives groundwater levels upward. In other words, the ~7-yr variability mitigates downward trends and accentuates upward trends. The Seno-Turonian chalk of Champagne is the only one not displaying this phenomenon. Around the hydrogeological entities of the Paris Basin, the effect of the ~7-yr variability on groundwater levels is more sporadic.

Figure 10. *Typical patterns of low-frequency variability removal influence on groundwater level trend estimates: (a) Analysis of the 1976–2019 period at Goupillières (Seno-Turonian chalk of Normandy and Picardy) and Beauval (Seno-Turonian chalk of Artois-Picardy) both in northern France; (b) Analysis of the 1996–2019 period at Goupillières (northern France) and Penol (southern France – fluvio-glacial formations of Rhône valley).*

In southern France, we see a reverse pattern from that found in the North (Fig. 8). Here, removing the ~7-yr variability mitigates downward trends (Fig. 10b; Penol), or results in downward trends becoming upward trends (Fig. 8b2). This pattern is observed in all southern hydrogeological units analysed, even if locally the removal of the ~7-yr variability may have no effect on the trends. This "non-effect" could be caused either by the fact that the ~7-yr variability does not, or weakly explain, the variability of monthly groundwater levels, or because this variability does not contribute to the trend at all. Overall, the ~7-yr variability drives groundwater levels down in most southern hydrogeological entities. In other words, the ~7-yr variability aggravates downward trends.

A transitional section between northern and southern patterns can be seen in the Jurassic limestones of Berry (Fig. 8). Here, the ~7-yr variability can drive groundwater levels upward or downward. This transition zone could be attributed to either a transitional climatic zone, or a high spatial variability in water table behaviour, related to a spatial discrepancy of aquifer properties.

The ~7-yr variability displays a similar pattern for the longer period (1976–2019) as for the shorter one in the Paris Basin (Fig. 9b). Removing this variability still results in accentuated downward or mitigated upward trends. The main discrepancy compared to the shorter period is due to the fact that, in many cases, removing the ~7-yr variability hardly affects the trend (Fig. 10a; Goupillières and Beauval). Hence, the ~7-yr variability either drives groundwater levels upward, so mitigates downward trends, or has no effect on the trend in the Paris Basin. The Seno–Turonian chalk of Champagne also displays this pattern, while the Upper Cretaceous chalk of Bourgogne does not.

The long reference period allows for a robust assessment of the influence of the ~17-yr variability on groundwater trends (Fig. 9), as it shows a consistent pattern in hydrogeological units of northern France, driving groundwater levels downward, so aggravating downward trends. The removal of this variability leads to mitigation of downward trends (Fig. 10a; Goupillières), accentuation of upward trends, or reversals in trend directions from downward to upward. The only hydrogeological unit where the ~17-

yr variability does not influence the trend is the Seno–Turonian chalk of Artois–Picardy (Fig. 10a; Beauval).

Figure 10a also shows the importance of the ~17-yr variability weakening since the late 2000s in carrying trend: the trend is largely mitigated when this variability is removed from the monthly groundwater levels at Goupillières. At Beauval, this is not the case, because the ~17-yr variability only accounts for a small part of total variability, and therefore has no influence on the trend.

The degree of influence of a specific variability on the trend can be related to two factors: (i) the proportion of total groundwater variability explained by this variability and (ii) the length of the time series. The greatest influence on trends of removing a specific variability occurs when it accounts for a large part of the total groundwater variability. This phenomenon is particularly remarkable in inertial formations. For instance, removing the ~7-yr variability over the 1996–2019 period strongly affects groundwater level trends in Beauce limestones, Seno–Turonian chalk, and fluvio-glacial formations in the Rhône valley (Fig. 8). As seen earlier, the ~7-yr variability explains much of the total groundwater variability in these units over the 1996–2019 period (Fig. 5b).

Similarly, removing the ~17-yr variability over the 1976–2019 period strongly affects groundwater level trends in Beauce limestones and southern Seno–Turonian chalk of Normandy (south of the Seine River), while this influence weakens farther north until it no longer affects trends in the Seno–Turonian chalk of Artois–Picardy (Fig. 9). This weakening pattern corresponds to a decrease in the significance of the ~17-yr variability in monthly groundwater variability from the Beauce limestones to the Seno–Turonian chalk of the Artois–Picardy basin farther north (Fig. 5a).

In addition to the explanatory variance, the other major factor that affects the importance of a given variability removal on trends magnitude and direction is the length of the time series. Thus, removing the ~7-yr variability over a long period (1976–2019) has less influence on trends than over a shorter period (1996–2019). We see an example of this in the northern part of the Seine River, in the Seno–

Turonian chalk of Normandy. During the 1976–2019 period, the ~7-yr variability still explains half of the groundwater level variability (Fig. 5a), but its removal from groundwater levels hardly affects trends (Fig. 9).

4. Discussion

In this section, we discuss the different items addressed in the section 3. First, we discuss how the length of groundwater time series can influence trend estimation and thus conclusions regarding groundwater level evolution. We also discuss to what extent it may be related to the presence of low-frequency variability in groundwater signals, and to what extent the length of groundwater time series is a key parameter to determine the trend origin. By trend origin, we refer to the physical phenomenon that leads to the groundwater level trend. Second, we discuss the presence of low-frequency variability in groundwater levels and the relationship with aquifer and catchments properties. Finally, we discuss the influence of multi-annual and decadal variabilities on groundwater trends and compare these results to those obtained for (effective) precipitation with the aim to determine whether these influences originate from precipitation or whether catchment and aquifer properties disrupt these influences. Furthermore, we develop the implications of such results on the interpretation of estimated groundwater level trends as well as on future evolutions and projections of groundwater levels.

4.1. Importance of time series length on trend estimates and to discuss the origin of groundwater trends

A few studies have previously examined the influence of time series length on the magnitude and statistical significance of hydroclimatic variable trends. It emerged that the shorter the study period, the greater its magnitude and statistical significance, which appeared to be directly linked to low-frequency variability (Hannaford et al., 2013; Peña-Angulo et al., 2020). The low-frequency variability also interferes in the statistical test results with high magnitude trends that may be statistically insignificant but may actually have important implications for water resources (Morin, 2011; Fatichi et al., 2015a).

The main method for mitigating the effect of multi-annual and multidecadal variabilities on trends is to lengthen the study period as much as possible (Peña-Angulo et al., 2020). However, the main limitation to lengthen the study period comes from the existence of historical data. In our case, the French piezometric network is relatively young, which constrains trend studies to be realised on short periods. Therefore, as much studies (Burn et al., 2012), our trend study is conducted using temporal windows that provide the best compromise between time series length and the spatial coverage of *in situ* stations.

We showed that some aquifers exhibiting inertial or combined behaviour of water tables are particularly susceptible to trend direction instabilities (alternatively upward and downward) when the length of groundwater time series is modified. It is therefore difficult to draw a conclusion on the groundwater level evolution. Shifting trend directions are not specifically inherent to groundwater levels but can also be observed in streamflow and precipitation (Hannaford et al., 2013; Stojković et al., 2014; Espinosa and Portela, 2020; Peña-Angulo et al., 2020). Such trends should be interpreted with great care, as they may actually correspond to the presence of low-frequency variability, and do not represent a physically meaningful trend behaviour, i.e., a change in the behaviour of the analyzed phenomenon that may eventually lead to a new (yet unknown) state, for instance as a consequence of anthropogenic climate change or changes in land use.

However, the existence of significant low-frequency variability in groundwater levels does not necessarily induce trend direction instabilities, as it was observed for some aquifers exhibiting water tables with inertial or combined behaviour. In such case with still upward or downward trends regardless the time series length, conclusions about groundwater level evolution may be drawn. Nevertheless, observing still upward or downward trends does not allow us to deduce the origin of the trend. For instance, the detected decreasing trends may be induced either by (i) the anthropogenic climate change resulting in a decrease in groundwater recharge, (ii) the internal climate variability (developed in subsequent paragraphs), or (iii) anthropogenic impacts (e.g., groundwater pumping, changes in land cover that may generate a decrease in groundwater recharge).

Internal climate variability (i.e. the low-frequency variability) may lead to stable trend directions in different ways according our observations (not exhaustive). First, since low-frequency variability displays an aperiodic behaviour with regular amplitude-modifications, consequently trends may be largely guided by these amplitude-modifications of low-frequency that may lead to a trend direction still upward or downward regardless the length of time series considered (developed in Section 4.3.). Second, trends detected over relatively short periods may actually be only sections of slower fluctuations. Consequently, the trend direction remains upward or downward regardless the time series length considered, since the available length of groundwater level time series is still too short to grasp certain low-frequency timescales as fluctuations, but they are grasped to be trends. So, these trends which over short study periods, without caution, would be imputed easily to climate change may actually only be sections of slower fluctuation (from internal climate variability) that cannot be evidenced by the length of the study period. Because large-scale atmospheric and oceanic fluctuations 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-yr timescales (Kerr, 2000; Enfield et al., 2001). As mentioned earlier, the age of French piezometric networks does not, in most cases, allow us to grasp such a low-frequency timescale as a fluctuation in groundwater levels, but it can be grasped to be trend. To overcome these drawbacks, some studies have used the Ensemble Empirical Mode Decomposition (EEMD) method to filter out climate variability in precipitation, streamflow, or meteorological drought signals and detect non-linear trends (Massei and Fournier, 2012; Sang et al., 2014; Guo et al., 2016; Song et al., 2020). For instance, Massei and Fournier (2012) concluded that the non-linear trend in the daily Seine River flow could be related to a larger scale NAO fluctuation, indicating the reversibility of the phenomenon. Therefore, this highlights the complexity to define whether the trends in hydroclimate variables can be related to climate change or are simply a portion of some low-frequency fluctuations of large-scale atmospheric or oceanic circulation.

Without considering the anthropogenic impacts (which data are often poorly referenced), the most limiting factor for distinguishing a climate change origin of the trend from an internal climate variability origin (in particular from segments of low-frequency fluctuations that may appear as short-term trends)

remains the availability of groundwater level data. Studies on groundwater level reconstruction might overcome this constraint via, for instance, deep learning approaches or tree-ring-based reconstructions (Vu et al., 2020; Tegel et al., 2020). However, disentangling climate change and large-scale climate natural variability would still remain difficult, even with longer time series data, as anthropogenic forcing may have already impacted climate variability (Dong et al., 2011; Caesar et al., 2018).

Disentangling the determinism of trends in terms of internal climate variability or climate change lies behind the scope of the present study. It is rather dedicated to assess how low-frequency variability can affect trend estimations. Owing to the database used, the trends possibly detected here cannot result from groundwater abstraction by pumping. However, as this database does not consider changes in land cover, some trends in groundwater levels could then result from such influence involving recharge modifications for instance.

4.2. Catchment and aquifer properties and their impact on variability time scales of groundwater levels

The analysis of the spatial distribution of multi-timescale variability revealed the predominance of ~1-yr, ~7-yr, and ~17-yr variabilities in groundwater levels throughout Metropolitan France. The ~1-yr variability can be explained by the hydrological cycle (winter recharge and summer recession), while the ~7-yr and ~17-yr variabilities originate from climatic/oceanic large-scale variability as already demonstrated by Massei et al. (2010), Massei and Fournier (2012), El Janyani et al. (2012) or more recently Rust et al. (2019).

The present study showed that the significance of the low-frequency variability in groundwater levels is highly variable between French hydrogeological entities. The low-frequency variability can be either predominant in the total variance of groundwater levels or weakly depicted. These discrepancies are primarily dependent on intrinsic catchment and aquifer properties such as the permeability and thickness of the unsaturated zone, the hydrodynamic properties (transmissivity and storage coefficient), the

aquifer geometry, the connection with neighbouring aquifers and river system (El Janyani et al., 2012; Rust et al., 2018).

Aquifers constituted of rocks with low matrix porosity and highly fracturated such as limestones and bedrock would tend to exhibit groundwater levels dominated by an annual variability and a weak low-frequency variability due to a high diffusivity. Conversely, aquifers with high storage capacity and thickness, low transmissivity, and significant thickness of superficial formations such as chalk aquifers tend to display groundwater levels dominated by multi-annual to decadal variabilities (Slimani et al., 2009; El Janyani et al., 2012). The exact same behaviour was also recently highlighted by Rust et al. (2019) in chalk aquifers of Great Britain.

However, the location in the regional geomorphology (valley, plateau) and hydraulic gradient would exert a strong control on the significance of multi-annual and decadal variabilities in groundwater levels (El Janyani et al., 2012), with high-amplitude low-frequency variations for downgradient piezometers. On the contrary, piezometers with lower amplitudes of low-frequency variations and high amplitudes of annual variations would be generally found at upgradient locations and then not associated to the drainage of large areas of subterranean watersheds. Such boreholes would then also be located on plateau areas, where superficial formations and unsaturated zone are thinner (Slimani et al., 2009). It then turns out that the geomorphological context and properties such as the presence of superficial formations, aquifer thickness and transmissivity, but also the location within the hydraulic gradient are determinant explanatory factors.

Local conditions would also play a major role in defining the hydrogeological determinism of groundwater level behaviour. For instance, piezometers located downgradient would correspond to the drainage of a large volume of aquifer and would then display enhanced low-frequency behaviour, but in karst areas such boreholes are also very likely associated to highly transmissive karst zones (the so-called “output karst”) that display strong and fast response to precipitation (i.e., favoring high amplitude high-frequency variations). The influence of such characteristics on the frequency behaviour of

groundwater levels have been successfully put in evidence using a physics-based modeling approach in the Seine watershed (Schuite et al., 2019).

On the scale of the whole Metropolitan France area, however, due to the lack of data about physical properties of aquifers and an insufficient gathering of existing data into a database, it would be hazardous to get any further into the interpretation of the impact of physical properties on the significance of low-frequency variabilities in groundwater levels. Hence, the development of such a database gathering the physical properties of aquifers near boreholes across Metropolitan France would be useful for further investigations.

4.3. Influence of multi-annual and decadal variabilities on groundwater trends and comparison with their influence on (effective) precipitation trends

Our analyses emphasized the need for long groundwater time series to get better insight into the existence and meaning of trends regarding the presence of low-frequency variability. Extending the groundwater time series period by 20 years revealed a decrease in the influence of multi-annual variability (~7-yr) on trends. Thus, this component only little affected the trend. Obviously, the significance of this influence also depends on the water table behaviour and thus on the relative importance of multi-annual or decadal variabilities in the total variance of groundwater levels. The more the considered variability (multi-annual or decadal) dominates groundwater levels, the more influence it has on the trend.

We also noted that some trends carried by either the multi-annual or decadal variability, are caused by changes in the amplitude of the low-frequency variabilities over time. These regular changes in the variance of low-frequency variabilities have been highlighted in many precipitation and streamflow studies (Fritier et al., 2012; Dieppois et al., 2013 and 2016; Massei et al., 2010 and 2017). In the Normandy chalk, downward trends detected in groundwater levels seem to be partly related to a weakening of the low-frequency variability over time, the decadal variability appearing to be the main

responsible for these downward trends. Its removal largely influenced trends (they became much smaller in magnitude), whereas that of multi-annual variability did little or not affect trend magnitude. This may also explain the stable downward trends detected in Normandy chalk and why changing the time series length has no effect on trend direction.

In Section 3.3., we demonstrated the significant influence of multi-annual and decadal variabilities on groundwater level trends. This large influence of such low-frequency variabilities on groundwater trends raises the following question: is this influence inherent to the aquifer systems, or does it influence trends of precipitation and effective precipitation in the same way? We thus also analysed these variables to answer this question.

In all hydrogeological units of the Paris Basin, the decadal variability drives groundwater levels down and thus aggravates downward trends over the 1976–2019 period (Fig. 9). Our analyses on precipitation and effective precipitation showed primarily the same influence of decadal variability on precipitation and effective precipitation trends as on groundwater levels (Fig. 11). It drives precipitation levels down, attenuating upward trends and accentuating downward trends. These consistent results indicate that this influence of decadal variability on groundwater trends is climatologically induced and is not affected by catchment and aquifer systems.

Figure 11. *Comparison of precipitation trend magnitude between cumulated monthly precipitation, ~7-yr filtered cumulated monthly precipitation and ~17-yr filtered cumulated monthly precipitation over 1976–2019;*

a) and b) show precipitation results, c) and d) show effective precipitation results.

The legend of hydrogeological entities can be found on Figure 8.

Our study also revealed a reversal of the effect pattern of multi-annual variability on trends over the 1996–2019 period between aquifers in northern and southern France (Fig. 8). The analysis of precipitation (P) data showed that over all of France the influence of multi-annual variability on trends

is homogeneous: it drives precipitation levels down, attenuating upward trends and accentuating downward trends (Fig. 12). Thus, the influence of multi-annual variability on trends indicates a reversed pattern between precipitation and groundwater levels in northern France, particularly in the Paris Basin. Either potential evapotranspiration (PET) and/or aquifer properties may affect the influence of multi-annual variability on trends and reverse its effect. However, we observed a similar influence of multi-annual variability on effective precipitation (EP) trends as on groundwater trends in the Paris Basin, driving effective precipitation levels up (Fig. 13). Knowing that EP is equivalent to P-PET, this result suggests that PET would be responsible for this reversal pattern between precipitation and groundwater levels, rather than catchment and aquifer properties.

Figure 12. *Comparison of precipitation trend magnitude between cumulated monthly precipitation and ~7-yr filtered cumulated monthly precipitation over 1996–2019.*

Figure 13. *Comparison of effective precipitation trend magnitude between cumulated monthly effective precipitation and ~7-yr filtered cumulated monthly effective precipitation over 1996–2019.*

In southern France, over the 1996–2019 period, the influence of multi-annual variability is the same on precipitation trends, effective precipitation trends and groundwater trends (Fig. 8, 12 and 13). Only the Mediterranean region shows atypical results, as the multi-annual variability drives precipitation and groundwater levels down, while driving effective precipitation levels up. This indicates that, first, PET would affect the influence of multi-annual variability on trends by reversing the effect between precipitation and effective precipitation, and second, that catchments and aquifer properties would affect this influence in turn to reverse it again between effective precipitation and groundwater levels. To better understand and explain this phenomenon, further investigations will be necessary at a regional scale.

Over the longer period of 1976–2019, the influence of multi-annual variability on trends of precipitation, effective precipitation and groundwater levels is heterogeneous in northern France (Fig. 9 and 11). Some regions (Normandy, Champagne, and Artois-Picardy) show a rather consistent influence of multi-annual

variability on trends, regardless of the variable (precipitation, effective precipitation, groundwater levels). For these regions, the multi-annual variability primarily drives levels up (attenuating downward trends or accentuating upward trends). In other regions however, such as Bessin, Beauce and Bourgogne, the available data indicate different influences of multi-annual variability on precipitation, effective precipitation, and groundwater level trends. We will not extend the discussion to these regions because the results showed disparities at the local scale.

Our analysis provides a first insight into the influence of multi-annual and decadal variabilities in groundwater levels on estimated trends. Generally, the influence of both low-frequency variabilities is also similar on precipitation and effective precipitation trends. We observe multi-annual and decadal variabilities that aggravate downward trends or mitigate upward trends either in groundwater, precipitation and effective precipitation. It is known that low-frequency variability (originating from internal climate variability) may modulate anthropogenically-driven trends, particularly those induced by climate change (Kingston et al., 2020). Our result indicates that low-frequency variabilities would be able to aggravate trends (i.e., amplify downward trends) that might be induced by anthropogenic climate change. For regions that are already submitted to regular meteorological and hydrological droughts, this result may be particularly alarming, such as for the Mediterranean region that is defined as an anthropogenic climate change “hotspot” (Diffenbaugh and Giorgi, 2012; Lionello and Scarascia, 2018; Drobinski et al., 2020; Tramblay et al., 2020). However, even if it is accepted that low-frequency variability may accentuate, attenuate or inverse the long-term effects of climate change on hydrological processes (Fatichi et al., 2014; Gu et al., 2019; Massei et al., 2020), our methodology in this article does not allow us to obtain residual trends that may be only related to climate change. Indeed, we subtracted individually each low-frequency variability to assess their specific influence on trends and consequently there is still some low-frequency in residual time series (filtered ones) on which the trend is re-estimated. Consequently, we do not estimate directly the aggravating or mitigating potential of low-frequency variability on trends that would be related only to climate change.

In some areas, however, discrepancies exist between precipitation and effective precipitation, suggesting the possible influence of PET that inverses the effect of multi-annual variability on trends (over 1996–2019) in the Paris Basin. Locally, discrepancies can appear between effective precipitation and groundwater levels, such as in the Beauce area over 1976–2019 due to aquifer properties that significantly filter the multi-annual variability, which then no longer affects groundwater trends. Further investigations will be necessary to better understand the processes and physical properties causing the reversal of the influence of low-frequency variability on trends between precipitation and groundwater levels.

The large influence of low-frequency variability on estimated groundwater level trends entails several implications. First regarding conclusions about traces of climate change in groundwater levels, since trends may actually correspond to the presence of low-frequency variability, and then be primarily the result of internal climate variability instead of anthropogenic climate change. Second regarding future evolutions of groundwater levels, since a potential change in the amplitude of internal climate variability (that may also be the consequence of anthropogenic climate change) – e.g. increasing or decreasing low-frequency variability – in the next decades may lead to substantial changes in groundwater level trends. Consequently, the extrapolation of trends estimated over the historical period seems particularly hazardous, due to the stochastic and unpredictable behaviour of such low-frequency fluctuations. Third regarding future projections, because internal climate variability is often improperly reproduced and is a major source of uncertainties in climate and hydrological projections resulting from GCM outputs (Terray and Boé, 2013; Qasmi et al., 2017). Consequently, trend estimates resulting from these hydrological projections (and *in fine* resulting from recharge and groundwater level projections) would be subject to strong uncertainty.

5. Conclusion

The analysis of groundwater level trends in France showed that a number of aquifers were susceptible to trend direction instabilities (i.e., changes in trend direction according to the length of time series),

leading to contradictory conclusions about groundwater level evolutions. This led to the question of the existence, importance and spatial distribution of low-frequency variability in groundwater levels of French aquifers. Groundwater levels were therefore broken down by MODWT to estimate the significance of low-frequency variabilities in total groundwater level variability. It turned out that most of aquifers susceptible to trend direction instabilities exhibit a hydrological variability characterized by a significant low-frequency variability: they are aquifers with inertial or combined behaviour of water tables. Given the significant presence of multi-annual and decadal variabilities in groundwater levels, we aimed to determine if, how and to what extent each of these components could affect trend estimates. To this end, MODWT filtering was performed to subtract individually the multi-annual or decadal variability from the entire signal, and then trends were re-estimated on the filtered groundwater level time series. The results showed that the groundwater level trends were highly sensitive to the presence of any of these low-frequency components, which may then strongly influence the estimated trends. Such results indicate that low-frequency variability (originating from internal climate variability) is capable of attenuating or accentuating groundwater level trends, including those that might be associated with climate change.

In general, trend detection is widely used as a tool for assessing changes in groundwater levels. Nevertheless, our study presents features that show that this tool should be used with caution, particularly for studying groundwater levels with significant low-frequency variability. We observed that: (i) trends are highly dependent upon the study period and time series length, and cannot be extrapolated; (ii) trends are strongly influenced and guided by low-frequency variability, and (iii) trends are often only segments of larger scale fluctuations resulting from large-scale atmospheric or oceanic circulation. Consequently, their interpretation and attribution to a physical phenomenon, such as climate change *vs*. climate variability, remains complex. In addition, since low-frequency variability strongly guides and influences the estimated groundwater level trends, potential changes in low-frequency variability – induced by changes in internal climate variability – would necessarily lead to a change in the estimated trends. In particular, this means that (i) estimation of trends in hydrological projections resulting from GCM outputs in which low-frequency variability is not well respresented would be

subject to strong uncertainty, (ii) a potential change in internal climate variability – e.g. increasing or decreasing low-frequency variability – in the next decades may lead to substantial changes in estimated groundwater level trends.

Consequently, future works should focus on assessing the impacts of a potential change in internal climate variability (i.e., low-frequency variability) on groundwater level trends using different scenarios of amplitude-modifications of low-frequency variability. In addition, a sensitivity analysis of the results of this study to decomposition method employed (e.g. wavelets, EEMD) should be conducted.

Acknowledgments

This work was partially supported by the GeoERA project TACTIC, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166. We would also like to thank the AESN and PIREN Seine programs for their support. Finally, we would like to thank Sandra Lanini for the calculation of effective precipitation; the two anonymous reviewers for their thoughtful comments that definitely helped improving the paper; Marinus Kluijver for editing the final English version; Jean-Jacques Seguin, Marc Laurencelle and Laurence Gourcy for the helpful discussions.

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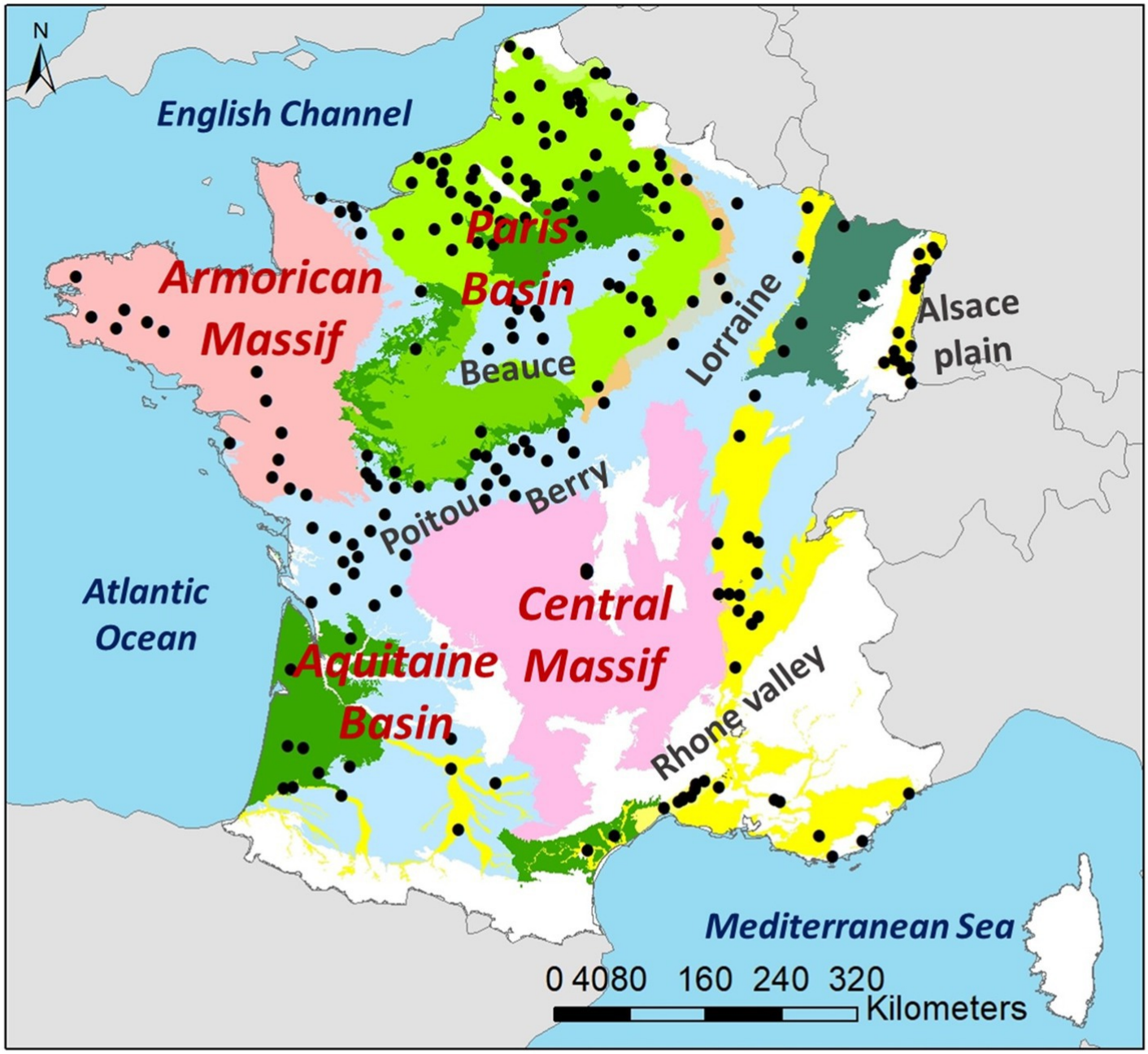


Legend

- Groundwater level observation wells

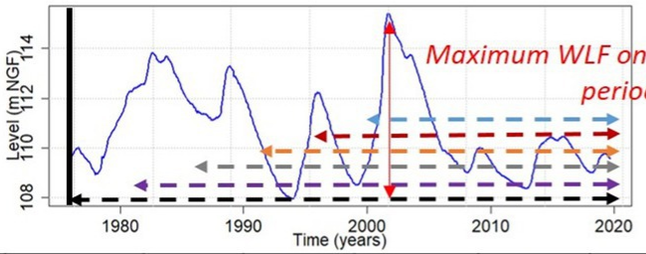
Aquifer group

- Bedrock
- Chalk
- Greensands
- Limestones
- Not studied formations
- Sand
- Sandstones
- Volcanic formations
- Alluvial formations

(a)

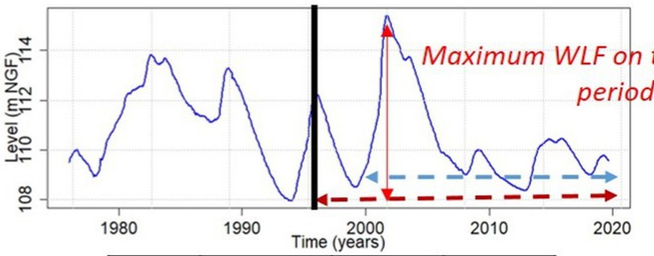
Step 1 : a. Assessment of Sen's slope; b. Normalisation by maximum WLF; c. Assignment to a magnitude class

Reference period : 1976-2019



Well		1976-2019	1981-2019	1986-2019	1991-2019	1996-2019	2000-2019
Xn	Sen's slope						
	Sen/WLF						
	Class						

Reference period : 1996-2019



Well		1996-2019	2000-2019
Xn	Sen's slope		
	Sen/WLF		
	Class		

Step 2 : Class comparison

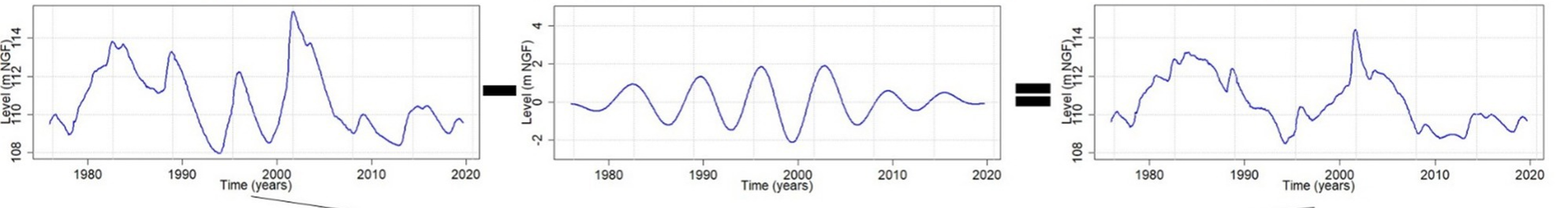
Well		1976-2019	1981-2019	1986-2019	1991-2019	1996-2019	2000-2019	Sign stability	Class stability
Xn	Class	Strong ↘	Strong ↘	Strong ↘	Moderate ↘	Strong ↘	Strong ↘	Still ↘	Unstable

Well		1996-2019	2000-2019	Sign stability	Class stability
Xn	Class	Strong ↘	Strong ↘	Still ↘	Stable

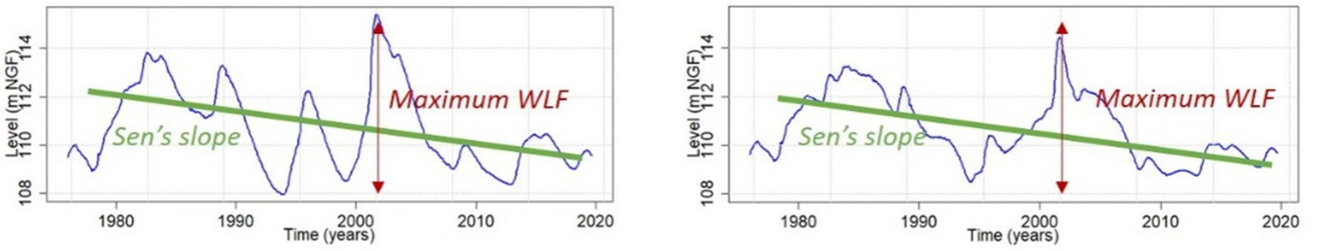
(b)

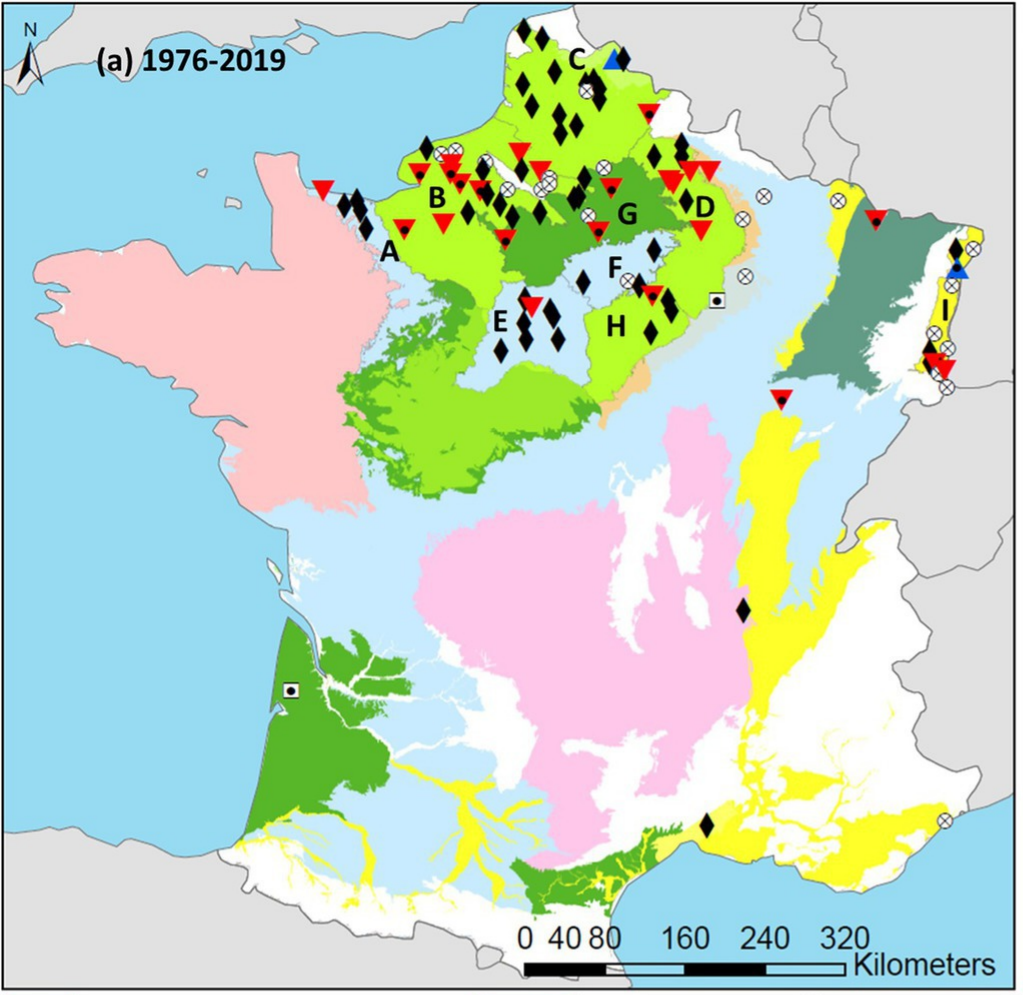
Step 1 : Subtraction of the time scale of interest

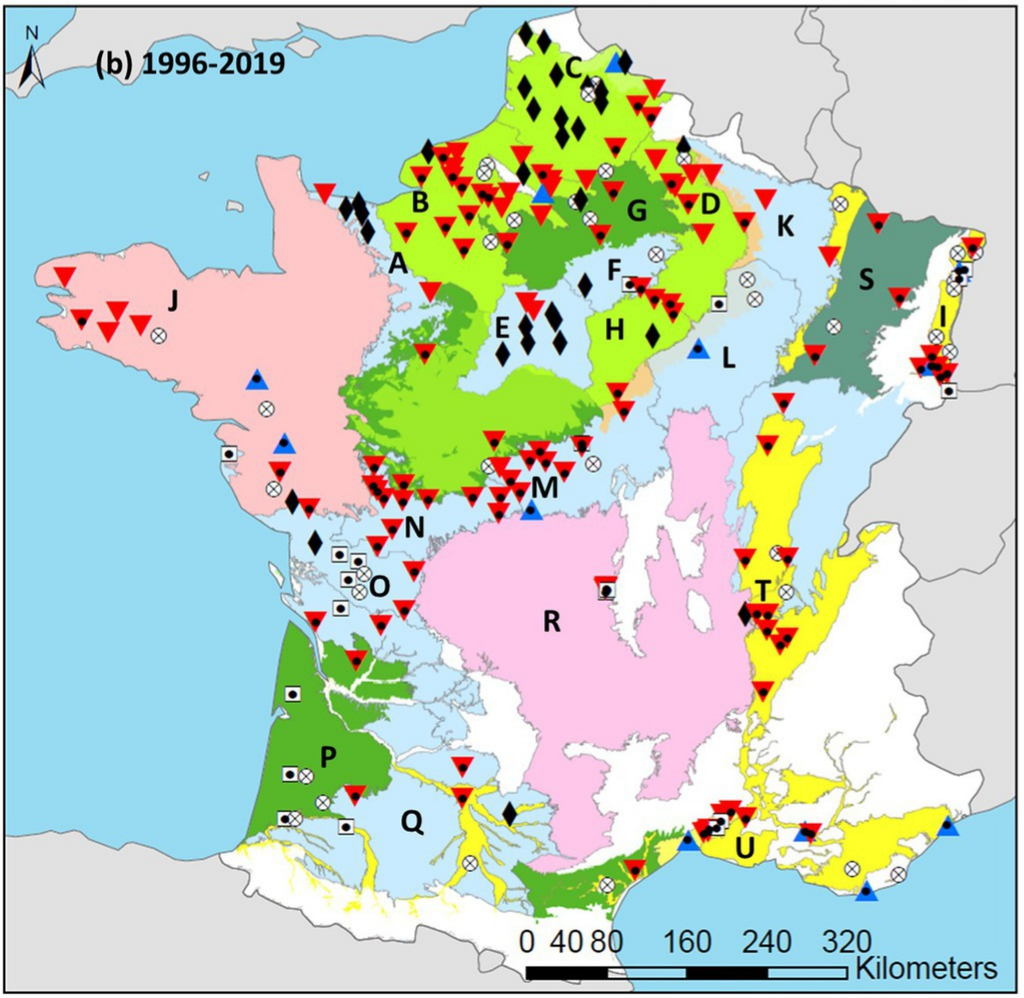
Original signal — *Wavelet detail subtracted (e.g. ~7 years)* — *Filtered signal of the ~7 years time scale*



Step 2 : Sen's slope calculation and normalisation by maximum WLF of original data







Legend

Trend magnitude stability

- Stable trend class

Trend direction stability

- Still upward trend
- Still insignificant trend
- Still downward trend
- Change of sign
- Emerging trend

Aquifer group

- Alluvial formations
- Bedrock
- Chalk
- Greensands
- Limestones
- Sand
- Sandstones
- Volcanic formations
- Not studied formations

Hydrogeological entities

A Jurassic limestones from Sarthe to Bessin

B Seno-Turonian chalk of Normandy/Picardy

C Seno-Turonian chalk of Artois-Picardy

D Seno-Turonian chalk of Champagne

E Limestones of Beauce

F Upper Eocene limestone of Paris Basin

G Lutetian and Ypresian sands of Paris Basin

H Upper Cretaceous chalk of Bourgogne

I Alluvial formations of Alsace

J Bedrock of Brittany

K Jurassic limestones of Lorraine

L Jurassic limestones of Côte-des-Bars

M Jurassic limestones of Berry

N Jurassic limestones of Poitou

O Fractured Jurassic limestones of northern Aquitaine Basin

P Plio-Quaternary sands of Aquitaine Basin

Q Various calcareous formations of Aquitaine Basin

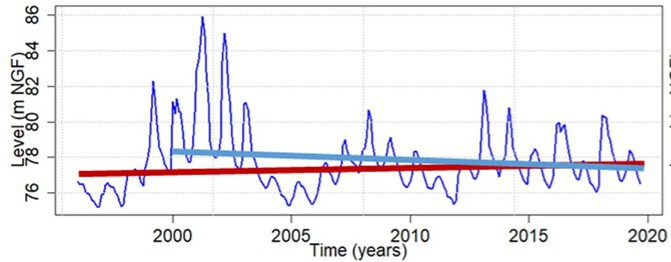
R Volcanic formations of Central Massif

S Triassic sandstones and limestones of Lorraine

T Fluvio-glacial formations of Rhone valley

U Alluvial formations of Mediterranean region

Beauval



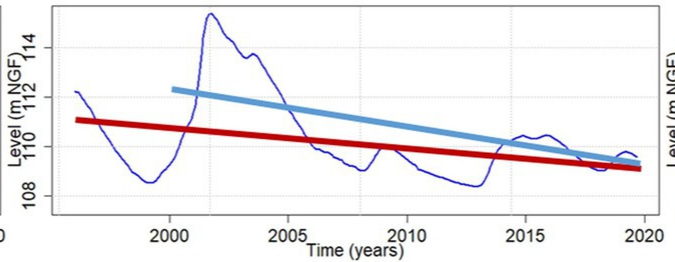
1996-2019 :

- Sen's slope = 0.2 cm/month
- *Slope/WLF = 10% of WLF*

2000-2019 :

- Sen's slope = -0.3 cm/month
- *Slope/WLF = -13% of WLF*

Goupillieres



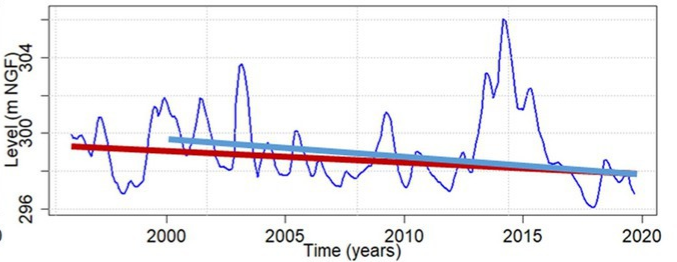
1996-2019 :

- Sen's slope = -0.7 cm/month
- *Slope/WLF = -43% of WLF*

2000-2019 :

- Sen's slope = -1.5 cm/month
- *Slope/WLF = -76% of WLF*

Penol

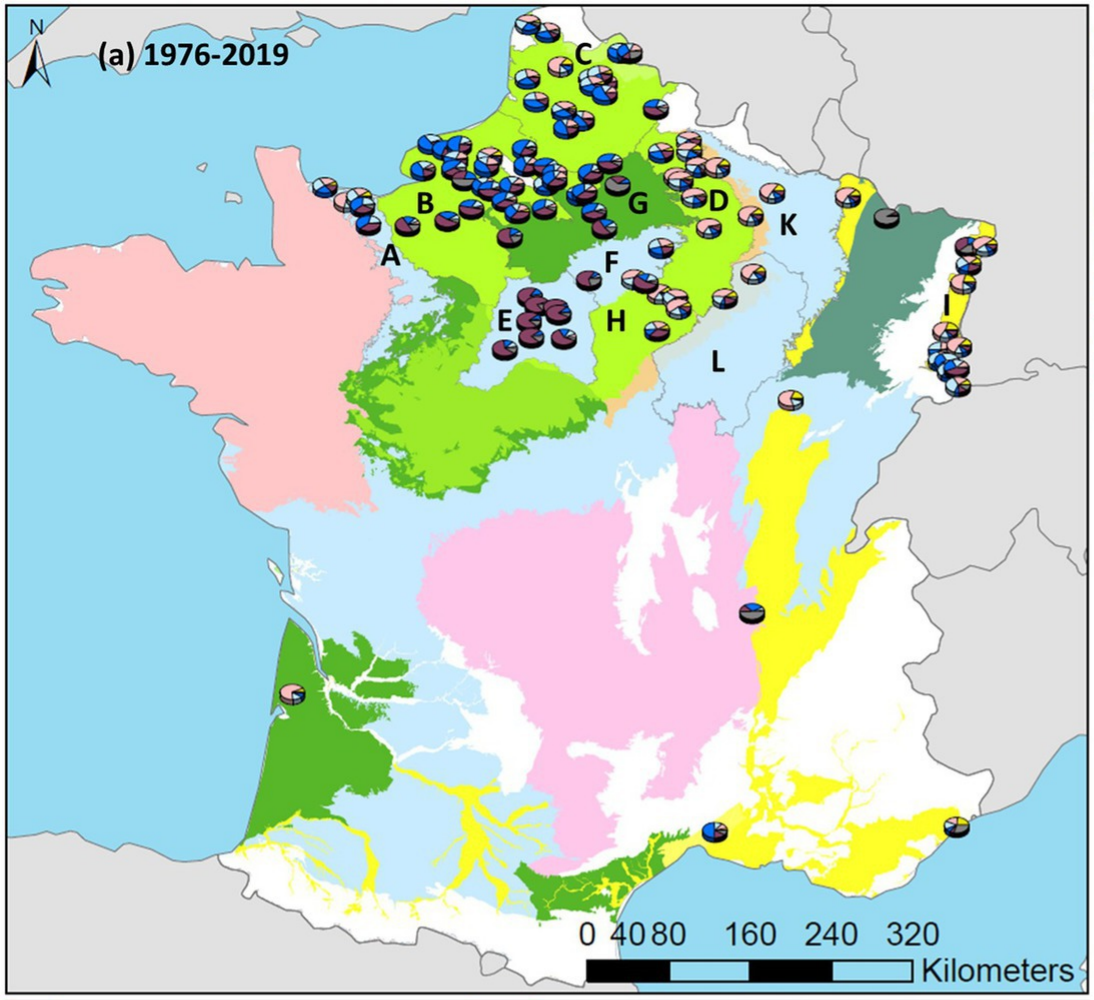


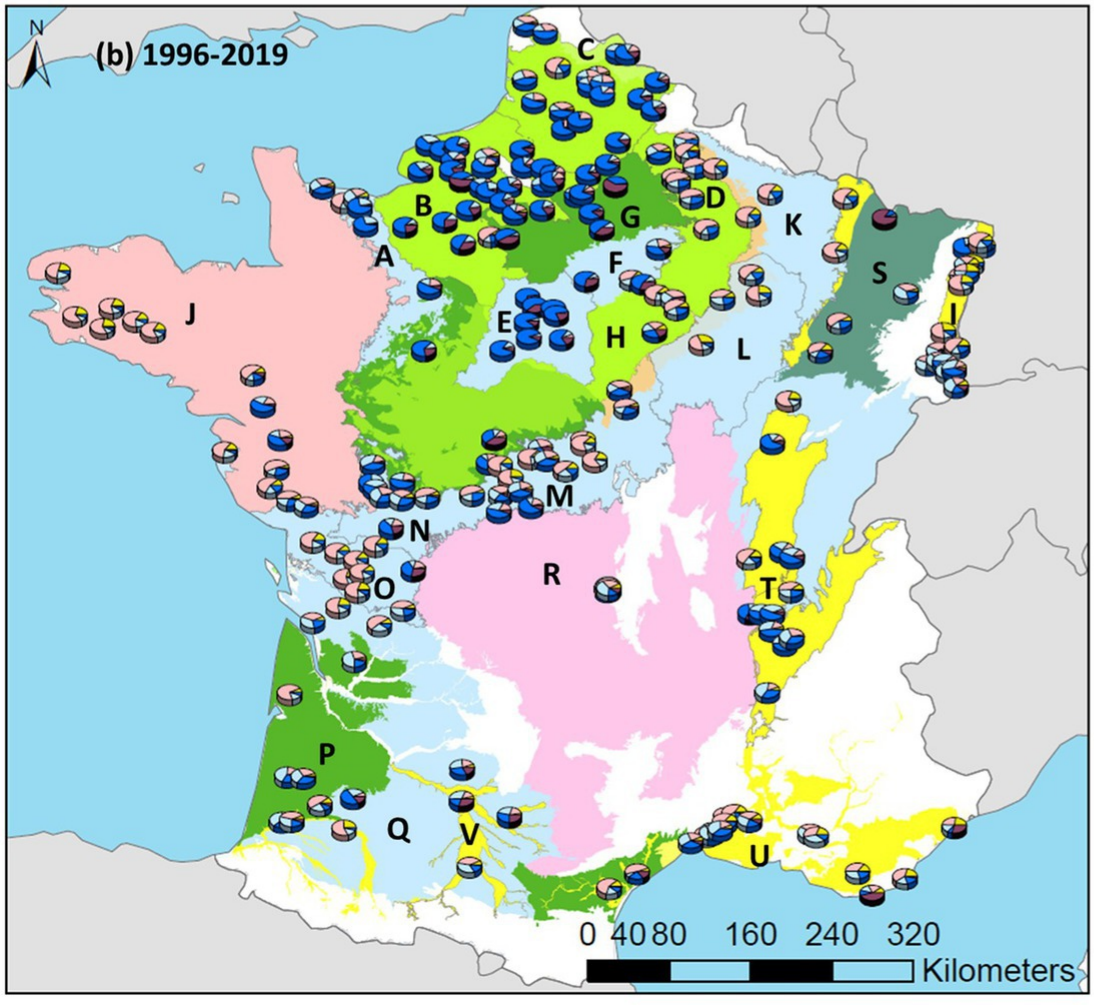
1996-2019 :

- Sen's slope = -0.4 cm/month
- *Slope/WLF = -15% of WLF*

2000-2019 :

- Sen's slope = -0.6 cm/month
- *Slope/WLF = -19% of WLF*





Legend

Aquifer group

- Alluvial formations
- Bedrock
- Chalk
- Greensands
- Limestones
- Sand
- Sandstones
- Volcanic formations
- Not studied formations

Energy distribution (%)

- < 1 year
- 1 year
- 1-5 years
- 5-12 years
- 12-24 years
- > 24 years

Hydrogeological entities

A Jurassic limestones from Bessin to Sarthe

B Seno-Turonian chalk of Normandy/Picardy

C Seno-Turonian chalk of Artois-Picardy

D Seno-Turonian chalk of Champagne

E Limestones of Beauce

F Upper Eocene limestones of Paris Basin

G Lutetian and Ypresian sands of Paris Basin

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J Bedrock of Brittany

K Jurassic limestones of Lorraine

L Jurassic limestones of Côte-des-Bars

M Jurassic limestones of Berry

N Jurassic limestones of Poitou

O Fractured Jurassic limestones of northern Aquitaine Basin

P Plio-Quaternary sands of Aquitaine Basin

Q Various calcareous formations of Aquitaine Basin

R Volcanic formations of Central Massif

S Triassic sandstones and limestones of Lorraine

T Fluvio-glacial formations of Rhone valley

U Alluvial formations of Mediterranean region

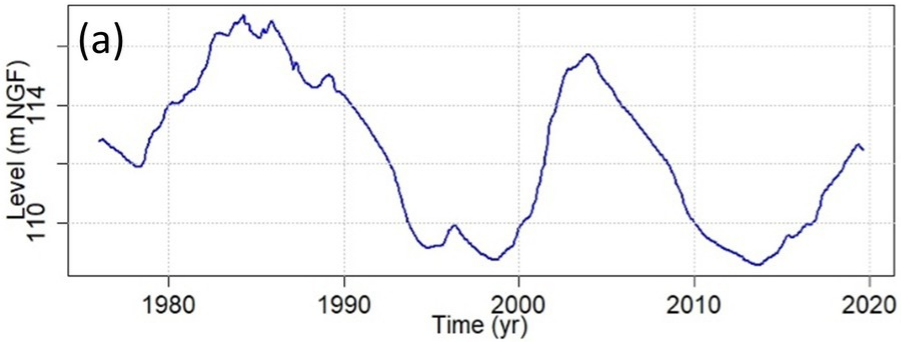
V Alluvial formations of Garonne

Inertial

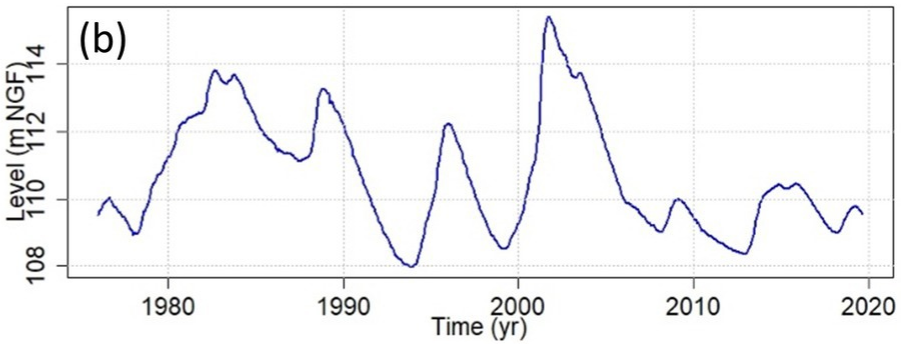
Combined

Annual

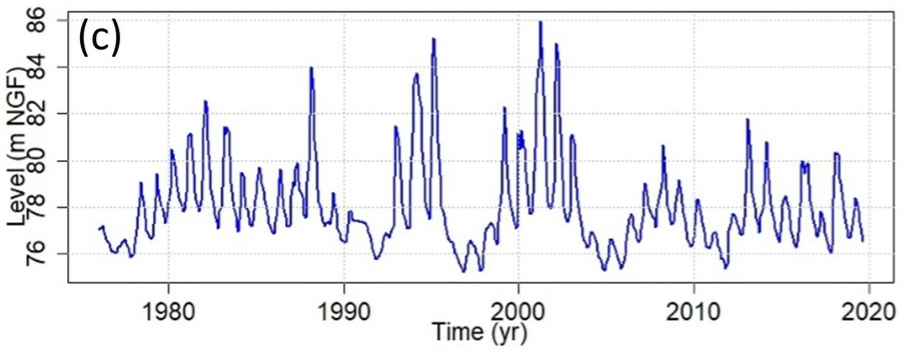
Limestones of Beauce



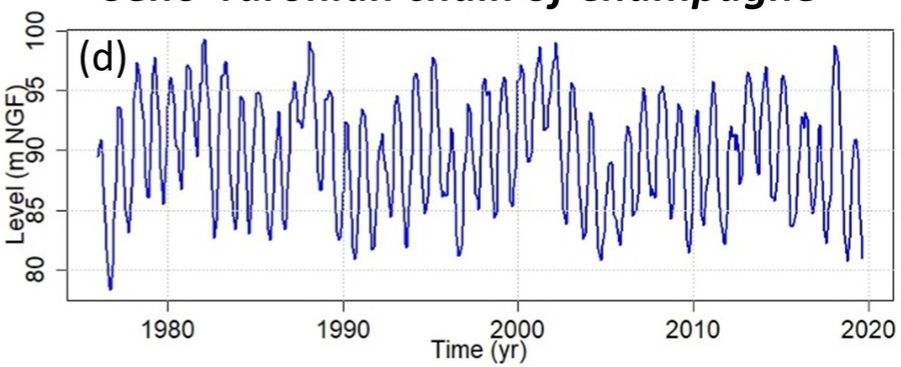
Seno-Turonian chalk of Normandy



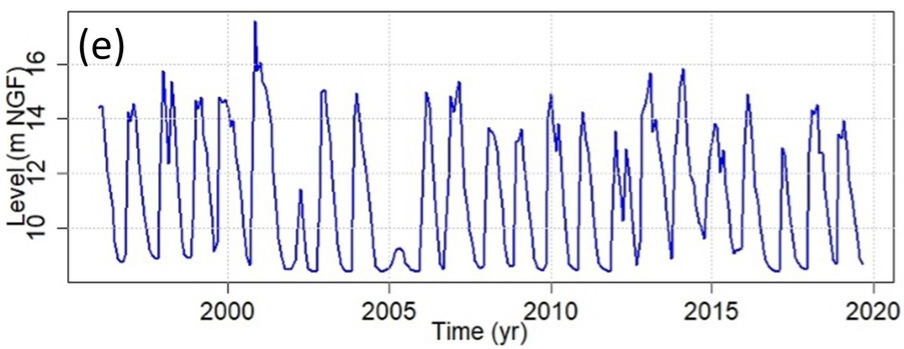
Seno-Turonian chalk of Artois-Picardy

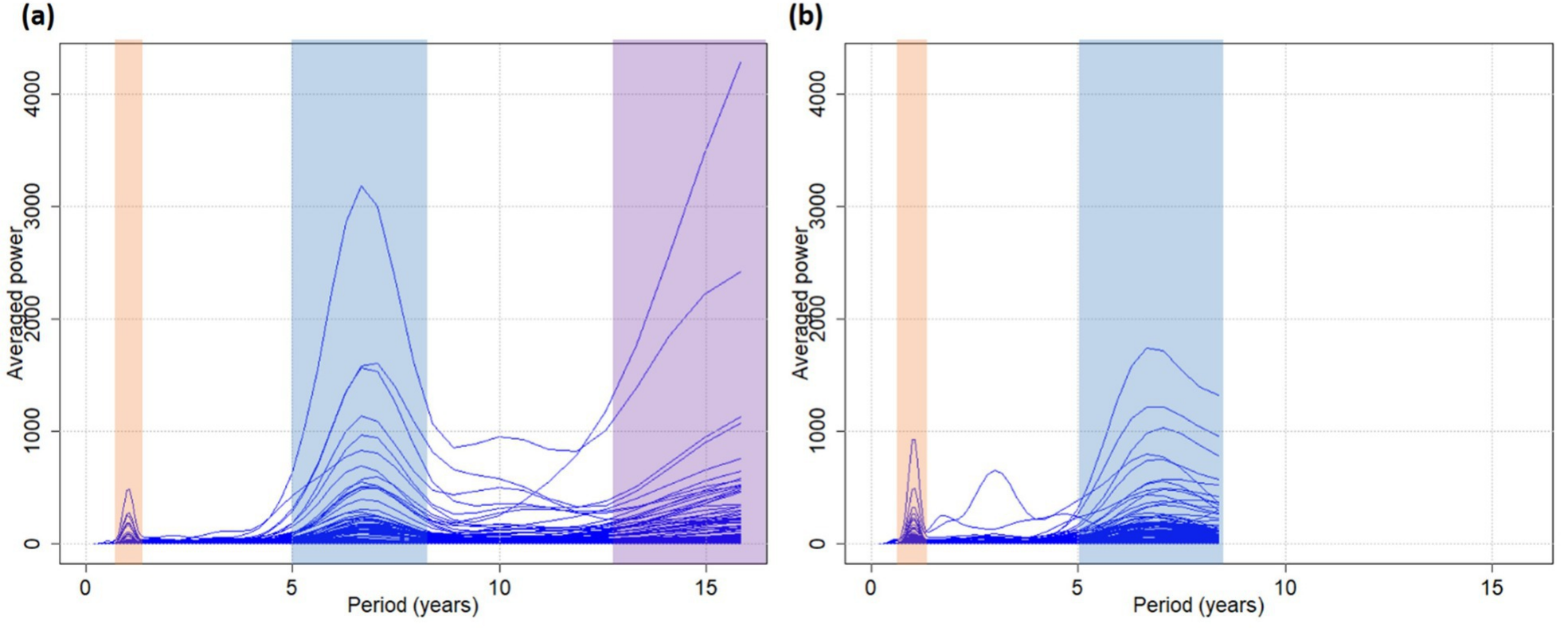


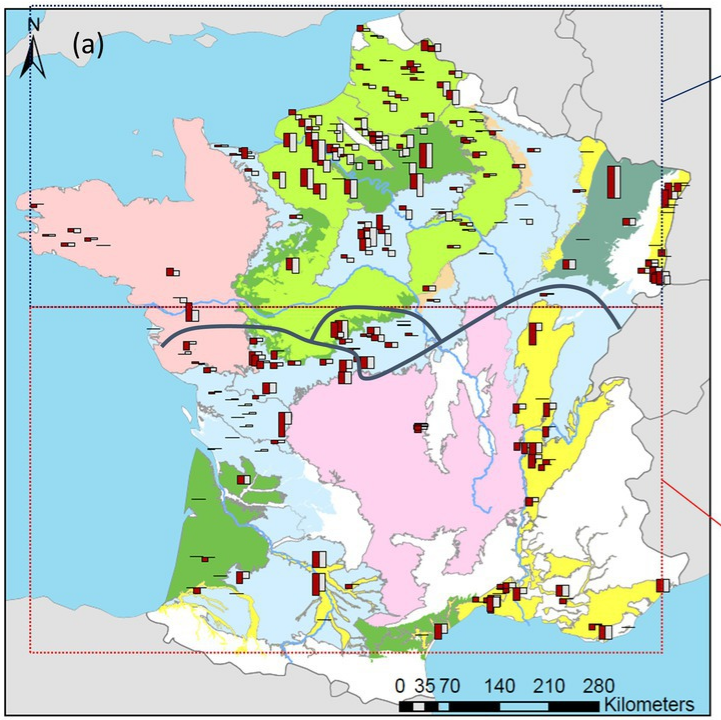
Seno-Turonian chalk of Champagne

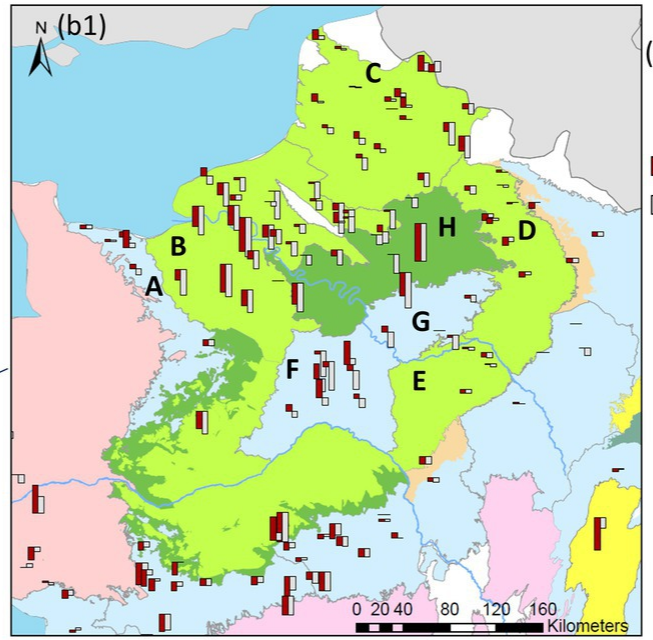


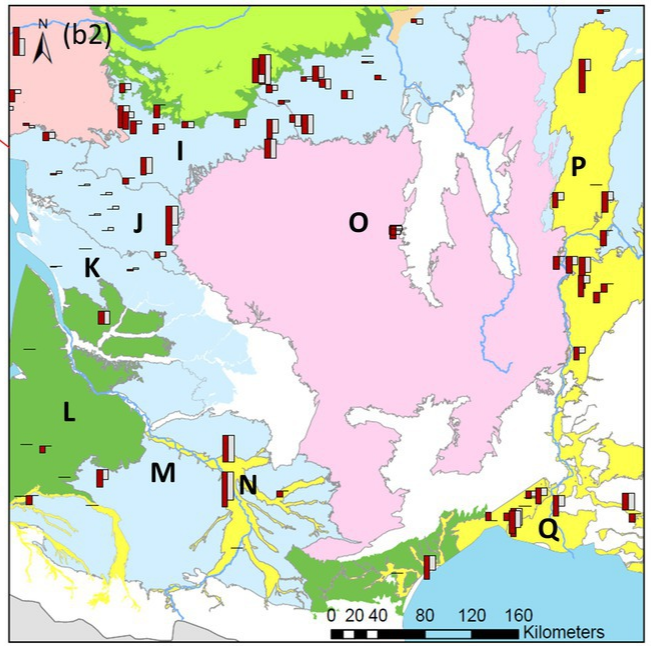
Jurassic limestones of northern Aquitaine Basin




(a)
(b)
Averaged power
0
1000
2000
3000
4000
0
5
10
15
Period (years)







~7 years timescale drives upward groundwater levels

~7 years timescale drives downward groundwater levels

Ratio Sen's slope/maximum WLF

(a) +80% / 0% / -80% — Upward trend / Downward trend

(b) +60% / 0% / -60%

Raw groundwater levels (monthly averages)

7yrs filtered groundwater levels

Pattern reversal boundary

Aquifer group

- Bedrock
- Chalk
- Greensands
- Limestones
- Not studied formations
- Sand
- Sandstones
- Volcanic formations
- Alluvial formations

Hydrogeological entities

A Jurassic limestones from Sarthe to Bessin

B Seno-Turonian chalk of Normandy/Picardy

C Seno-Turonian chalk of Artois-Picardy Basin

D Chalk of Champagne

E Upper Cretaceous chalk of Bourgogne

F Limestones of Beauce

G Eocene limestones of Paris Basin

H Lutetian and Ypresian sands of Paris Basin

I Jurassic limestones of Poitou

J Fractured Jurassic limestones of northern Aquitaine Basin

K Upper Cretaceous limestones of Angoumois

L Plio-Quaternary sands of Aquitaine Basin

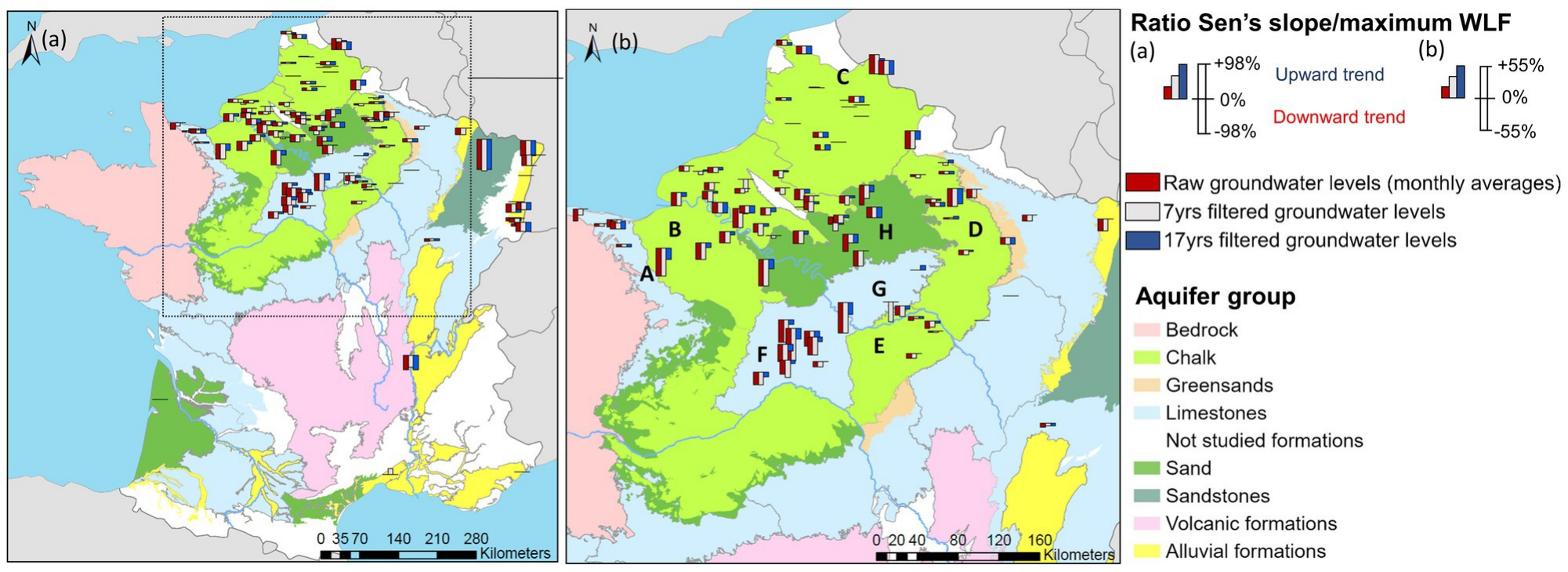
M Calcareous formations of Aquitaine Basin

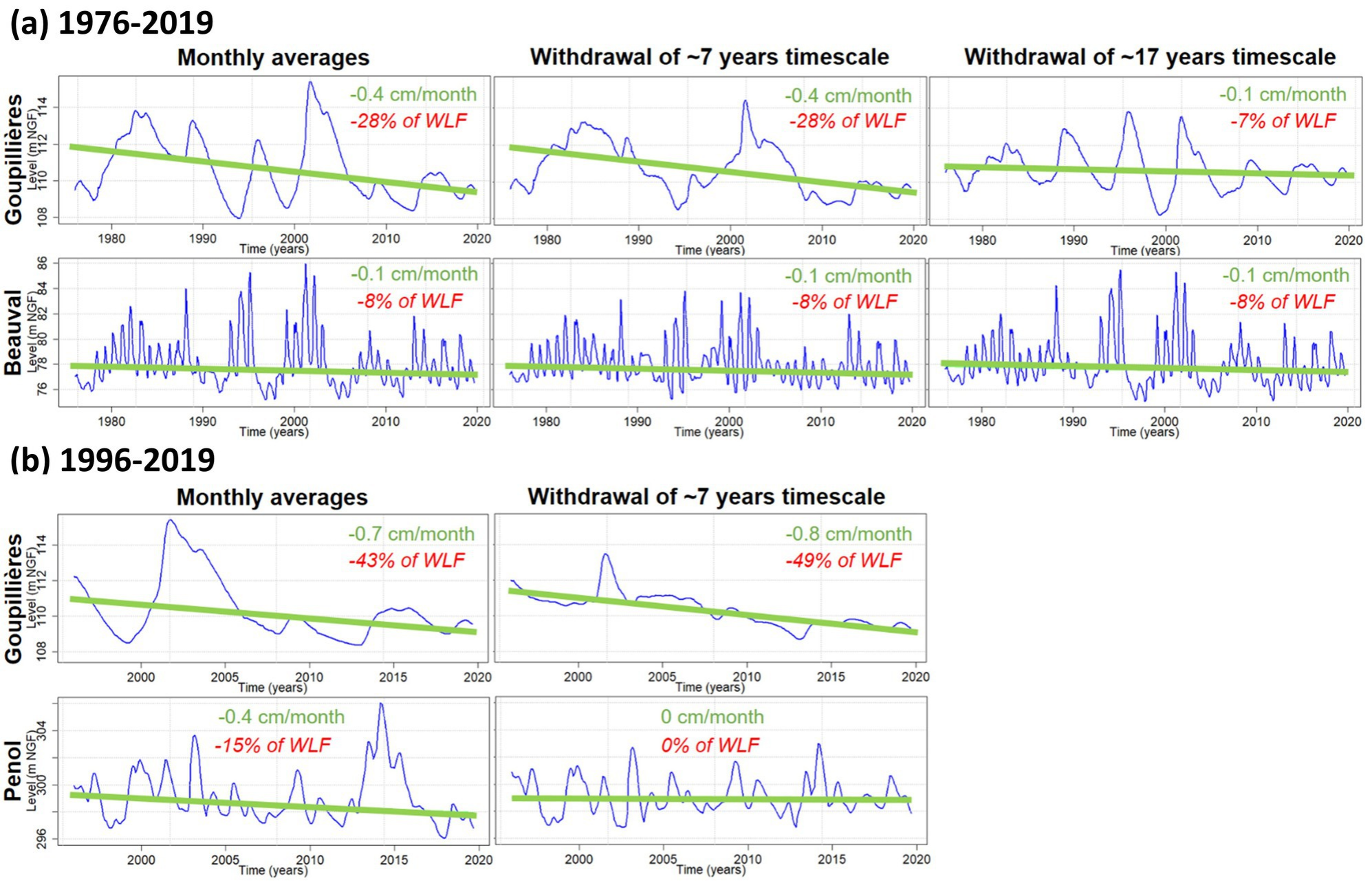
N Alluvial formations of Garonne

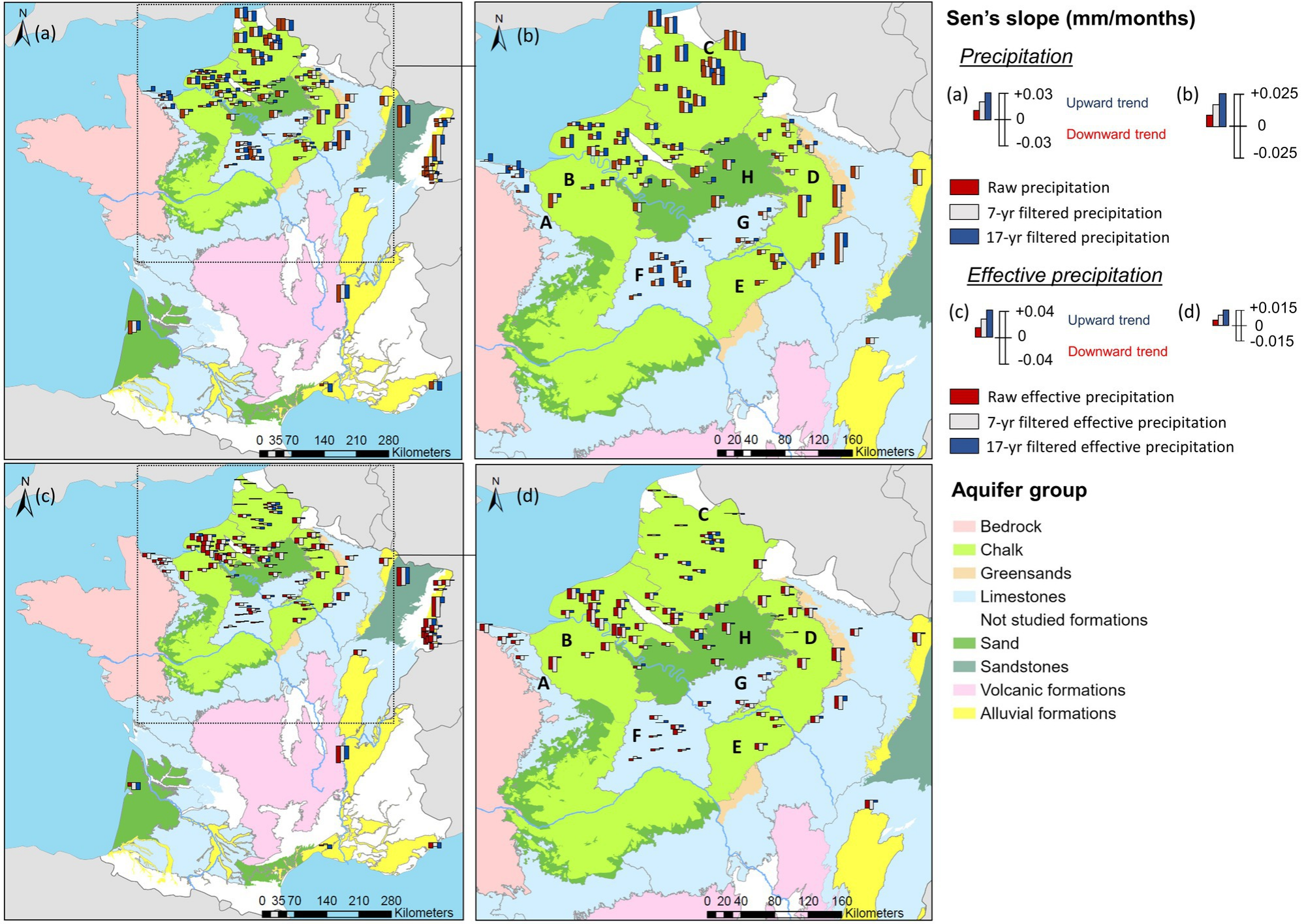
O Volcanic formations of Central Massif

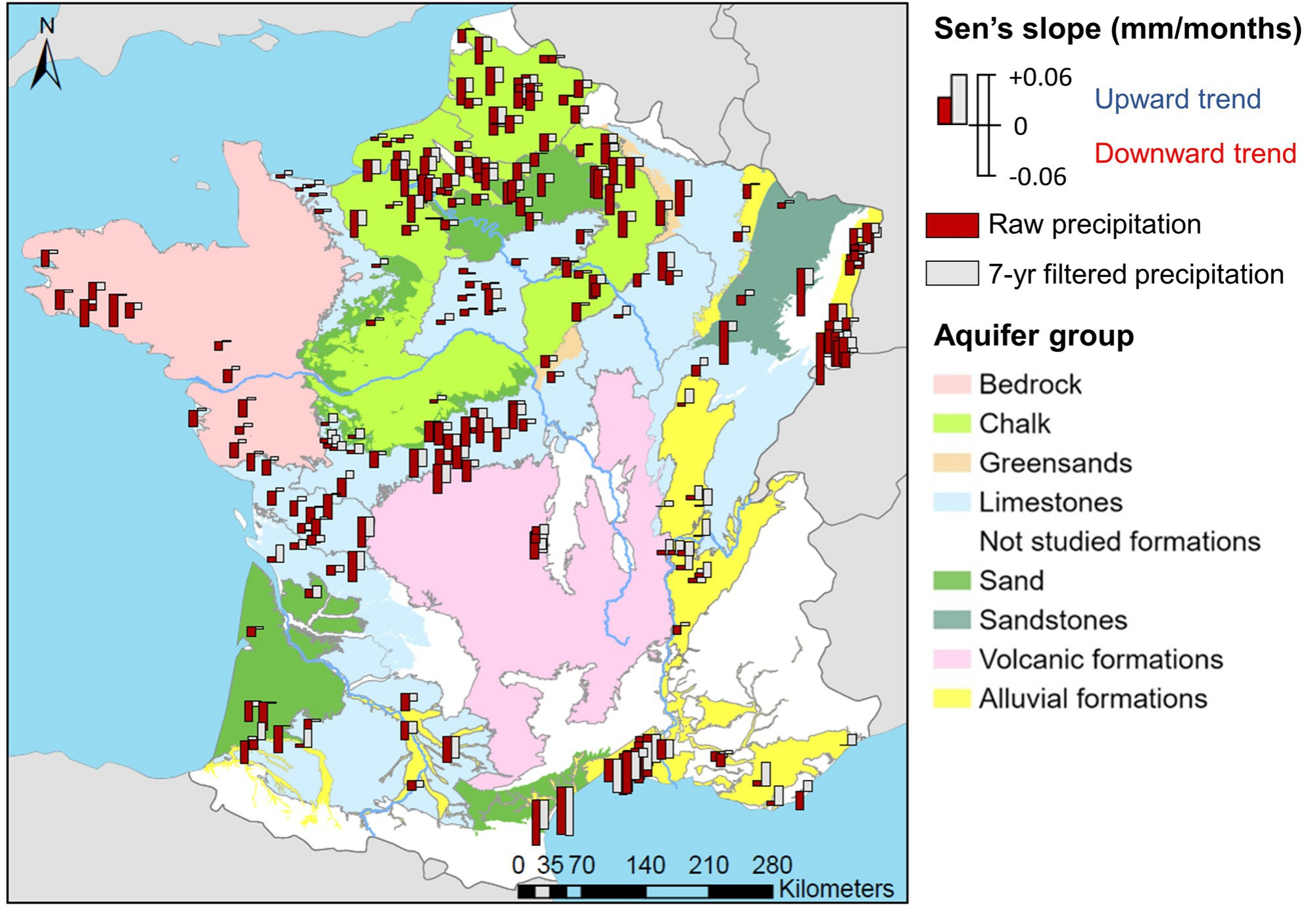
P Fluvio-glacial formations of Rhone valley

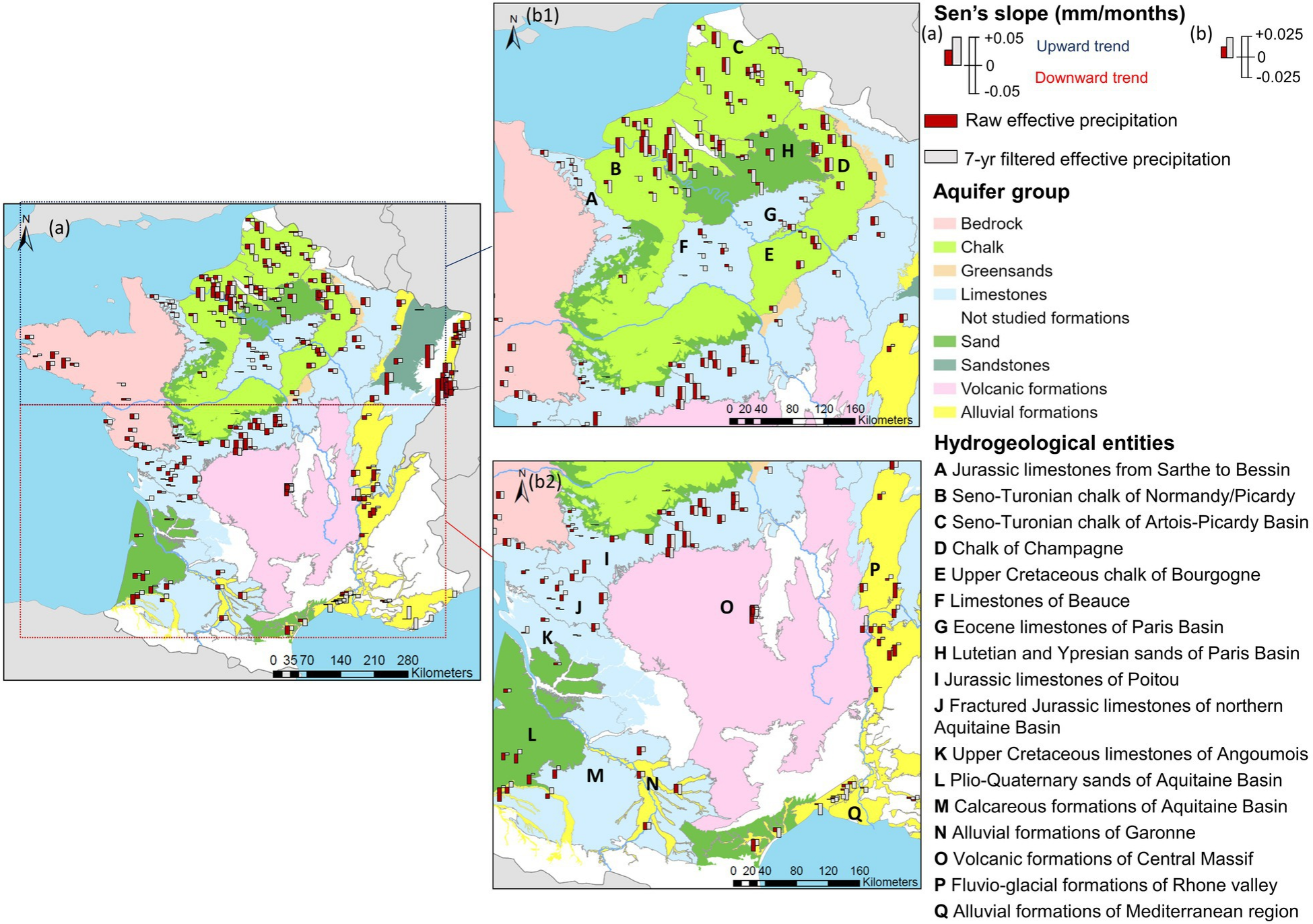
Q Alluvial formations of Mediterranean region


(a)
N
0 35 70 140 210 280
Kilometers
(b)
N
A
B
C
D
E
F
G
H
0 20 40 80 120 160
Kilometers
Ratio Sen's slope/maximum WLF
(a)
+98%
0%
-98%
Upward trend
Downward trend
(b)
+55%
0%
-55%
Raw groundwater levels (monthly averages)
7yrs filtered groundwater levels
17yrs filtered groundwater levels
Aquifer group
Bedrock
Chalk
Greensands
Limestones
Not studied formations
Sand
Sandstones
Volcanic formations
Alluvial formations


(a) 1976-2019
Monthly averages
Withdrawal of ~7 years timescale
Withdrawal of ~17 years timescale
Goupillières
Level (m NGF)
-0.4 cm/month
-28% of WLF
-0.4 cm/month
-28% of WLF
-0.1 cm/month
-7% of WLF
Beauval
Level (m NGF)
-0.1 cm/month
-8% of WLF
-0.1 cm/month
-8% of WLF
-0.1 cm/month
-8% of WLF
Time (years)
(b) 1996-2019
Monthly averages
Withdrawal of ~7 years timescale
Goupillières
Level (m NGF)
-0.7 cm/month
-43% of WLF
-0.8 cm/month
-49% of WLF
Penol
Level (m NGF)
-0.4 cm/month
-15% of WLF
0 cm/month
0% of WLF
Time (years)


(a)
(b)
(c)
(d)
N
0 35 70 140 210 280
Kilometers
0 20 40 80 120 160
Kilometers
A
B
C
D
E
F
G
H
Sen's slope (mm/months)
Precipitation
(a)
+0.03
0
-0.03
Upward trend
Downward trend
(b)
+0.025
0
-0.025
Raw precipitation
7-yr filtered precipitation
17-yr filtered precipitation
Effective precipitation
(c)
+0.04
0
-0.04
Upward trend
Downward trend
(d)
+0.015
0
-0.015
Raw effective precipitation
7-yr filtered effective precipitation
17-yr filtered effective precipitation
Aquifer group
Bedrock
Chalk
Greensands
Limestones
Not studied formations
Sand
Sandstones
Volcanic formations
Alluvial formations


N
Sen's slope (mm/months)
+0.06
0
-0.06
Upward trend
Downward trend
Raw precipitation
7-yr filtered precipitation
Aquifer group
Bedrock
Chalk
Greensands
Limestones
Not studied formations
Sand
Sandstones
Volcanic formations
Alluvial formations
0 35 70 140 210 280
Kilometers


(a)
(b1)
(b2)
N
0 35 70 140 210 280
Kilometers
0 20 40 80 120 160
Kilometers
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
Sen's slope (mm/months)
(a)
+0.05
0
-0.05
Upward trend
Downward trend
(b)
+0.025
0
-0.025
Raw effective precipitation
7-yr filtered effective precipitation
Aquifer group
Bedrock
Chalk
Greensands
Limestones
Not studied formations
Sand
Sandstones
Volcanic formations
Alluvial formations
Hydrogeological entities
A Jurassic limestones from Sarthe to Bessin
B Seno-Turonian chalk of Normandy/Picardy
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K Upper Cretaceous limestones of Angoumois
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M Calcareous formations of Aquitaine Basin
N Alluvial formations of Garonne
O Volcanic formations of Central Massif
P Fluvio-glacial formations of Rhone valley
Q Alluvial formations of Mediterranean region