École Polytechnique - Master 2 Water, Air, Pollution & Energy (WAPE)

Internship report

carried out in the Laboratoire de Géologie de l'ENS
under the supervision of Florence Habets

Return of experience on the first year of operational seasonal forecasts of the groundwater resource

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Declaration of Academic Integrity

Hereby I, André Mounier, confirm that:

- The results presented in this report are my own work.
- I am the author of this report.
- I have not used the work of others without clearly acknowledging it, and quotations and paraphrases from any source are clearly indicated.

André Mounier September 7, 2021

First and foremost, I would like to deeply thank Florence Habets for having supervised my internship, for having introduced me to the work teams and for having presented the issues and topics of the internship in a pedagogical and well-ordered way. I would also like to thank the entire Aqui-FR project team, and especially Simon Munier and Jean-Marie Willemet, who were very attentive to my questions and queries throughout my internship.

I sincerely thank Antoine Sobaga, Hélène Rouby and all the members of the Laboratoire de Géologie de l'École Normale Supérieure for having welcomed me since April 2021. I also thank Nathan Vani for the mutual support during our internships.

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Introduction

An aquifer is a soil or a reservoir rock, originally porous or fissured, containing water and sufficiently permeable for water to circulate. Far from being isolated from the water cycle, these groundwater aquifers communicate with surface water environments and meteorological phenomena influence their dynamics. Global groundwater withdrawal increased by nearly 6 times from $\approx 500\,\mathrm{km}^3.\mathrm{yr}^{-1}$ in 1900 to $\approx 3000\,\mathrm{km}^3.\mathrm{yr}^{-1}$ in 2000 representing 25% of the freshwater abstractions [1]. Of these withdrawals, 70% are for irrigation, 20% for domestic needs and 10% for industry [1]. In France, the share of groundwater intakes was 50% in 2019 (excluding energy), of which 60% was for drinking water supply, 25% for irrigation and 15% for industrial uses [2]. The differences between the French values and the international averages are explained by the geographical and climatic specificities of France. The French aquifers are vast, recharge relatively quickly thanks to abundant precipitation and the climate reduces the need for massive irrigation.

However, climate change due to anthropogenic greenhouse gas emissions is likely to affect water resources in France. The rise in temperature and the modification of the climate in Western Europe could lead to an aridification of the territory [3]. This risk, coupled with the weak understanding of the resource by citizens and decision-makers [4], reinforces the relevance of related studies. Water, and especially groundwater, is a strategic resource [5] for which analysis and forecast studies are crucial.

The Aqui-FR platform aims to forecast groundwater resources over an increasing fraction of the French territory (currently about 30%). Forecasts can be monthly or seasonal (6 months) or even participate in climate projections for the end of the century. The objective of my internship is to characterize the quality of the seasonal forecasts of Aqui-FR low water period by developing computing tools (Python codes) with a focus on real time in order to produce future analyses automatically. To develop such tools, I had to discuss with the different Aqui-FR members and with many regional groundwater experts and local public service actors of aquifer management. These actors have permitted to better delimit the uses and the expectations around the Aqui-FR seasonal forecast processing tools.

This report is divided into three parts. First, the architecture of the Aqui-FR platform is presented, as well as the Aqui-FR models and the different data used: observations, Aqui-FR reanalyses and Aqui-FR forecasts. Then, the verification of the operational forecasts is conducted, in relation to the observations and the reanalyses. Finally, a focus on drought periods is carried out in order to analyse and characterise their forecasts.

Part 1

Structure of the Aqui-FR platform and data acquisition

1.1 Structure and models of the Aqui-FR platform

1.1.1 Context and contributors to the Aqui-FR project

In recent years, new predictive models of groundwater levels have been developed. These models are mainly local, for given aquifers at risk [6], but there are also models on a quasi-national scale such a model in Denmark[7]. This Danish model is a physical model like Aqui-FR but there are also behavioural models using Artificial Neural Network [8].

The Aqui-FR project is a national hydrogeological modelling project involving the Bureau des Recherches Geologiques et Minières (BRGM), Météo-France, the Ecole des Mines ParisTech, the Ecole Normale Supérieure (ENS), the Centre National de la Recherche Scientifique (CNRS) and the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS). At the time of my internship, the Office Français de la Biodiversité (OFB) was also funding the project.

For now, the area covered by Aqui-FR is mainly the Paris basin (composed of the Seine, Somme, Normandy and Nord-pas-de-Calais basins), Poitou-Charente and two areas in Alsace and Tarn-et-Garonne [Figure 1.1]. This coverage will be extended over the years by integrating local models developed by some of the actors [9]. Aqui-FR is not intended to replace local studies and models, but rather to provide an overall view of the hydrogeological situation in France. In addition, the models make it possible to carry out forecasts in the more or less long term. I focused on so-called seasonal forecasts, i.e. forecasts for the next 6 months.

The main objective of these seasonal forecasts is to anticipate water shortage periods that may occur during low water periods (between July and October). An accurate and reliable forecast of drought periods would allow better management of the strategic and precious water resource Therefore, the Aqui-FR forecasts are used by the Comité d'Anticipation et de Suivi Hydrologique (CASH) created by the French Ministry of the Environment in May 2021 [10].

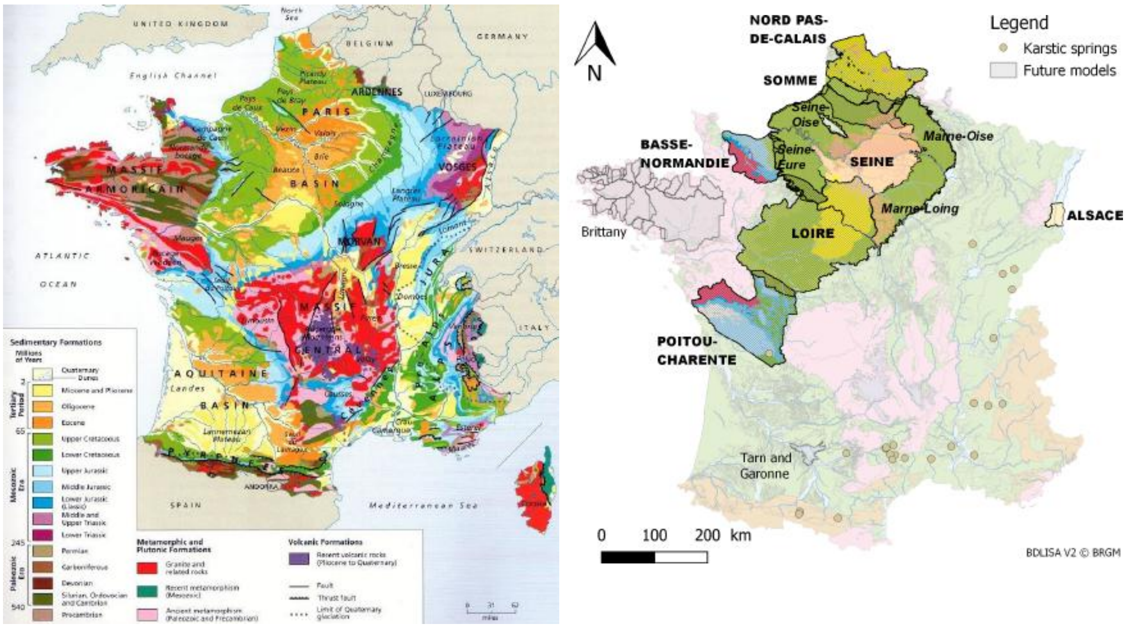

Figure 1.1: Geological map of France and Aqui-FR domain
Comparing the map of the different geological layers of France with the Aqui-FR domain map, it can be seen that the areas currently covered by Aqui-FR correspond to the large sedimentary aquifers of northern France. The Aqui-FR domain map was made in 2019, when the Tarn-et-Garonne application was not yet implemented. At the time of my internship, the basement aquifers of Brittany are still being added.

1.1.2 The Aqui-FR model

The Aqui-FR platform is an assembly of regional models (at the scale of applications) based on two numerical models: Eaudyssée and Marthe [9]. Some of the Eaudyssée applications overlap with Marthe applications, which makes the area covered by Aqui-FR a puzzle of various applications [Figure 1.1]. The link of all the model is made *via* OpenPalm, a diagram of which is presented below [Figure 1.2].

The different Eaudyssée and Marthe applications are multi-layered but the number of layers differs between models and applications. In addition, the Aqui-FR models have a good resolution as the mesh sizes range from 100 m^2 to 64 km^2. The grid cell areas vary between the different applications but also within the same application, depending on the physical properties of the modelled area. The models solves the transfer of water from the unsaturated soil to multi layers aquifers, in connexion with river flow *via* aquifer-river exchanges, and taking into account groundwater abstraction. The surface water budget is in all cases computed by a land surface model: SURFEX. The SURFEX platform (Surface Externalisée) [11] is a surface modelling platform developed by Météo-France composed of various physical models for natural land surface, urbanized areas, lakes and oceans. It allows the reconstruction of the surface water and energy balances, and especially infiltration and run-off over the whole Aqui-FR domain.

Although it is well known that seasonal forecast of precipitation has low skill in Europe, groundwater seasonal forecast are still usable because they rely on the inertial properties of the different aquifers and a threshold effect occur when evaporation is greater than the precipitations. One should then expect more accurate weather forecasts when starting a forecast in April than in October, as aquifer recharge is lower during the period covered by the first forecast [12]. However, when using a frequency standardised index such as the monthly computed Standardised piezometric Index Level (SPLI) presented hereafter, the evolutions become more difficult to predict. Nevertheless, the models used by Aqui-FR have demonstrated a certain reliability, even with this type of index, as shown in Leroux *et al.* paper [13].

1.1.3 Meteorological models and Aqui-FR structure

In order to run simulations with the Aqui-FR platform, climate data, or atmospheric forcings, must be provided. To do this, the System 7 climate prediction model from Météo-France is in use since 2020 [14], replacing the Arpège 6 model [15]. Every 18 months, the weather forecasting models are updated and made more efficient, but the precipitation forecast on a seasonal scale remains difficult.

Despite the difficulties of meteorological forecast, they are still relevant in the context of Aqui-FR forecasts. In an in progress paper, Leroux *et al.* have studied the reliability of the seasonal forecast on a 25 years hindcast and have shown that the piezometric level forecasts were better when the atmospheric forcings comes from weather forecasts compared to two other types of data: a random corpus of past atmospheric forcings (noted PCLIM) and the assumption of a constant standardised index over the whole forecast (noted NOPERT) [13]. These results justify the use of six-month weather forecasts and the fact that such forecasts give reliable and accurate results is allowed by the hydrogeological dynamics of the aquifers. The weather forecasts are actually the association of 51 weather forecasts that are used for as many hydrogeological forecasts. These 51 forecasts are called members and their variability reinforce the forecasts robustness.

As stated above, three types of atmospheric forcings are usually compared. Among these three types, I was led to use weather forecasts and PCLIM forcings. The PCLIM forcings are produced by using data from several years in the past. These past data come from the SAFRAN [16] analysis and are called reanalyses because they are the result of modelling plus observations. It will be shown later that these reanalyses play a key role in the Aqui-FR forecasts. The link between atmospheric forcings, SURFEX calculations and Aqui-FR models is made with Open-Palm (a CERFACS and ONERA software) [Figure 1.2].

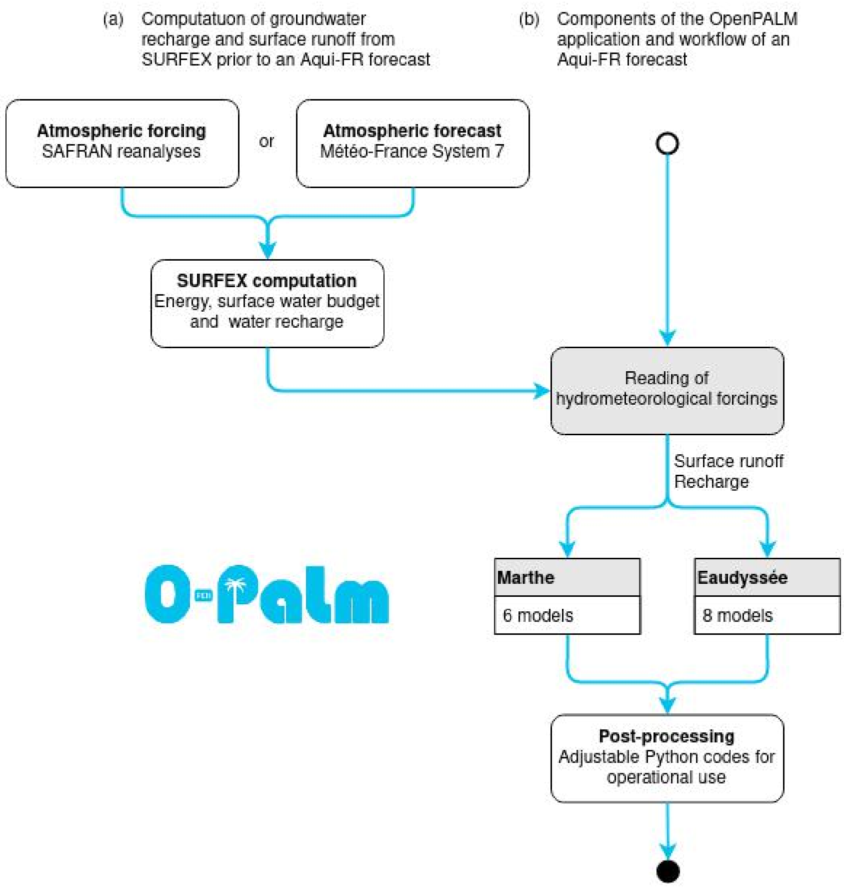

Figure 1.2: Diagram of the numerical implementation of Aqui-FR
This scheme is a modified version of the one presented in Vergnes et al. 2020 [17]. The main focus of this internship is the evaluation part, with the development of the post-process in Python.

1.1.4 Evaluations and validations

The Aqui-FR model outputs have already been evaluated and validated in two articles. The evaluation of the reanalyses with respect to the observations was carried out by Vergnes *et al.* [17] and the absolute bias between these two quantities is quantified. The map below illustrates the spatial variations in bias that may exist [Figure 1.3].

The validation of Aqui-FR forecasts was presented in the article by Leroux *et al.* [13]. This work allowed to relate the forecasts to the reanalyses from 1993 to 2016. The results of this study show a very good correlation of seasonal forecasts, particularly during periods of low groundwater recharge [Figure 1.4]. Moreover, Leroux's article also focuses on the forecasting of low water periods, on which I will return later.

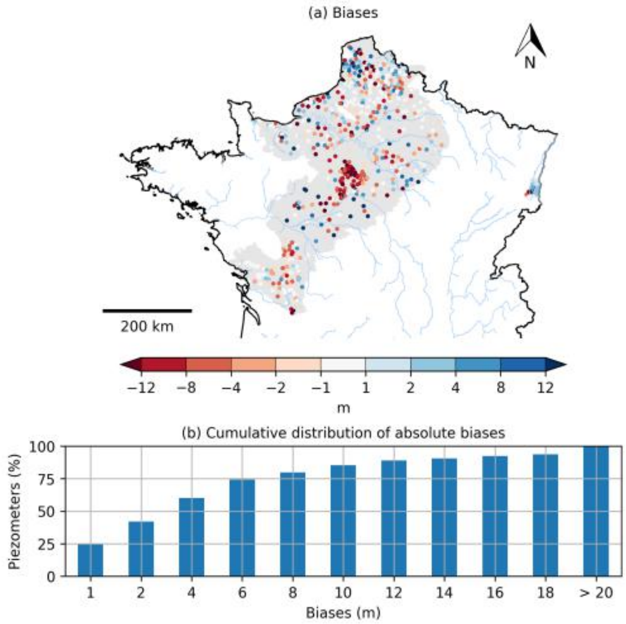

Figure 1.3: Spatial distribution of the biases

This figure is taken directly from the article by Vergnes et al. (Figure 6) [17]. Cumulative distribution of absolute biases for all piezometers is also displayed.

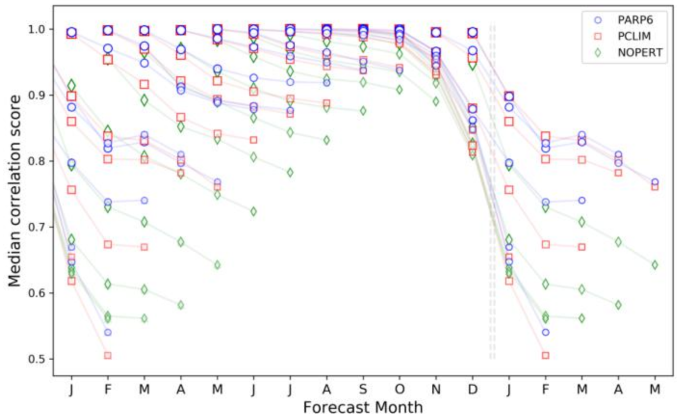

Figure 1.4: Median correlation scores

This figure is taken directly from the article by Leroux et al. (Figure 5) [13]. The graph displays median correlation scores for PARP6 (blue circles), PCLIM (red squares) and NOPERT (green diamonds) as a function of initialization month and lead time. Single lines indicate a continuous 6-month forecast and the markers become smaller with the lead time.

Therefore, it can be seen that one step has not yet been carried out: the verification of the forecasts against the observations. This is the subject of the internship, using the operational forecasts.

1.2 Overview of model output and observed data

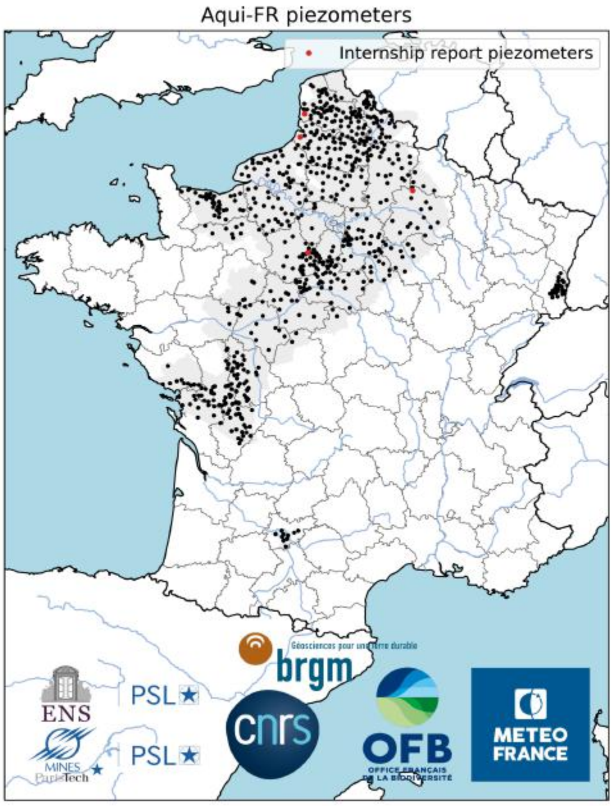

Figure 1.5: Map of the Aqui-FR piezometers
The map shows the 701 piezometers selected as output of the Aqui-FR platform. These piezometers were selected for their reliability, data quality and representativeness. Also shown in light grey is the area covered by Aqui-FR. It is easy to notice the spatial variations in density as well as the areas where there are virtually no piezometers, especially on the edges of the domain. The four piezometers in red are the ones I use as examples throughout this report.

1.2.1 Observational data on Aqui-FR coverage area

An essential step is to retrieve the observed data from the piezometers selected by the Aqui-FR team for their reliability. To access the observed data on these piezometers, I used an API of Hub'Eau, a EauFrance (public service of information on water) tool to download the piezometric levels chronicles [Figure 1.6]. The Hub'Eau Piezometry API data comes from the ADES (Accès aux Données des Eaux Souterraines) platform, developed by BRGM. I coded this data retrieval in such a way as to be able to easily update the databases when new measurements are added by BRGM, as the analysis described in this report is to be completed every month.

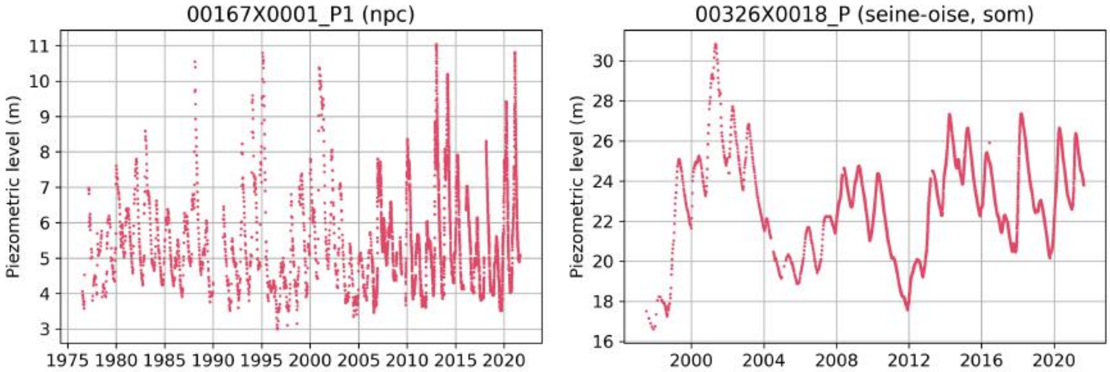

Figure 1.6: Examples of observed time series

These two piezometers present data over different periods and at increasingly higher sampling frequencies. More and more piezometers are equipped with antennas to transmit their information remotely at a daily time scale.

In fact, the majority of the piezometers do not have records as good as piezometer 00167X0001/P1. Some start much later and others cease to be operational and these fluctuations are very pronounced depending on the application [Figure 1.7]. Thus, piezometers not currently maintained cannot be used to characterise the Aqui-FR forecasts as they did not start until 2019, while the operational forecast started in 2020.

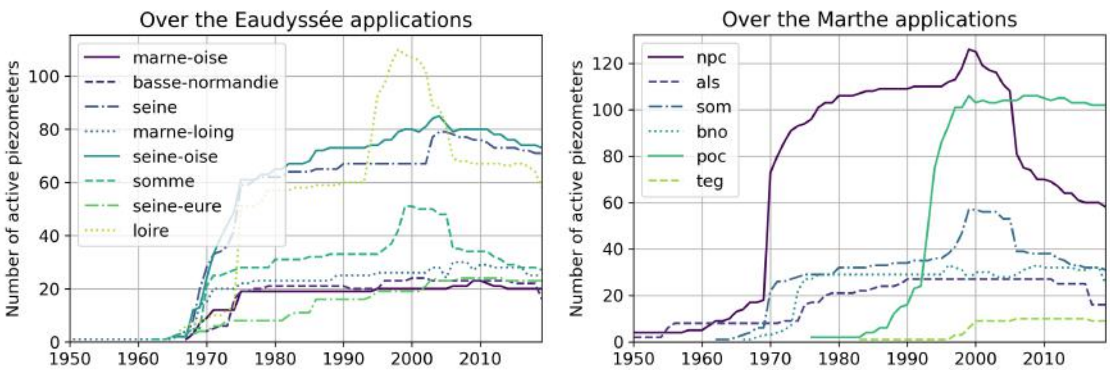

Figure 1.7: Evolution of the number of active piezometers

For most applications, the number of piezometers increases in the early 1970s. The exception is the "poc" application, where the vast majority of piezometers are installed in the 1990s. It is also interesting to note the significant decrease in piezometers in the early 2000s. Here, the different applications are split into two graphs so as not to plot all 14 applications on the same one. But in the analysis, the Eaudyssée and Marthe[1] applications are not discriminated.

[1]"npc": Nord-pas-de-calais, "als": Alsace, "som": Somme, "bno": Basse-Normandie, "poc": Poitou-Charente, "teg": Tarn-et-Garonne

I set up some quality criteria to select the piezometers with given characteristics. I was thus able to establish that, among the 701 piezometers in the Aqui-FR domain, 349 have more than 30 years of data, 362 have monthly data with no gaps (less than one month between two successive measurements) and 450 piezometers have data in 2019, 2020 and 2021, the Aqui-FR forecast years.

1.2.2 Aqui-FR reanalyses

For each of the grid cells of each of the Aqui-FR applications, the SAFRAN analysis was used to construct a groundwater reanalysis from 1958 to the present. It is then possible to recreate the evolution of the piezometric level (PL) for each piezometer [Figure 1.8]. These reanalyses are compared to observations and allow the calibration of the different models for future forecasts. The benefit of reanalyses is that they present uninterrupted data over a large time period. I will show later that this is of great importance.

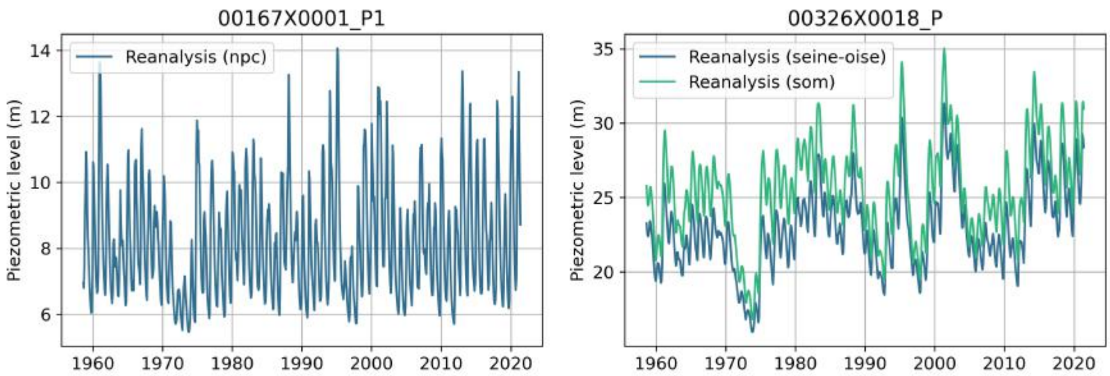

Figure 1.8: Examples of simulated piezometric levels

Some piezometers, such as piezometer 00167X0001/P1, are only present in one application, while others, such as piezometer 003226X0018/P, are included in several applications. In this case, the differences can sometimes be significant. It is therefore often necessary to pay attention to the chosen application when manipulating piezometer data.

In the same way as in the article by Vergnes *et al.* [17], I characterise the bias for all the piezometers used for my analysis on the intersections of the time periods of observations and reanalyses, but from 1958 to 2020. The absolute difference map is close [Figure 1.9] and similar findings to those presented in the article are obtained. For example, 50% of the piezometers had a bias of less than 3 m (in absolute value).

Neither of the two maps perfectly describes the bias between observations and reanalyses. On the one hand, the absolute difference exacerbates the continental regions where the piezometric levels are very high. Even a small relative deviation will then result in a very large absolute deviation. On the other hand, the relative difference accentuates the coastal regions. A very small level difference for a piezometer whose average value

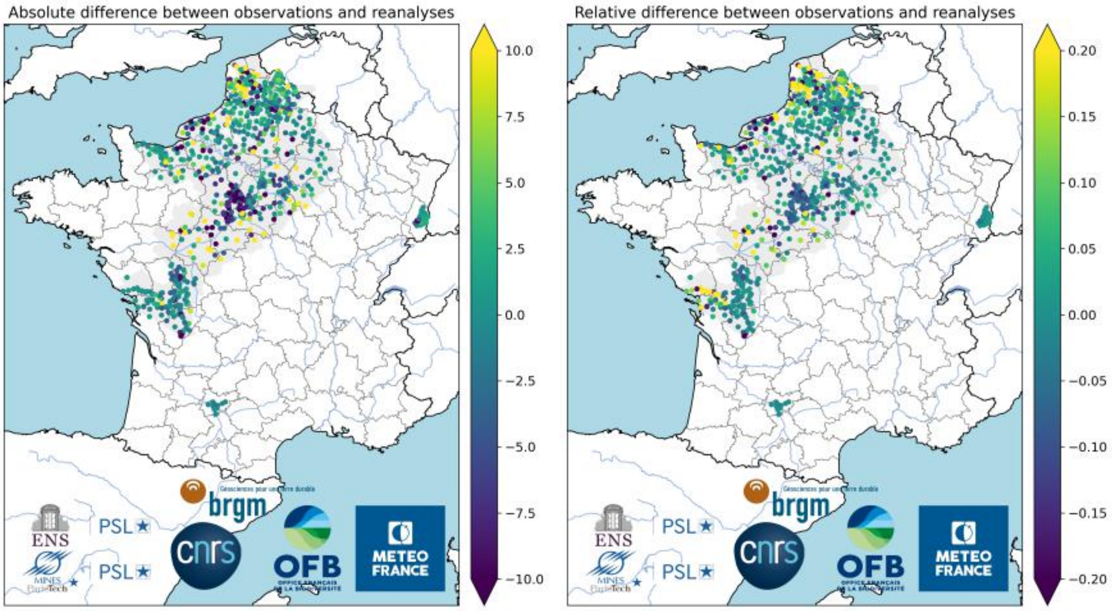

Figure 1.9: Differences between observations and reanalyses

On both maps, an area between Eure-et-Loire and Loiret (corresponding to the Beauce region) shows an under-estimation of the mean observed groundwater level. Elsewhere, no significant patterns appear.

may be 5 m will induce a very large relative difference. Nevertheless, systematic biases between reanalyses and observations are of limited interest when switching to frequency indices. In this way, the correlation coefficient between the quantities is computed.

For each of the Aqui-FR piezometers, the correlation coefficient between the observations and the reanalyses is calculated. The map below shows a mean value of 0.65 and a median of 0.71 [Figure 1.10]. These values are consistent with the ones given in the article by Vergnes *et al.* (whose average is 0.71) [17].

The cumulative distribution of the correlation coefficients [Figure 1.10] shows that about 30% of the piezometers present correlations higher than 0.8. However, there is still a non-zero fraction of piezometers with significantly worse results ($\approx$ 20% lower than 0.5). Furthermore, the map reveals certain areas (Nord-Pas-de-Calais, Alsace, Loire Basin) for which the correlations are low, between 0 and 0.5.

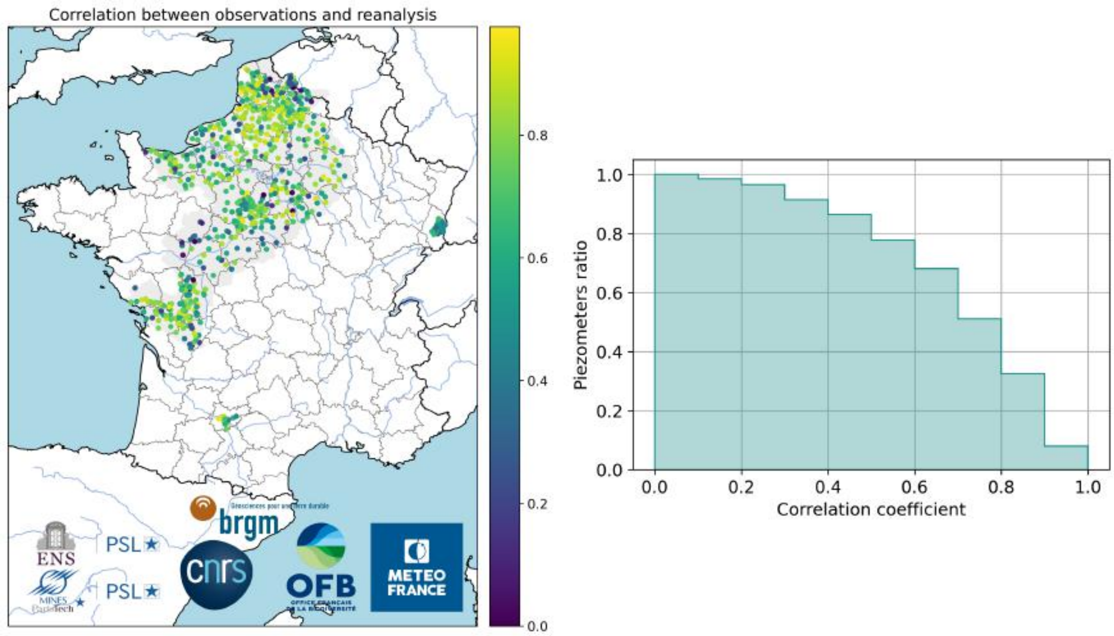

Figure 1.10: Correlations between observations and reanalyses
Map of the correlation coefficient between observations and reanalyses over the intersection of their definition period (left) and cumulative distribution of the correlations coefficients (right).

1.2.3 Aqui-FR forecasts

As mentioned, the hydrogeological forecasts using seasonal weather forecasts are composed of 51 members. As the lead time forecast increases, the dispersion between the members also increase. This explains why the inter-quantiles widen in the following figure [Figure 1.11]. This is especially true when the forecast is started in autumn or early winter. Indeed, the winter months present lower evapotranspiration [12] and are thus more sensitive to bias in precipitation forecasts. Thus, there is more uncertainty for these months and the variability between the different forecast members increases.

Aqui-FR forecasts are monthly averages of daily forecasts. This monthly average is mainly driven by the monthly calculation of the Standardised Piezometric Level Index (SPLI) presented in the following section. In addition, the initial forecast is a hybrid forecast because the simulation is launched on the 15th of each month. Thus, the first forecast includes 15 days of real time analysis and 15 days of forecasting.

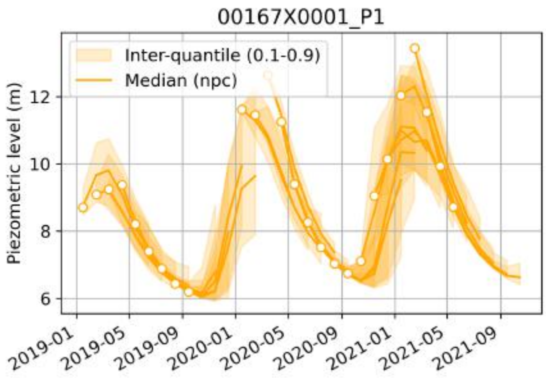

Figure 1.11: Examples of forecasts

The white points on the graphs correspond to the first month forecast (i.e. "first forecast"). At this point, the inter-member variability is almost zero. On the right-hand graph, the initial values for March 2020 are not even included in the inter-quantiles of the two previous forecasts. This reflects heavy rainfall that was not anticipated by the System 7 forecasts.

1.3 Standardised Piezometric Level Index: advantages and challenges of a frequency index

1.3.1 Presentation of SPLI and its benefits

The Standardised Piezometric Level Index (SPLI) is a frequency index that allows comparison of levels between different piezometers. Keeping the piezometric level (PL) (in m) make it difficult to compare an inland piezometer with a seaside piezometer, for example, as the seaside piezometer will necessarily have a much lower average level than the inland piezometer. By analogy with the Standardized Precipitation Index (SPI) in meteorology [18], the SPLI makes it possible to define a level relative to a reference period. As with the SPI, the objective is to obtain, *via* the standard normal distribution, a standardised, symmetrical scale of values between - 3 and +3.

The diagram below explains the calculation of the SPLI for a given piezometer [Figure 1.12]. Each piezometer has a cumulative distribution function (CDF) for each of the twelve months of the year [Figure 1.13]. When a new PL is measured, it is placed on the x-axis and the projection of this point on the y-axis by the CDF gives us a value between 0 and 1. This value is then placed on the y-axis of the right-hand curve representing the CDF of the standard normal distribution. The projection on the x-axis then gives us a value between -3 and +3: the SPLI.

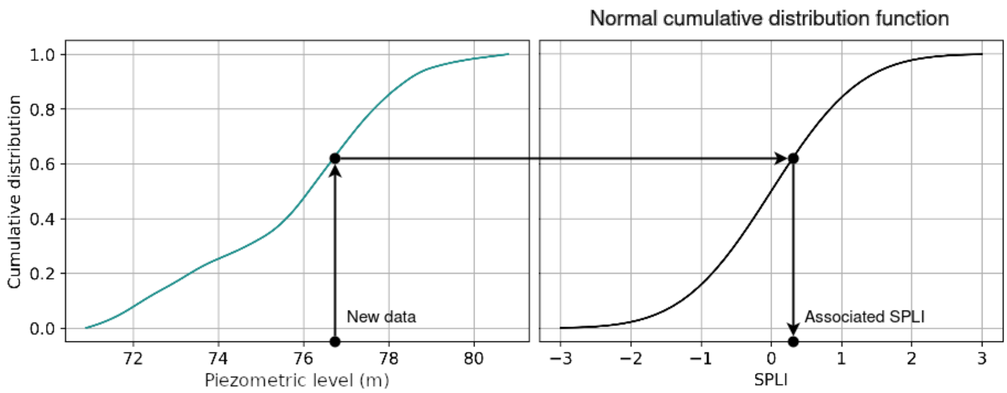

Figure 1.12: Schematic diagram of the SPLI calculation

The graph on the left is an example of a cumulative distribution function (CDF) for a given piezometer and for a given month while the graph on the right is the standard normal distribution CDF.

For each piezometer it is therefore necessary to compute 12 CDFs which are constructed in 3 steps:

- reference period selection
- cumulative distribution construction over the reference period
- CDF computation using kernal density estimators (KDE) [19]

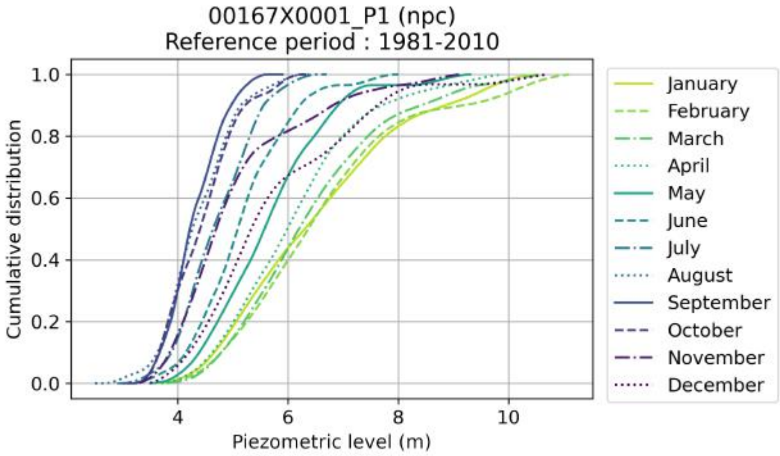

Figure 1.13: Example of monthly cumulative distribution function
As piezometer 00167X0001/P1 is close to the coast, its piezometric level (PL) is relatively low throughout its reference period. The seasonal variability is nevertheless significant and the amplitude of precipitation is much greater in winter than in summer. It is crucial to have a CDF per month to be able to compare for example the January PL with the other January months of the reference period.

The reference period is chosen by analogy with the SPI. Until 2021, the meteorological reference period is 1981 to 2010 [20]. This is therefore the period I used in my internship. However, some piezometers do not have data for this entire period, but I will come back to this later.

Groundwater resource categories can then be assigned to the SPLI to help in its understanding and interpretation [21] [Table 1.1].

SPLI value	Classification	Return period	Color
$[1.28, 3]$	Very high	$>$ 10 years wet	blue
$[0.84, 1.28]$	High	$>$ 5 years wet	light blue
$[0.25, 0.84]$	Moderately high	$>$ 2.5 years wet	pale blue
$[-0.25, 0.25]$	Around normal		light green
$[-0.84, -0.25]$	Moderately low	$>$ 2.5 years dry	yellow
$[-1.28, -0.84]$	Low	$>$ 5 years dry	orange
$[-3, -1.28]$	Very low	$>$ 10 years dry	red

Table 1.1: Classification of groundwater levels according to SPLI level

In the report, the term "drought period" then refers to a SPLI less than -0.84, i.e. a return period of more than 5 years.

1.3.2 SPLI calculation applied to observational data

As mentioned above, some piezometers do not allow the period 1981-2010 to be used as a reference period. Therefore, I decided to select the longest possible period, included in the period 1981-2010. In this way, a piezometer only starting in 1998 has a reference from 1998 to 2010. This leads to differences in the duration of the reference periods between the piezometers, which is not optimal. This choice was made in order to include a maximum of piezometers in the analyses. Indeed, only 200 piezometers out of 701 present data between 1981 and 2021, and, as shown previously, they are not evenly distributed among the different applications. The BRGM made the same kind of choice in the ADES database.

A challenge then arises. It is difficult to compare SPLI that have not been defined over the same reference period. At this stage, the forecasts (in SPLI) are defined on the 1981-2010 reference period of the reanalysis (always available because the reanalysis is continuous from 1958 to today) whereas the observations are defined on a variable reference period depending on the piezometer considered. Therefore, it was necessary to recalculate the CDFs of the reanalysis as well as the SPLI in order to be able to compare reanalyses and forecasts with observations [Figure 1.14].

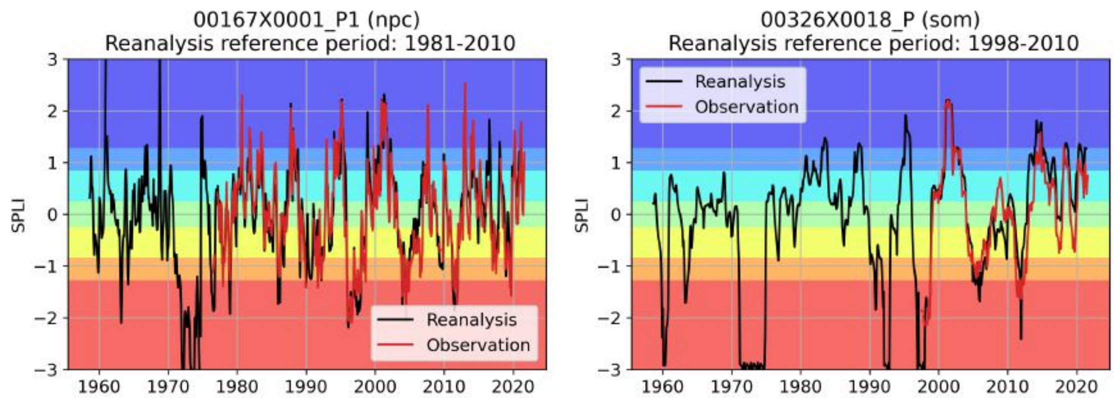

Figure 1.14: Examples of SPLI chronicles

On the graphs, the colours associated to SPLI levels [Table 1.1] are displayed. Also, chronicles are centred on 0 at the reference period, which is an expected result. Thus, dry periods prior to the reference periods saturate at -3 because such dry periods did not occur afterwards. Finally, "Reanalysis reference period" indicates that it has been modified to fit the available reference period of the corresponding observation.

1.3.3 Influence of the reference period

It becomes important to note how much the forecasts change when the reference period is modified. For this purpose, it is possible to plot on the same graph the SPLI forecasts coming directly from the Aqui-FR platform as well as the recalculation of the SPLI from the piezometric level forecasts [Figure 1.15].

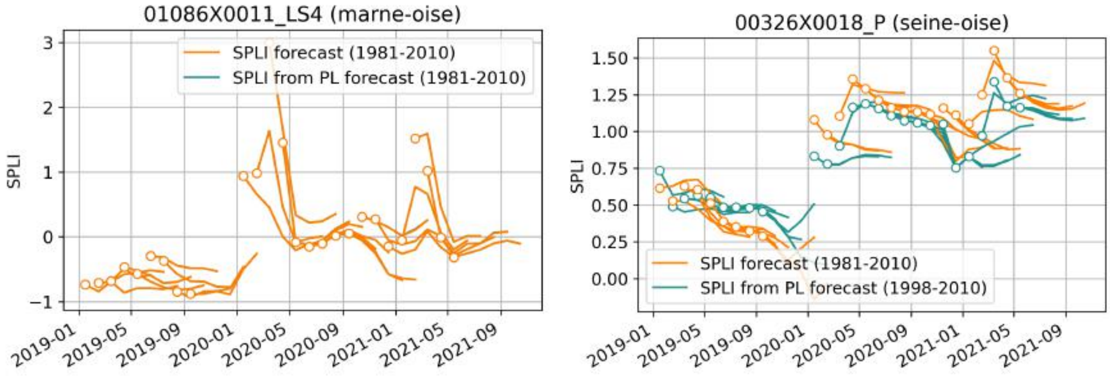

Figure 1.15: Examples of SPLI forecasts
SPLI forecast and SPLI from PL forecast are the same when the reference periods are identical (left). When they differ (right), deviations appear, but the amplitude of these deviations is not constant and I had neither the opportunity nor the interest to characterise them.

When displaying Aqui-FR forecast maps in the same way [Figure 1.16], it can be seen that the areas that change the most (most often wetter) are those for which the piezometers are recent (such as Poitou-Charentes) because they induce many changes in reference periods.

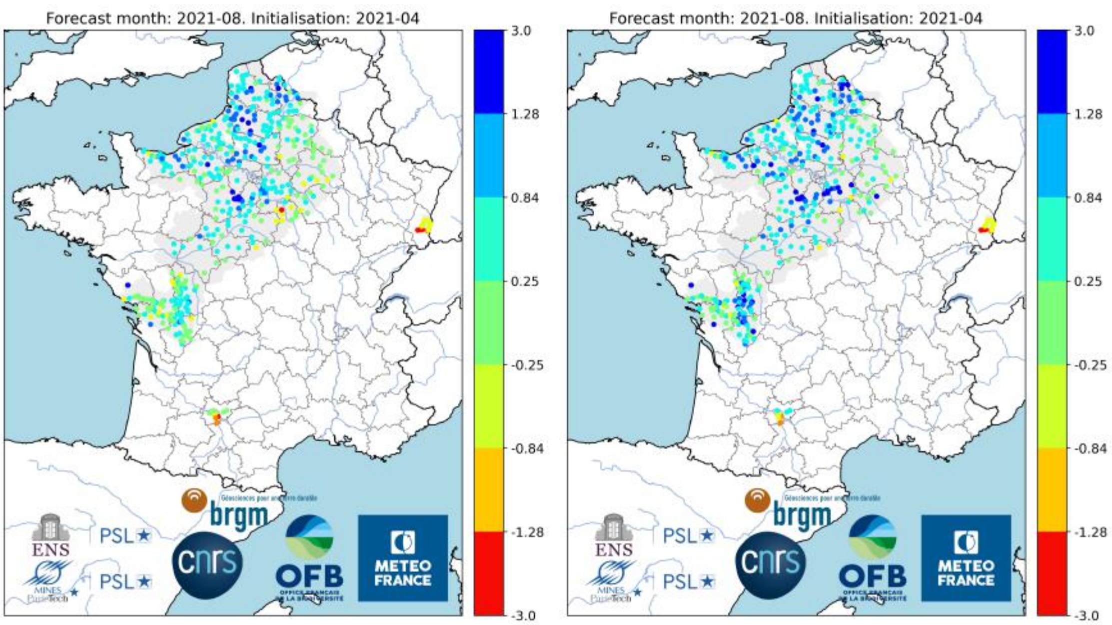

Figure 1.16: Piezometers forecasts maps
SPLI forecast map (left) and SPLI from PL forecasts map (right). The second map should be interpreted with caution as it shows SPLI with varying reference periods.

BRGM also opts for variable reference periods to produce maps on a national scale and these maps represent a sort of reference for the various water operators. The BRGM's Bulletin de Situation Hydrologique (BSH) for July 2021 [22] gives an idea of the groundwater situation on July. After checking the validity of my SPLI calculation, I juxtaposed my SPLI observation map with the BSH map [Figure 1.17] and found that the orders of magnitude are similar. Above all, the map on the left was approved by the regional experts at various meetings.

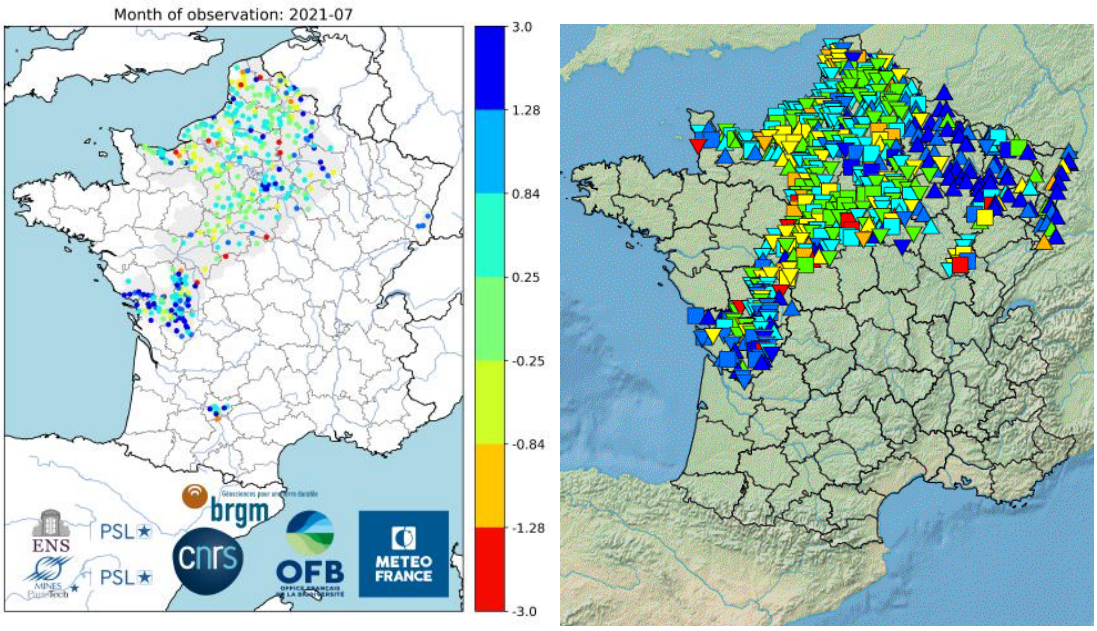

Figure 1.17: SPLI maps for July 2021

The piezometers on the left map seem to have the same SPLI categories as on the right map. Even the few red piezometers can be found from one map to the other, which gives confidence in the validity of the observations but this comparison should only be considered for orders of magnitude. The map on the right shows more piezometers because it extends over a larger area and the piezometers have not been selected as they were in Aqui-FR. It is interesting to mention the high spatial variability of the results.

The differences in the choice of reference period make comparisons between reanalyses and other local operators' studies difficult, as well as between BRGM observations and data. This choice of reference period is a key point which does not enjoy any consensus among water actors due to the short availability of the data.

On the one hand, many local actors (Water Agency, Direction Régionale de l'Environnement, de l'Aménagement et du Logement - DREAL, etc.) carry out analyses concerning the situation of the aquifers they are responsible for managing. During a Piezometry & Drought exchange day organised by the Direction Régionale et Interdépartementale de l'Environnement, de l'Aménagement et des Transports (DRIEAT) of the Ile-de-France region, I realised that the different operators of the Seine-Normandie basin use various reference periods. For example, the DREAL of Hauts-de-France uses the period 1980-2019 [23] while the DREAL of the Grand-Est region operates the 1999-2018 period [24]. This difference is most likely due to the fact that the northern French piezometers have longer and better quality records [Figure 1.7]. These changes make inter-regional comparisons subtle and lead to a multiplicity of drought thresholds in France.

On the other hand, as mentionned juste before, BRGM did not choose a reference period in the SPLI definition reports [21]. Thus, the entire available chronicle for each piezometer was taken as the reference period. The periods are therefore variables and extended for each new measurement. This also adds complexity to the interpretation of the SPLI maps. However, in the new tools developed by BRGM such as the MétéEAU Nappes software [25], it is possible to choose the desired reference period. This kind of option allows all operators to use the ADES data in a consistent way with their usual analyses.

Part 2
Aqui-FR forecasts verification

2.1 Verification of forecasts in relation to observations

2.1.1 Piezometer comparisons between forecasts and observations

For each piezometer, a reference period is now defined to compare the SPLI of the predictions with the SPLI of the observations. As mentioned in part 1, this forecast verification process is a new step for the Aqui-FR project since Leroux *et al.* [13] used only the reanalyses as reference.

To compare the forecasts with the observed data, it is relevant to start the analysis at a single piezometer scale to better understand the nature of the different data. The forecasts are seasonal and therefore last for 6 months while a new forecast is performed every month. Thus, the forecasts overlap each other [Figure 2.1].

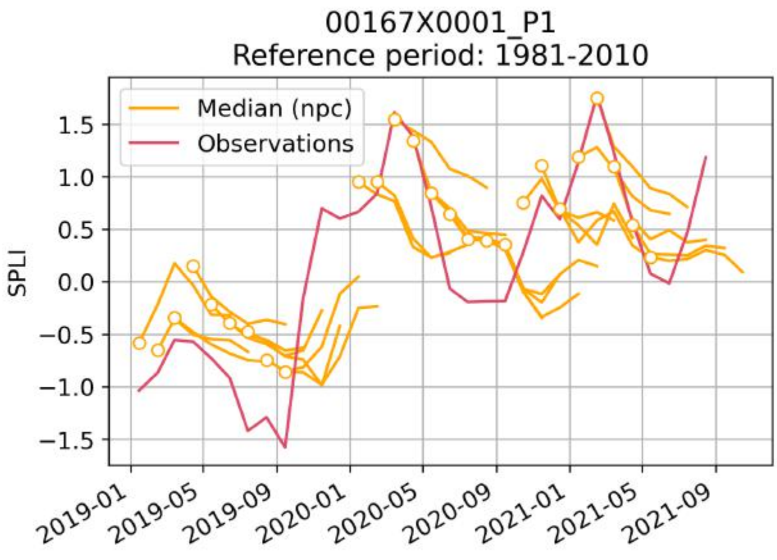

Figure 2.1: SPLI forecasts for the 0167X0001/P1 piezometer
This graph is similar to those shown in Figure 1.15 with the addition of the observation curve. The different white points still represent the initial values of each forecast. Note that the forecasts between September 2019 and January 2020 are not available.

The main purpose of the comparison is to determine whether the forecasts follow the observation trends. Thus, I aimed to quantify, for each forecast, the correlation between the predicted and the actually observed SPLI over the same period. The calculated correlations for each piezometer and for each new forecast date are therefore temporal correlations over a period of 6 months (i.e. correlations over 6 points).

2.1.2 Multi-piezometer analysis

A correlation coefficient is then calculated for each forecast start date and for each piezometer. These results can then be represented on maps, one map is therefore displayed per beginning month of the forecasts and the piezometers are coloured according to the correlation coefficient over the 6 months of the forecasts [Figure 2.2]. This mode of representation allows to visualise the disparities that may exist in the Aqui-FR domain.

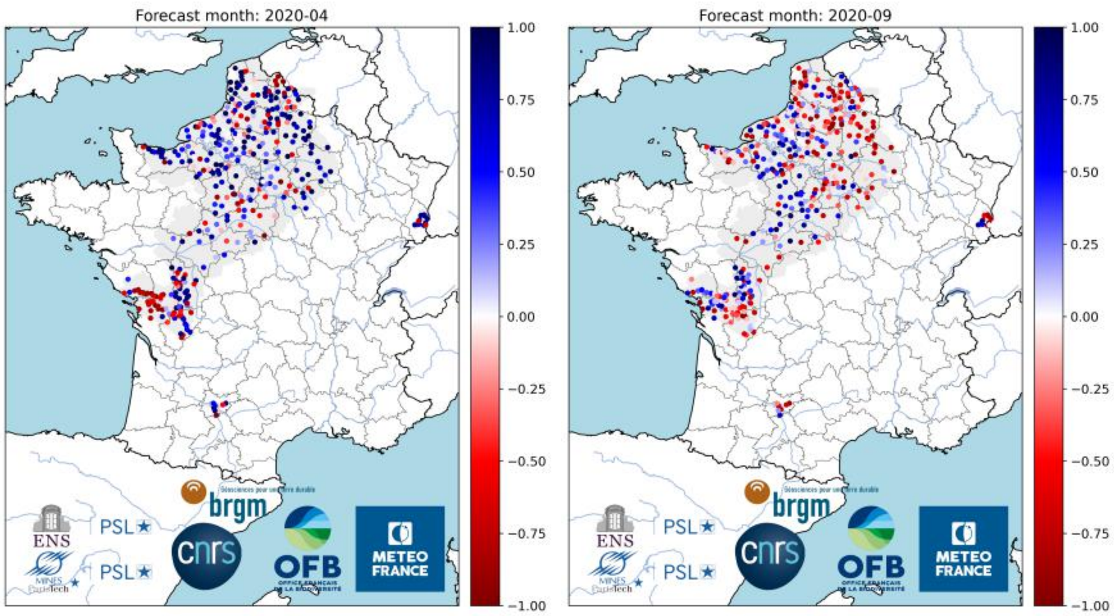

Figure 2.2: Correlation maps between observations and forecasts
The correlation coefficient maps are those of April 2020 and September 2020. The April forecast has much better correlations than the September forecast. On the April forecast map, it can be seen that Poitou-Charente performs significantly worse than the rest of the country. This difference could be explained by heavy local precipitation or faster groundwater dynamics.

When juxtaposing the maps of different forecast months, some months appear redder than others. For example, forecasts starting in September 2020 have a median correlation coefficient of -0.17 while those starting in April 2020 have a correlation coefficient of 0.49. To see these annual variations, the evolution of the median correlation coefficient of all the piezometers can be plotted [Figure 2.3]. The considered piezometers are the ones on the above maps. They present data at least in 2019, 2020 and 2021 (i.e. ≈ 450 piezometers).

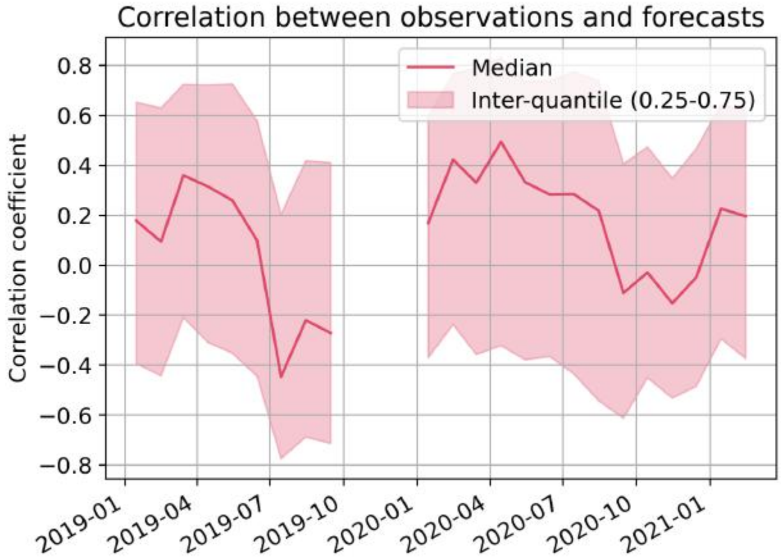

Figure 2.3: Temporal correlation between observations and forecasts
This graph represents the median (and inter-quartile) of the temporal correlations between the observations and the medians of the 51 members of the Aqui-FR forecast (over the same reference period as the observations). It should also be underlined that the meteorological model used for the 2019 weather forecasts is Météo-France Arpège 6 [15] whereas it is Météo-France System 7 [14] since January 2020. The gain between these two periods may be due to this change or simply to annual variations. Finally, the x-axis ends in February 2021 because the six months of forecasts must be correlated with observations. The last month of the graph is therefore at least 6 months behind the current month.

An interesting outcome is that the April forecasts have much better correlations than the other months, even though they barely reach 0.5. On the other hand, the September and October forecasts show a negative median correlation, which indicates that the forecasts do not correspond well to the observations over the whole domain. This seasonal variation in correlation reflects the difficulty of forecasting rainfall events. Thus, forecasts including larger recharge periods will have a greater tendency to diverge from reality. Nevertheless, this graph supports the potential ability of the Aqui-FR forecasts to correctly anticipate drought periods, which occur mainly between July and October [12].

The shape of the annual variation of the correlation coefficient is similar to the trends obtained during the verifications conducted by Leroux *et al.* [13] but with weaker scores. To check whether these variations correspond or are due to the specific year, I continued the forecast analyses by replacing the observations with the reanalyses.

2.2 Relating the model predictions to the reanalyses

2.2.1 Comparisons between forecasts and reanalyses

Contrarily to the Leroux *et al.* [13] research, whose verification covered the whole period 1993-2016, the validation I conduct between forecasts and reanalyses only concerns the forecasts of 2020 [Figure 2.4], to which have been added those of 2019 although the meteorological model has changed between the two years. Because of this difference in period, one can expect to observe different results.

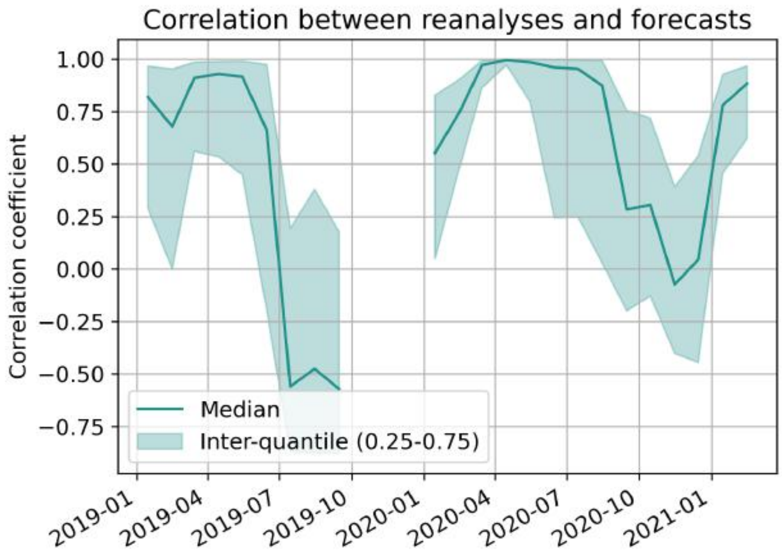

Figure 2.4: Temporal correlation between reanalyses and forecasts
This graph is very similar to the previous graph [Figure 2.3] and the same comments apply. However, the correlations are much better, especially for the months of April and May.

In the article, Leroux *et al.* obtain 6-month correlation coefficients above 0.9 for the April and May forecasts. This coefficient falls to 0.5 for the November forecasts. The results of the 2020 comparison between forecasts and reanalyses are in agreement with those of the paper. The correlations of the April and May forecasts are close to 1 and the inter-quartile is very tight, which means that such a high quality of correlation is shared by the majority of the 450 piezometers included in the graph above. The higher correlation coefficient obtained by Leroux *et al.* for November could be explained by the number of years taken into account in her calculation. The variability of the forecasts could increase the average correlations.

The very high correlation obtained here for the low recharge periods seems to indicate that the lower scores obtained for the observations are not due to the singularity of the year 2020 but to something else. It is then supposed that this difference may be due to discrepancies between observations and reanalyses.

2.2.2 Evolution of the forecasts' initial condition

To support this hypothesis, I examine the gap between the first forecast and the reanalyses. This gap is the difference between the value of the first forecast of each new forecast and the value of the corresponding reanalysis [Figure 2.5].

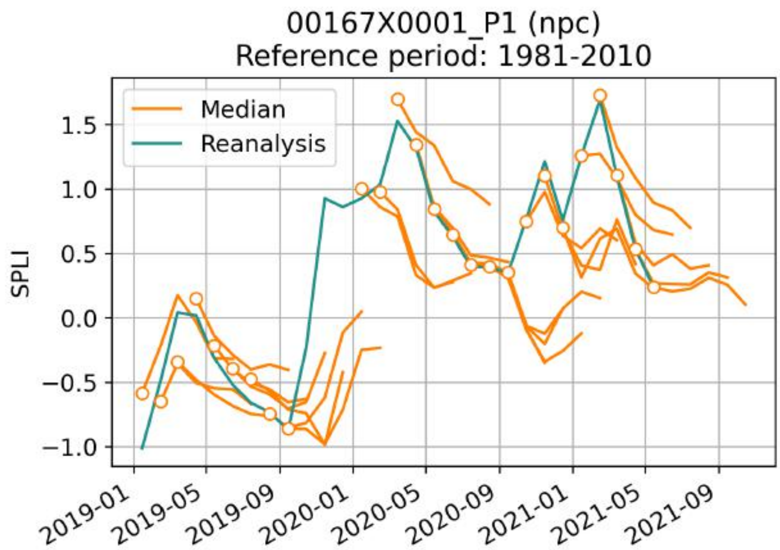

Figure 2.5: SPLI forecasts for the 0167X0001/P1 piezometer

This graph is equivalent to the one shown in Figure 2.1. It can be seen, however, that the initial values fit the curve much better, especially for the period between May and November 2020.

To extend the analysis to all available piezometers, I averaged the differences between the initial predictions and the reanalyses of all piezometers for each application. Conducting this process by application allows the detection of possible differences between them [Figure 2.6], as the 14 Aqui-FR applications have been calibrated independently [9].

However, there are no significant behaviour differences between the applications. One common pattern is a decrease in the difference between the forecast and the reanalysis during the high recharge months in 2020 and 2021. This means that the reanalyses are wetter than the forecasts and it is therefore likely that this deviation is due to heavy precipitation not anticipated by the weather model.

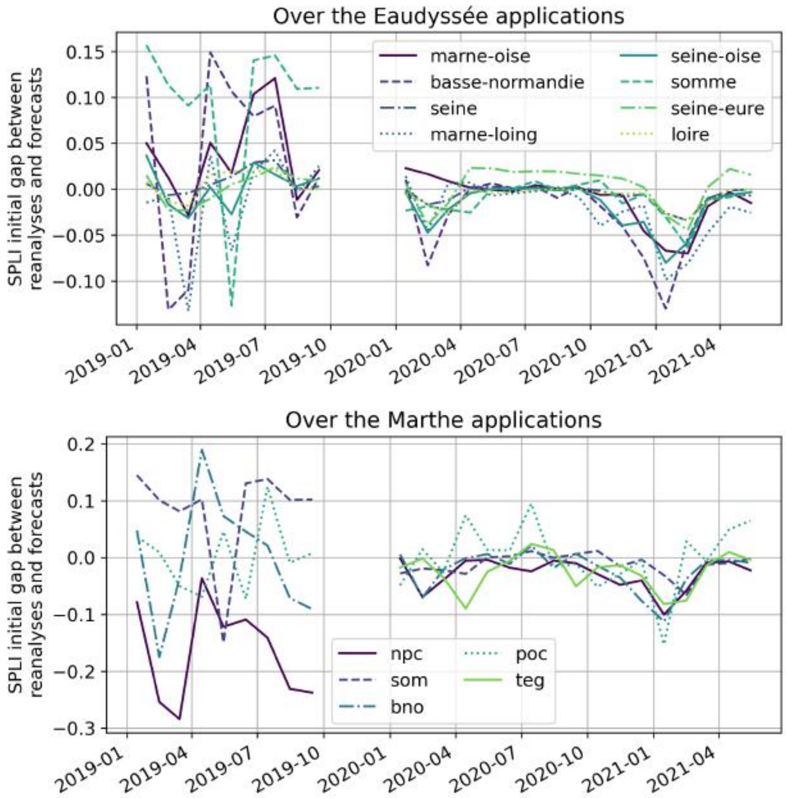

Figure 2.6: Initial difference between reanalyses and forecasts
The graph presents the evolution of the initial forecast value minus the reanalysis value. A positive difference indicates that the forecast is wetter than the reanalysis and vice versa. In the lower graph, Alsace has been removed because this application had too high values in 2019 (around 2.5) which did not suit the chosen scale. Finally, for all applications, there is a significant change between the differences in 2019 and the others. This shift could be attributed to the increased performance of the weather forecasting model but especially to the hybrid nature of the first forecasts since 2020, as explained above.

Finally, it could be concluded that the forecasts follow the reanalyses extremely well during the low-water periods, with almost zero initial differences and correlation coefficients close to 1. Thus, it reinforces the hypothesis that the lack of precision found between the forecasts and the observations comes mainly from the deviations between observations and reanalyses. In order to characterise these discrepancies, the third part of this report is principally dedicated to comparisons between these two variables, with a focus on drought periods.

Part 3

Focus on drought periods

3.1 Coincidence of dry periods between observations and reanalyses

3.1.1 Drought period definition without using SPLI

The prediction of drought periods is a particularly important socio-economic issue in France, especially when trying to anticipate aquifer states during the irrigation season. The importance of forecasting low water recharge periods is enhanced by the fact that these periods are the most accurately forecast by the models.

To compare the dynamics and the variations of the observations and the reanalyses without defining a reference period necessary to the SPLI calculation, a new frequency variable reserved for the drought characterization is created. In this case, the term "drought" do not refers to a SPLI < -0.84 but to a period where the PL in a given month is lower than the first decile of the PLs of the same months over the whole period considered. The monthly frequency is important, for the same reasons as for the SPLI.

In this way, this new drought variable is similar to the SPLI but is restricted to droughts and is more easily calculated. The time period considered is identical between the observation and the reanalysis of each piezometer. It is the intersection between the period over which the data exists and the period of the reanalysis. This method of characterising low water periods is inspired by the internship of Nalivaev [26].

3.1.2 Matching of dry periods

For each of the Aqui-FR domain applications, the low water periods as defined above, are plotted for observations and reanalyses [Figure 3.1]. It should be borne in mind that the number of piezometers included in the average application varies.

Overall, the low water periods overlap well between the reanalyses and the observations. The peaks are very often coherent, which allows to say that the reanalyses provide a reliable description of these periods.

However, this conclusion can be tempered, especially when looking at the evolution of peak amplitudes between observations and reanalyses. For most of the applications, a similar pattern can be observed. Between the 1970s and 1990s, the reanalyses tend to overestimate the low water periods. The models are then on the right order of magnitude between the 1990s and the 2000s. Finally, the low water periods observed in 2018, 2019 and 2020 are practically not represented in the reanalyses (or very little). Several elements are proposed in the following section to try to explain this variation in low water period modelling.

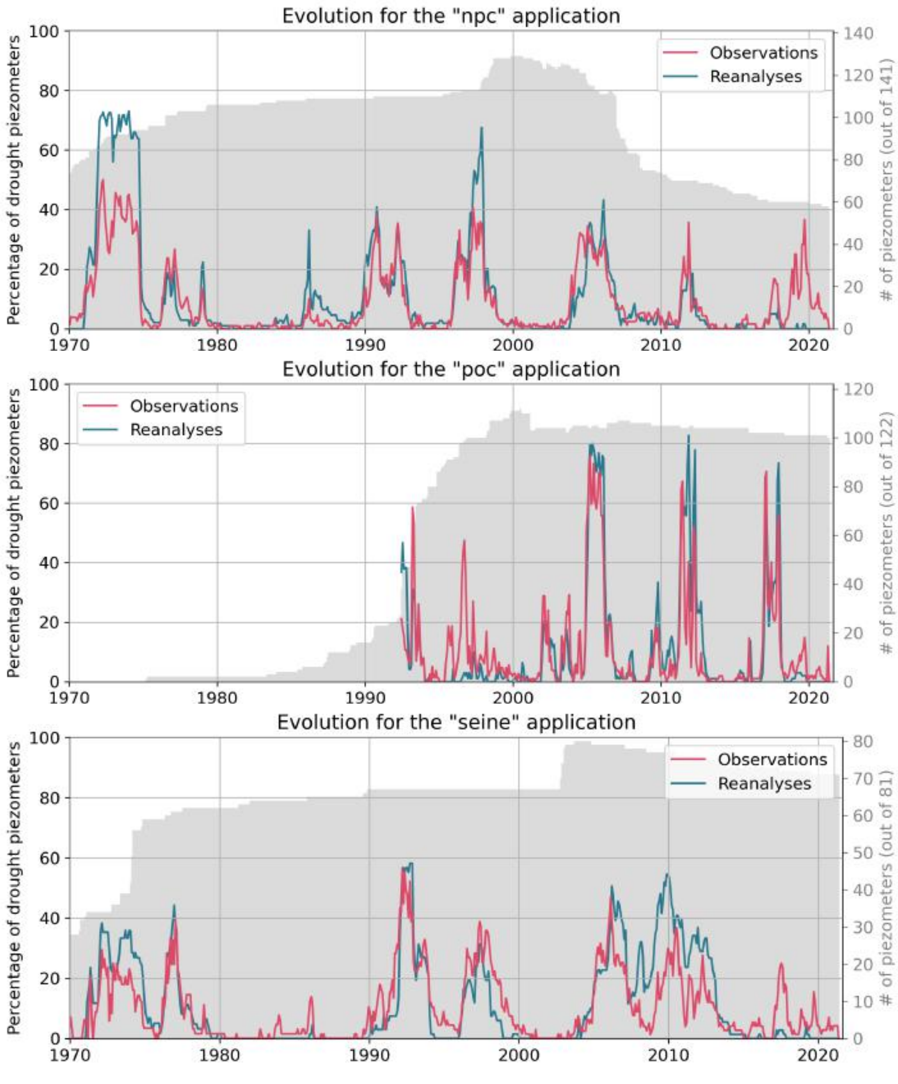

Figure 3.1: Evolution of drought periods

For the three graphs, two scales are shown. On the left hand side, the percentage of drought piezometers for the considered application is displayed. On the right-hand side, the evolution of the number of active piezometers within the application is presented (similar to the Figure 1.7). The different lines are drawn when more than 25% of the piezometers in the application are available, which is why the chronicles of the "poc" application start in the 90s. This choice makes it possible to preserve significant results.

3.2 Potential influence of long-term elements

3.2.1 Effect of the calibration period

When considering drought period detections for the 14 applications, there is a trend from over- to under-estimation between 1970 and 2020. A first possible explanation for this shift lies in the calibration periods of the various application models and SURFEX fluxes. Indeed, these periods are different for each application [9], but are mainly situated between 1990 and 2010 [Table 3.1], the period for which the estimates of the low water periods are the most accurate.

	M-O	B-N	Se	M-L	S-O	So	S-E	L	npc	als	som	bno	poc	teg
Calibration periods	1994 2014	1986 2012	NC	1996 2014	1996 2014	NC	1996 2014	2000 2010	1982 2012	1992 2004	1989 2012	1994 2010	1994 2004	

Table 3.1: SURFEX calibration periods

The various abbreviations used are detailed below[1]. The Seine and Somme (EauDyssée) applications did not need to be recalibrated for the results to be exploitable.

In this way, if water uses change in relation to this period, calibrations will no longer be completely valid. I did not find very long-term data on groundwater withdrawals. But considering that groundwater is mainly used for drinking water distribution and irrigation [2] and that the French population has only increased since the 1980s [27] without any major decrease in agricultural areas [28], it is likely that groundwater withdrawals have increased over time. However, these assumptions and reasoning are too crude to be able to make a real hypothesis about the influence of changes in water resources with respect to calibration periods. Accurate and good quality information would be necessary to draw a better conclusion.

3.2.2 Multi-year variations in the water tables

Not to mention the calibration period, it is also possible that the observations show long-term trends not captured by the reanalyses. To understand why the droughts of the last three years were not correctly caught by the model, the trends over the last 20 years are studied. These trends are compiled in the following table [Table 3.2], with the results of the associated Mann-Kendall [29] tests. These tests make it possible to check whether an observed trend is really significant or not.

[1] M-O: Marne-Oise (EauDyssée), B-N: Basse-Normandie (EauDyssée), Se: Seine (EauDyssée), M-L: Marne-Loing (EauDyssée), S-O: Seine-Oise (EauDyssée), So: Somme (EauDyssée), S-E: Seine-Eure (EauDyssée), L: Loire (EauDyssée), npc: Nord-pas-de-Calais (Marthe), als: Alsace (Marthe), som: Somme (Marthe), bno: Basse-Normandie (Marthe), poc: Poitou-Charente (Marthe), teg: Tarn-et-Garonne (Marthe)

		M-O	B-N	Se	M-L	S-O	So	S-E	L	npc	als	som	bno	poc	teg
Trends	Observations	-6.3	-4.3	-8.7	-3.4	-12.9	-12.2	-9.6	-8.0	-4.8	-0.8	-12.1	-4.1	0.0	-1.7
($cm.yr^{-1}$)	Reanalyses	-2.6	0.0	-4.7	-2.9	-7.1	-2.6	-5.2	-1.0	-1.6	-1.0	-2.7	-0.2	-3.6	-3.9
MK test	Increasing (%)	4	12	18	25	10	0	4	7	8	19	0	11	12	10
(Obs)	No trend (%)	30	44	32	33	30	18	31	21	23	7	18	39	66	60
	Decreasing (%)	75	44	50	42	60	82	65	72	69	74	82	50	22	30
	# of piezometers	23	25	80	36	91	51	26	114	137	27	57	36	120	10
MK test	Increasing (%)	4	4	22	6	9	10	0	10	18	0	30	2	3	0
(Rea)	No trend (%)	87	69	57	64	46	90	73	77	69	59	70	95	63	10
	Decreasing (%)	9	27	20	31	45	0	27	13	13	41	0	2	34	90
	# of piezometers	23	26	80	36	91	51	26	115	139	27	57	42	121	10

Table 3.2: Linear trends in observations and reanalyses over the 2000-2020 period
The differences between the trends of the observations and the reanalyses are significant, about 4 $cm.yr^{-1}$. On average, the decrease in piezometric levels between 2000 and 2020 is under-estimated by the reanalyses. The various Mann-Kendall tests reinforce this conclusion. Only the last 20 years are considered here in order to be able to perform this analysis in a meaningful way over the whole range of applications.

In the table, it can be seen that the observations from the different applications show decreasing trends between 2000 and 2020. Although these trends are not significant for all the piezometers ($\approx$ 70% of them are), similar trends are not detected among the reanalyses and most of the piezometers do not present significant trends over this same period ($\approx$ 80%). Further analysis would be required to understand more precisely where this discrepancy comes from.

It should be specified that the trends presented above should not be considered in an absolute way because the reference period 2000-2020 does not allow to set up a real trend at the scale of a piezometer. Many piezometers present inter-annual variabilities with periods up to several decades, such as the piezometer shown below [Figure 3.2]. On this record, the 2000-2020 trend is clearly negative, while the overall trend is more complex to determine. Thus, only the comparisons between observations and reanalyses are relevant here.

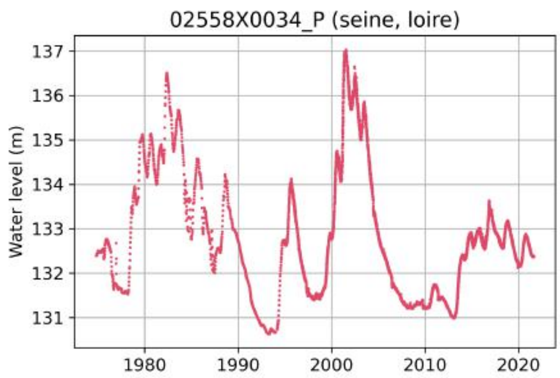

Figure 3.2: 02558X0034/P piezometric level chronicle

3.2.3 Climatic trends

Climatic trends may potentially be detected when the evolution of some variables is considered on a longer time scale. Thus, the evolution of annual run-off reconstructed by SURFEX and the reanalyses of piezometric levels over the period 1958-2016 are studied here. Trend calculations and Mann-Kendall tests are carried out on these values and the results are compiled in the following table [Table 3.3].

			M-O	**B-N**	**Se**	**M-L**	**S-O**	**So**	**S-E**	**L**	**npc**	**als**	**som**	**bno**	**poc**	**teg**
Run-off	Trends	$mm.yr^{-1}$	0.17	-0.41	0.13	-0.09	0.56	0.48	-0.08	-0.01	0.60	-0.8	0.56	-0.45	-1.19	-2.78
	MK		NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT	(↓)
PL	Trends	$cm.yr^{-1}$	0.6	-1.0	0.6	-1.0	3.7	2.4	1.8	1.7	1.7	-0.2	2.4	-0.9	-2.9	-2.9
	MK	(↑) %	35	81	39	8	82	80	58	60	71	0	74	7	0	0
		NT %	65	19	40	53	16	20	27	27	26	26	26	36	14	0
		(↓) %	0	0	21	39	1	0	15	13	4	74	0	57	86	100
		# of pzo	23	26	80	36	91	51	26	115	139	27	57	42	121	10

Table 3.3: Trends over the 1958-2016 period

In the table, the letters "MK" stand for the significance of the Mann-Kendall tests. The results of this test are described by the symbols "(↑)" (increasing), "NT" (no trend) and "(↓)" (decreasing). Finally, the abbreviation "# of pzo" refers to the number of piezometers counted for the PLs of each application. The runoff shows no significant trends for any of the applications except for Tarn-et-Garonne. Concerning the PLs: several applications seem to show significant trends but the direction of these trends differs. However, the trend directions are consistent between the LPs and the runoffs.

In light of the results, it seems difficult to correlate these trends with the discrepancies found between the detections of low water periods from observations and reanalyses. However, the study of climatic trends remains important for studying the impacts of climate change on groundwater resources and their recharge dynamics.

3.3 Relation of the forecast maps to the drought decrees maps

The drought decrees maps published by the Propluvia platform are map compilations of the drought decrees and I automatically collected them.

Finally, it can be attempted to compare the Aqui-FR drought forecasts with the declared droughts to check whether the forecasts (despite the points discussed above) do not still anticipate drought events. On the map on the left [Figure 3.3], the grid cells that are forecast in drought (SPLI < -0.84) are shown in red. This map corresponds to an initialisation in May 2019 for a September 2019 forecast. The year 2019 is chosen because it is a much drier year than 2020 and the example is therefore more relevant.

This drought forecast map is interesting because it presents data at the grid scale. It can be seen that there are large areas of the Aqui-FR domain that are not covered by any piezometer. In this way, there is little way to confirm or not the forecasts made there. The drought decrees map for September 2019 allows a rough comparison [Figure 3.3].

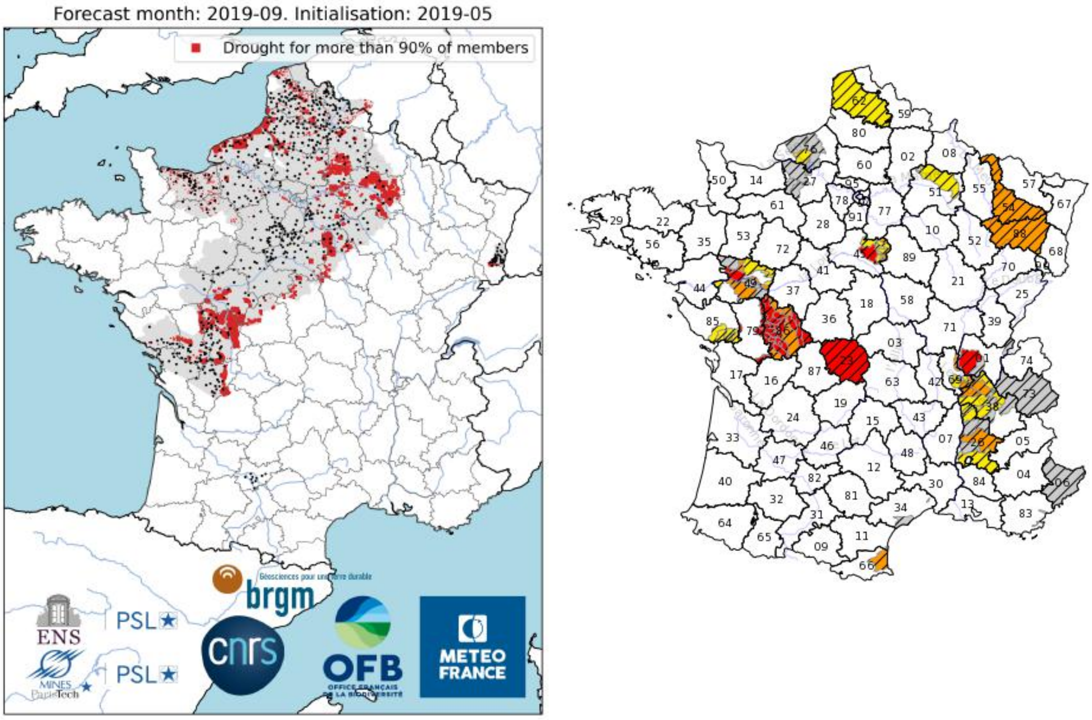

Figure 3.3: Drought maps for September 2019

The forecast map is made at grid scale and also shows the location of piezometers. It can be seen that there are large (sometimes dry) areas that are not covered by any piezometers. This may not be a coincidence and some areas may be less pumped than others due to their known monitoring. Also, grid cells are only in drought when at least 90% of the 51 members agree on a SPLI < -0.84. This 90% value is purely empirical and seems to be adapted to drought decrees.

I mentioned it was a rough comparison and this is why. In the first instance, it should be borne in mind that drought decrees are decided by prefects at departmental scale [30] and are therefore political acts. Drought decrees do not always objectively describe the state of groundwater. Secondly, the Aqui-FR drought forecast maps reflect the state of the surface aquifer layer, whereas the drought decrees are established for accessible aquifers of a territory. This difference can be a source of discrepancies and even misunderstandings between actors, as I have seen during certain meetings.

Nevertheless, most of the drought regions are common from one map to the other, meaning that the Aqui-FR forecasts could be part of the future drought decrees discussions.

Conclusion

The objective of verification of the first year of operational seasonal forecasts of the groundwater resource and the work carried out in this respect have brought to light several results.

Firstly, the variability of data availability led to the use of variable reference periods, in particular for the calculation of the Standardised Piezometric Level Index (SPLI). This approach is shared by BRGM but makes inter-regional comparisons difficult as the different groundwater operators also use their own reference periods. Therefore, it is necessary to be able to produce different analyses:

- Results, and especially forecasts, obtained over a homogeneous reference period are very valuable as they allow for a consistent visualisation when represented.
- In addition, it is necessary to provide results that are comparable to the observations used by the different water operators on their own reference periods.

Each of these different analyses is now possible thanks to the different tools I was able to develop during my internship.

Secondly, we found that direct forecasts comparisons to the observations are better from March to June. However, the research carried out during the internship showed that the Aqui-FR forecasts are much closer to the reanalyses than the observations. This result is particularly true for the periods of low recharges (from March to September). These results confirm the ability of hydrogeological models to use seasonal weather forecasts in an accurate manner and the difference in correlation between forecasts and observations and between forecasts and reanalyses allows to hypothesise that the discrepancy is mainly due to the differences that may exist between observation and reanalyses. In this way, further studies are probably desirable. A first step would be to study the feasibility and impact of calibrating real-time reanalyses on observations using data assimilation methods.

The verification of the groundwater resource forecasts required the writing of numerous computer programs (from reproducible data recovery to automated analyses) that could be implemented in the future Python module of the Aqui-FR platform: “apyfr”. The development of these codes allowed me to make significant progress in the overall vision required to develop long-term tools that can be reused regularly, over a long period of time and in an operational way.

This internship was also the occasion to realise the high constraints induced by the quality and/or the availability of raw data. The WAPE course “Introduction to data assimilation” acquired a much more tangible meaning thanks to this experience. The impact of the availability of quality data is particularly important for complex issues such as low water periods forecasts several months in advance. Moreover, until the end of my internship, I was confronted with the counter-intuitive nature of the word “drought”. By definition, it is an exceptional period, which was supported by a water manager during a meeting: “A drought cannot be declared every year”. However, water resources are likely to be restricted more and more frequently in the future, especially in some areas of southern France.

During the internship, I learned a lot about the links that could exist between academic research, the different water operators, and the Ministère de la Transition Écologique. The discussions I had the chance to attend reinforced my interest in resource management issues and associated long-term strategies.

I am deeply convinced that my internship has been helpful to me to better prepare my last year at the École Normale Supérieure Paris Saclay within the master’s degree Energy Transition and Territories of the École des Ponts ParisTech.

I would like to thank Florence Habets one last time for her supervision since April, a regular supervision which allowed me to assimilate the key ideas and subtleties of the Aqui-FR project, of the groundwater seasonal forecast and even of hydrogeology in France.

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