Exporatory Study to assess the impact of climatic anomalies and agricultural yields on water quality from agricultural drainage

Matthieu Descout

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Matthieu DESCOUT

Internship Report

“Exporatory Study to assess the impact of climatic anomalies and agricultural yields on water quality from agricultural drainage”

Internship hosted by team *ARTEMHYS* (Research Unit *HYCAR*) and financed by *CLAND*

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Abstract

The development of intensive agricultural practices, especially abusive use of mineral and synthetic N-fertilizers, are leading to increased levels of Nitrate pollution of water in regions where anthropologic N inputs are the highest. Strong contamination of water by Nitrate is leading to severe inconveniences for populations and ecosystems, undrinkable water and coastal eutrophication being the main ones. Agricultural drainage is often used for agricultural plots to remove winter excess water in agricultural regions located on *"hydromorphic soils"* suffering from recurring water saturation damaging crop development. Watersheds with high drainage intensity can be seen as giant reservoirs behaving like lysimeters exporting incoming water and nutrients – including different forms of Nitrogen – from potentially polluted agricultural plots to surface watercourses thanks to the network of tile drains (Minaudo et al., 2019). Therefore, higher Nitrate content in drained soil exposes affected territories to bigger NO3 exports by drainage. In this report, we investigate whether extreme climate events recorded during the last decades in France lowered agricultural yield, which implies bigger quantities of available NO3 for export by drainage during the first months of the following hydrological season. We used a panel of different databases to have access to data on discharge, climate, agricultural yields, and Nitrate concentration for 37 French watersheds selected because of their drainage intensity. We also include the drained watershed of Mélarchez (709ha) – involved in a French research observatory on water quality – to this research. We used the SIDRA-RU model to assess the contribution of drainage to the hydrological behavior of these watersheds, and we performed Anova statistical tests to analyze if there is a decrease of agricultural yields and increase of NO3 concentration when drainage restarts in winter after the watersheds experienced climatic anomalies.

Our results show that drainage has a big influence on the hydrology of studied watersheds. We also observed that extreme climate events affect significatively agricultural yields in these studied watersheds, and that lower yields lead to an increased contamination of water by NO3 in Mélarchez, attributed to a bigger export by of available Nitrate in soil by drainage possibly because of a lower N-uptake by plants following a lower crop development. Even if we did not observe such relation between agricultural yields and Nitrate concentration at the outlet of the 37 selected watersheds, our exploratory study tends to reveal that small watersheds with intensively drained agriculture are exposed to bigger Nitrate exports to surface watercourses after climatic anomalies that affected crop growth and development. This emphasized the need for better agricultural practices managing N inputs to the soil and curative measures aiming at enhancing nitrate retention or elimination through natural processes occurring in the drainage network.

Introduction

The role of Nitrogen in crop's development has been discovered in the mid-19th century. However, the cycle of this chemical element has been deeply disturbed by human interventions after the invention of the Haber-Bosch process in 1913 that converts atmospheric N2 to NH3 and provides an unlimited supply of Nitrogen that could be used for the agricultural sector. As a result of the sharp increase of global population and food production since the 20th century, a huge flux of reactive Nitrogen is now distributed to the environment, mainly to sustain a sufficient food production. The Net Anthropogenic Nitrogen Inputs (NANI) characterize these human perturbations of the natural N cycle. NANI are the sum of four processes that contribute to this additional flux: Synthetic fertilizer application; N_2 fixation in agroecosystems; Net import of N in human food and animal feeds; and the atmospheric deposition of Nitrogen oxides NO_y (Howarth et al., 2006). At the global scale, 144TgN/yr enters the watersheds as NANI (Billen et al., 2013), with agriculture clearly contributing to the largest part of this additional flux distributed by human activities to the environment (Zhang et al., 2015). In agricultural landscapes, Fertilizer application alone accounts for approximately 70% of the NANI released in the environment. This perturbation is also unequally distributed at the global scale and strongly impacts "N-intensive" areas since 43% of the total continental area accumulates 85% of global NANI. Unsurprisingly, regions with very intensive agricultural systems are the most impacted (North America, Europe, India, and Eastern Asia) and synthetic fertilizers are the primary source of NANI (Schaefer et al., 2009).

There is a strong correlation between NANI and the N fluxes exported by the watersheds (Hong et al., 2012), which does not mean that the totality of reactive N added by human activities is exported by rivers. Once it is introduced in the system, the reactive Nitrogen has three possible outcomes (Galloway et al., 2002): I) Storage within the system; II)Transfer to another system, like vegetation uptake; III) Denitrification to N_2.

According to previous studies (Howarth et al., 2006; Howarth et al., 2012) 74% of the human inputs of N to the landscape is retained in the landscape or lost through denitrification and approximately one third of the NANI that is not exported by rivers accumulates in soil and biomass, while the rest is denitrified (Howarth et al., 2006). This means that 26% of the NANI is exported in downstream river exports, which leads to an addition of biogeochemically active nutrients to the environments with consequences on water quality and the ecosystems (Zhang et al., 2015).

Consequently, Nitrogen pollution of water and its contamination by Nitrate is leading to severe inconveniences for the environment and human societies. It threatens production of drinking water and good ecological status of waterbodies. It is a major source of imbalanced nutrient loads at the river outlet that can lead to coastal eutrophication with disastrous consequences on the marine ecosystems (Passy et al., 2012). Reducing nitrate contamination of ground and surface water became one of the most important challenges faced by environmental policies in developed countries with intensive agriculture. It is the case in China, where poor natural water quality affects 25% of surface water and 35% of groundwater in some districts leading to a population of 0.3 billion people suffering from unsafe drinking water-related problems (Xia et al., 2011). This is mostly due to rapid social–economic developments and intensification of agriculture. There are two main reasons why agriculture has a negative impact on Nitrogen pollution of water (Agence de l'eau Seine-Normandie, 2011 & Billen et al., 2013): I) It increases N fertilizer inputs; II) It converts landscapes with high N-retention rate (forests and grasslands) to croplands with low retention capacity.

In watersheds with strong agricultural nutrient pressure (N-surplus added on the fields, percentage of land-use dedicated to agriculture), several factors play a key role on riverine N export and contamination of surface and subsurface water by Nitrate and many researches highlight the necessity to consider landscape; agricultural practices; and physiographic and hydrological characteristics of the watersheds to analyse Nitrate pollution efficiently (Dupas et al., 2015[1]). Indeed, each watershed is characterized by its "retention potential" which represents the partition of N surplus between retention and transfer in the watershed. This retention power is driven by watershed's characteristics, mainly its reactivity (Dupas et al., 2013). Additionally, Nitrate losses from agricultural fields can be attenuated by different agricultural management practices and crop sequences that favour N uptake by the plants and the crops (Dupas et al., 2015[1]). Climate variables and hydrological behaviour of watersheds are also important processes driving N transfer from watersheds. Previous research concludes that factors such as the intensity of streamflow and residence time of nutrients have been suggested to control the proportion of N input that is exported through the streams (Schaefer et al., 2009 & Howarth et al., 2012). Authors attribute this relationship to the effect of moisture and discharge on denitrification rate and N transfers (Hong et al., 2012). Watersheds with lower precipitation and lower discharge have higher fractional N-retention rate since they have a higher N-residence time which favours accumulation of N in the biomass and the soil (Howarth et al., 2006). On the contrary, it appears that wetter watersheds indicate lower denitrification rates and thus lower N-retention (Dupas et al., 2015[2]).

With all this information and knowledge, we have a general picture of the different processes involved in Nitrate pollution of water in regions that are strongly impacted by intensive agriculture. After its uptake by the plants, the N-surplus – mostly added by N-fertilizer application – is available to be exported by watercourses as function of climate and characteristics of the watershed after it is converted into Nitrate (NO3). According to Legeay et al (2016), it is thus possible to create models linking agricultural pressure to water quality inside a catchment as function of its characteristics and its climate. To assess water contamination by Nitrate in a given catchment, the nutrient pressure coming from the agricultural must be combined with transfer coefficients driving the share of additional reactive Nitrogen that is (1) exported by rivers; (2) taken by plants; (3) retained/stored in the soil; (4) or transformed by denitrification.

In this report, we focus on the assessment of the quality of water coming from agricultural drainage to analyse if we can observe the impacts of extreme climate events (i.e. droughts, heat waves and abnormally high temperatures) on agricultural yields in different regions of France, and if it increases Nitrate concentration recorded in watersheds with high drainage intensity after these specific climate events. Drainage deeply influenced the development of agriculture in the second part of the 20th century. Subsurface drainage systems are used to increase aeration and workability of the soil by evacuating excess water (Figure 1), which stabilizes yields in area where excess water causing the saturation of soil is common (Strock et al., 2018). In these regions, increased drainage intensity may be required for water removal, aeration of soil and maintains a sufficient soil moisture (Servant et al., 2020). In 2010, the total drained surface area in France reached 3Mha with an average yearly increase of 120000 additional hectares (Vincent, 2020). Drainage has been widely developed since the 1970's in the different regions where crop growth was difficult due to their "*hydromorphic soils*", i.e. waterlogged soil for which winter excess water could be damageable for winter crops such as winter cereals or rapes. (Lagacherie, 1987). Consequently, we have several large drainage-intensive agricultural regions located in South-western France, around the Poitevin marshlands, in the western part of the Parisian basin, in Anjou, etc (Vincent, 2020).

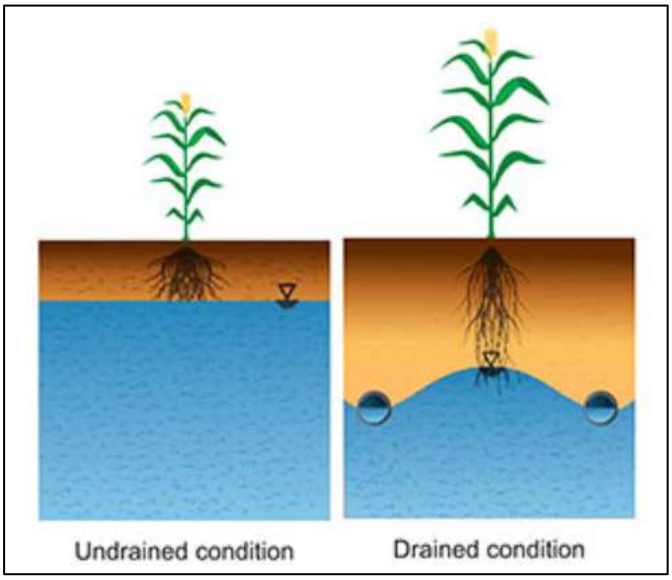


Figure 1: Impact of drainage

Drainage usually contributes to the hydrological signal of watersheds during late autumn, winter, and early spring. During these seasons, Subsurface drainage evacuates the excess of water and Nitrate from soil (Tournebize et al., 2008). Williams et al. (2015) showed that in a watershed with a surface of 389 ha and a drainage intensity of 80% of agricultural land, the average contribution of drainage to total watershed discharge and NO3 loads reach 56% and 62% respectively. Discharge and available Nitrate content in soil is a key factor driving Nitrate export by agricultural drainage. Higher drainage discharge can lead to two opposite consequences: I) Higher Nitrate concentration due to increasing nutrient leaching if enough NO3 content is available; II) If Nitrate content in soil is low, increasing drainage dilutes Nitrate pollution, thus decreasing Nitrate concentration. Figure 2 illustrates these two options. Remaining Pools of Nitrate at the Beginning of Winter season (RNBW) correspond to this excess Nitrate content available in soil that can be transported by drainage in the first flow occurring during late autumn and winter, when drainage strongly contributes to the watershed discharge and NO3-loads (Williams et al., 2015). This brings us to one of the main assumptions of this study: Subsurface drainage can be viewed as a main seasonal contributor for discharge and nitrogen transfer- because of pipe connection to surface waterbodies-, but also as a giant lysimeter, giving access to easily monitoring effect of agriculture on water quality.

Drainage is often being targeted as a conduit for pollution, particularly nutrient pollution (Strock et al., 2010) and drainage intensity is suspected to be positively correlated with Nitrate leaching in agricultural areas (Castellano et al., 2019). Some results tend to show that tile drains transport water with higher NO3 concentrations directly to streams (Williams et al., 2015), but also enhance N-mineralization in the soil and then transfers nutrients from potentially polluted agricultural fields directly to surface watercourses (Servant et al., 2020).

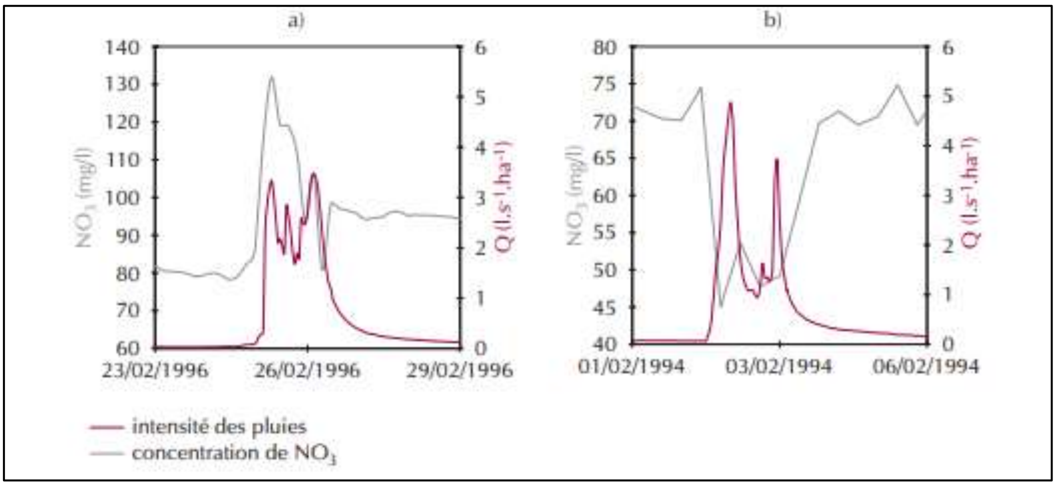


Figure 2: Two types of Nitrate leaching by agricultural drainage provoked by increased waterflow (site of La Jaillère). A: Amplification of Nitrate leaching following the 1996-flood. B: Dilution of Nitrate pollution following the 1994-flood (Tournebize et al., 2088).

French agriculture is also an intensive user of N-fertilizers. As a result, if it is not taken by the crop for its development, a large amount of nutrients remains potentially available for leaching during fall and winter when drainage resumes, which leads to large Nitrate losses from cropping systems to the landscape directly by watercourses or by infiltration in the soil, especially during autumn and winter seasons which are the critical periods for nitrate leaching (Dupas et al., 2015[3]). This quantity of excess N on a given agricultural surface that risks to be transferred to the hydrologic network is called “Nitrogen-surplus” and corresponds to the balance between entering N fluxes and outgoing fluxes on a given agricultural surface. Total N-surplus in France reaches 1.1 million of tones (36kg/ha), accounting for 23% of the total N fertilization and 50% of mineral N fertilizers inputs (Commissariat Général au développement Durable, 2012).

Even with its well-developed agricultural sector, France experiences important yield variations because of climatic conditions that fluctuate and are more or less favourable for crop growth and development. The best example occurred in 2016 when this country suffered from an extreme yield loss. During this year, yields in the breadbasket region dropped on average by 27.7% compared to trend expectations and by 39.5% compared to the previous harvest (Ben ari et al., 2018). It appears that this huge yield loss is the result of a conjunction of unusual and unfavourable climatic conditions during the growth season forming a compound extreme. Overall, the 2015–2016 growing season was characterized by a unique combination of abnormally warm temperatures in the late autumn and abnormally high precipitation, with concurrent low radiation and potential evapotranspiration, in the spring (Ben Ari., 2018). This raises a lot of concerns because extreme climatic events such as droughts, heat waves are likely to increase in frequency and severity in the northern mid-latitudes in the next decades. If we make the assumptions that that impact N-uptake by crops.

Here, we focus on France to study this impact of climate and agricultural yields on the quality of water coming from subsurface drainage, as France is one of the main and crop producer in the world and the biggest producer of wheat in the European Union (FAOSTAT, 2018) thanks to its agriculture that relies on Nitrogen-fertilizers and subsurface drainage in some regions. We combined national databases gathering information on climate, hydrology, agricultural yields, and water pollution to assess if water quality coming from drained agricultural surfaces is impacted by climate and agricultural yields in a selection of different French watersheds influenced by agricultural drainage. We make the assumptions that climate indicators (related to drought events and humidity), and crop yield data are relevant predictors for nitrate concentrations in surface waterbodies during the following hydrological year. We also assume that watersheds strongly influenced by drainage behave like giant lysimeters that export excess water and nutrients entering the system. We postulate that extreme climatic events or anomalies, impact crop's development and growth and therefore have the potential to increase the RNBW because of a lower uptake of N-fertilization by the crop and the plants. As a result, a bigger amount of Nitrate remains available and can be exported at the beginning of the following hydrological years – especially during the first month when drainage reaches its peak – leading to higher concentrations of Nitrate in rivers of affected watersheds, especially between November and January of the next hydrological season. We will test these hypotheses on a small watershed monitored by GIS Oracle and for which we have access to daily measurements on discharge and Nitrate concentration since 1975.

Materials and Method

Our explanatory research relies on a particular assumption. Drained watersheds act like giant lysimeters. Therefore, water exported by agricultural drainage has a particularly "rapid" hydrological behaviour because drained systems are supposed to have an annual hydrological reactivity. Water entering the system during a given hydrological year is mostly exported by tile drains during this same particular hydrological year or during the first months of the following one. Our objective is to select watersheds that are influenced by agricultural drainage because by doing so, the water sampled by the different monitoring stations corresponds to the hydrology of drainage and provides information on climate and agricultural practices of the same hydrological year.

1) Case-study: The experimental watershed of « Mélarchez »

1.1 Study area: Mélarchez

Before we operate our analysis on the different French watersheds from the collected database, we included an additional watershed of "Mélarchez" to our research as a specific case study in order to test our hypotheses (Figure 1). Itis located in the department of Seine-et-Marne in the Parisian Basin and is involved in the Scientific Interest Grouping (*Groupement d'Intérêt Scientifique*) called "ORACLE" - *Observatoire de Recherche sur les bassins versants ruraux Aménagés, pour les Crues, les Etiages et la qualité de l'eau* - led by the INRAE (https://gisoracle.inrae.fr/). The main advantage of this site is that we have long and strong datasets for hydroclimatic variables – discharge, precipitation and ETP – and water quality (NO3 concentration) since the 70's, unfortunately with 3 periods of data gap (1972-1974; 1995-1996 & 2001-2003). This is a strong advantage to test the influence of extreme climate events on water quality.

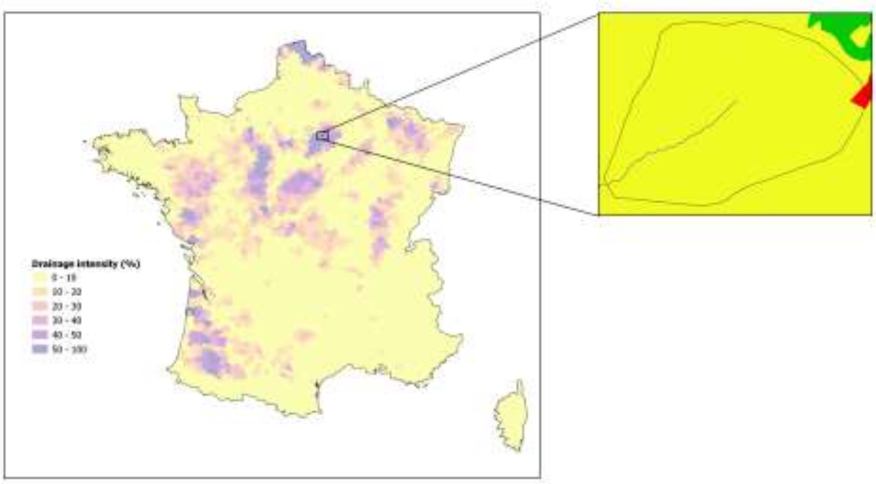


Figure 3: Localisation and land cover of the study area of Mélarchez (yellow = agricultural land; green = forests and semi-natural areas; red = artificialized land).

This watershed has a surface of 709 ha, is almost exclusively dedicated to agriculture and is entirely drained (Bouvier, 2015), which is a particularly good characteristic to test our hypothesis. The crops produced by the farmers of the area are dominated by winter wheat.

1.2 Presentation of the SIDRA-RU model

We used the SIDRA-RU model in order to describe the hydrological behaviour of the different watersheds that we selected. SIDRA-RU is a semi-conceptual lumped model developed by the

ARTEMHYS team of the INRAE and describing hydrological process of drained agricultural plots based on the principle of rain-flow conversion. Its main utility is to use rainfall and ETP to simulate discharge leaving the outlet of the drainage network. It is built with two distinct modules (Figure 4): The RU module converts precipitation entering the system and evapotranspiration into recharge in a soil reservoir module and transfers it to the SIDRA module, which converts it into a value of drained discharge (Q) by solving the Boussinesq's equation.

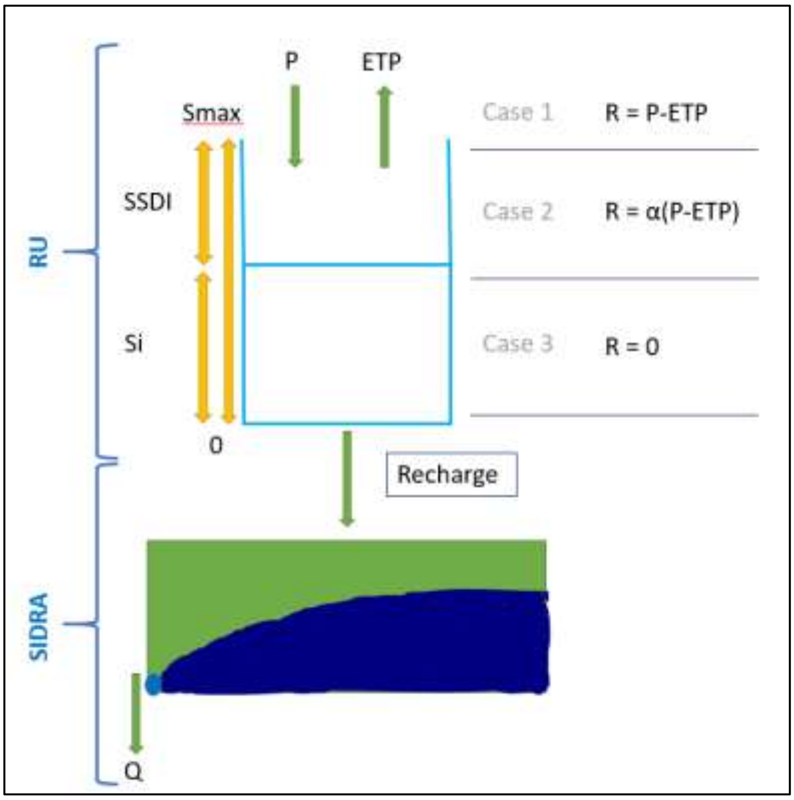


Figure 4: General principles of the SIDRA-RU model.

Within the RU module, water level (S) in the reservoir depends on the weather conditions and controls the recharge transferred to the SIDRA module. Two parameters characterize this water level: S_i("*Seuil Intermédiaire*"), defining the necessary water quantity to simulate a flow, and S_{max} (maximal capacity of the storage) from which the net infiltration is fully converted into recharge. After calculating the net infiltration "P_{net}" (P-ETP), the water level "S" is used to determine the necessary recharge R for the SIDRA module, following three distinct situations:

1. S < S_i: the water level in the soil is too low to generate flow to the drains and R = 0,
2. S_i < S < S_{max}: the water level is high enough to generate a flow R but only a part of P_{net}. Therefore, R = α(P-ETP), with α corresponding to the sharing coefficient of P_{net}, experimentally fixed at 1/3 (Henine et al., s. d.),
3. S > S_{max}: R = P_{net} = (P-ETP).

Recharge R finally feeds the SIDRA module that predicts water table level and drained flow. To be completely operational, the SIDRA-RU model calibrates four parameters for each site in order to integrate the specific conditions from pedoclimatic context:

- k: permeability of the soil,
- µ: drainage porosity,
- S_i,
- S_{max}.

When watersheds are tested by SIDRA-RU to calibrate these different parameters, we asked this model to search within ranges defined in Table 1 bellow.

As a result, SIDRA-RU gives us the simulated discharge leaving the drain outlet. This simulated discharge corresponds to drainage contribution to the global discharge leaving the watershed and is computed using data on Precipitation and ETP, and the different parameters set/calibrated for each watershed. During our research, we tested this model on French watersheds to describe their hydrological behaviour and assess if they are influenced by agricultural drainage. This study was also an opportunity to improve this model as we added a new fifth parameter to be calibrated by SIDRA-RU: the simulated drained agricultural surface within the watershed to be compared with the administrative drainage rate from RGA database. The performance of the calibration and the simulation of the model is measured by the Kling-Gupta Efficiency coefficient (KGE), ranging from -∞ to 1 (if KGE = 1, the model is perfect). We consider that the quality of the simulation and calibration is sufficient when KGE is higher than 0.4. The objective here is to evaluate if the hydrological behaviour of each watershed can be explained by agricultural drainage. In order to answer this question and validate our assumption that drainage influences the hydrological behaviour of watersheds that we will be selected later, we will calculate a ratio between simulated and observed discharge, with three distinct options and three different interpretations:

1. Qsim<Qobs ➔ Groundwater contribution
2. Qsim>Qobs ➔ Water river losses (due to sunkhole or direct infiltration)
3. Qsim=Qobs ➔ Drainage contribution

To sum up, we will use this ratio to assess drainage contribution to global watershed's discharge and the impact of drainage on the hydrological behaviour of the watershed.

Parameter	**Unit**	**Ranges (min – max)**
Permeability (k)	-	0.1 – 1
Porosity (µ)	-	0.01 – 0.1
S_i	Cm	60 – 300
SSDI	Cm	5 – 300
Drained Surface	Ha	$Drained\ Surface_{th}/10 - Drained\ Surface_{th} * 10$

Table 1: Parameters to be calibrated by SIDRA-RU and their corresponding ranges.

2) Gathering and cross-tabulation of data at the national scale

2.1 Datasets

Since our study affects various disciplines, we collected relevant databases providing accurate information for the following variables: meteorology, hydrology, agricultural yields, land-use, and water quality. One of the main difficulties of this report and cross-tabulation of data is that we are working on watersheds, but these databases work at different spatial scales, which will be detailed in the following paragraphs. Table 1 summarizes the datasets used for this report.

2.1.1 Meteorology

The meteorological database SAFRAN (Delaigue et al., 2020) produced by Météo-France (http://meteofrance.com/) is an open database for research providing daily climatic values (Temperature, Precipitation, and ETP) recorded in the 4.190 French watersheds since 1958. It is based on an optimal interpolation method operated through the different homogeneous climatic zones of France. The model used to obtain the values of the different climatic parameters covers the whole French territory with a regular spatial grid of 8km²/8km².

2.1.2 Hydrology

The database “Banque Hydro” (Delaigue et al., 2020) is the source of our hydrological data. The 4.190 Hydro-stations located at the outlet of each watershed collect daily measurements on discharge on a daily timeframe. These stations are part of the French flooding surveillance network system and collect data. Another issue is that the Banque Hydro collects data hydrological measurements of watersheds with different surface, but which are generally large (>100mk²). These data will be used for the assumption assessment of drainage influence (giant lysimeter) by comparing discharge and monthly flow. As a first step, we would like to verify that discharge measures at the outlet of our selected watersheds can be attributed to agricultural drainage thanks to our analysis with the SIDRA-RU model. The objective is to determine the part of simulated drainage explaining the observed discharges, by fitting a theoretical drained area compared to administrative drainage rate.

2.1.3 Drainage intensity

The general agricultural census (RGA) from French government collected by Agreste (https://agreste.agriculture.gouv.fr/agreste-web/), i.e. the statistical service of the French Ministry of Agriculture, gives an estimation of the share of agricultural surface that is drained in 2010 in every French cantons. Therefore, the administrative division of this database does not match with the watersheds of the Banque Hydro, which makes it more difficult for us to estimate the percentage of Utilized Agricultural Area (UAA) that is drained within each watershed. This information is in open access but is not regularly updated. However, drainage intensity is not evolving fast since 2010 because of the restrictions provoked by the enforcement of water protection laws. In order to select the most relevant regions for our study, we assume that cantons with a drainage intensity higher than 50% of drained UAA are “the most influenced by agricultural drainage” and are selected for the following steps.

2.1.4 Water quality

The database “Naiade” (http://www.naiades.eaufrance.fr/) will be used to assess water quality at the outlet of our selected watersheds. It gathers measurements on physicochemical variables – including Nitrate concentration – collected by each the 20.105 Naiade-stations located in Metropolitan France on almost all the French watercourses. The oldest measurements were made in 1962 but this dataset suffers from a major quality problem. The data are financed and gathered by the regional French *Water Agencies* (“*Agences de l’eau*”) but are collected by local structures and agencies. These local structures have to pay a non-negligible price - approximately 20% - for the collection and the analysis of the sampled water. Unfortunately, many local agencies do not have the financial means to perform these assessments of water quality at a regular basis. As a result, the Naiade-stations are very heterogeneous in terms of frequency of measurements and length of chronic. Consequently, even though Naiade-stations are distributed throughout the country, we have a severe chronic lack of physicochemical data for a large majority of French watercourses because the regional Water Agencies did not collect measurements at a regular basis. This impacted our study because we did not imagine that this problem would occur when we started our research. To overcome this problem, we decided to focus on Naiade-stations providing decent datasets on water quality. The rules we adopted is a time serie of at least 10 years including minimum 3 nitrate data per year. We set this threshold to make sure we have continuous records of water quality with reasonable frequency of measurements to analyse the variations of Nitrate concentration in watercourses. However, these thresholds are low and more frequent measurements on water quality would be essential to improve the assessment of Nitrate pollution in rivers and its origin.

2.1.5 Agricultural yields

On the platform API-AGRO (https://api-agro.eu/), we collected a database giving an estimation of the yearly agricultural yields for each department and for each crop. This open database enables us to assess the variations of agricultural yields in every departments of France in the last decades. For each watershed, the attributed agricultural yield corresponds to the mean annual yield recorded for the dominant crop inside the department that covers the biggest part of the catchment. Winter wheat was the crop used for a majority of watersheds, which is positive because it is often cultivated on drained soils. Some watersheds in Southern and Western France are dominated by maize, for which we also have long records on yields. These yields have evolved since the beginning of these records in 1958 as they increased sharply until the 90's and stabilized in the last decades.

2.1.6 Climatic anomalies

We wanted to target the different years during which France suffered from extreme climate events that are likely to impact agricultural yields. Therefore, we decided to search records of the following climatic anomalies in France: severe droughts, heatwaves, high winter temperatures, extreme low-flow periods, and humid hydrological years. We decided to search records of these extreme climate events in the scientific literature and found different documents listing them with a very decent precision. The scientific documents used for each climatic anomaly can be found in the Table 1 bellow. Soubeyrou et al. (2012), Soubeyrou et al. (2016) & the INRAE (personal communication) provide archives of the different droughts, heatwaves and abnormally high winter temperatures that affected France since 1962, 1957 and 1966, respectively. We assume that all the French watersheds were impacted by these events without taking account of their location. The contrary, the record of extreme low-flow periods provided by Caillouet (2016) is much more precise and delivers the list of low flow periods from 1871 to 2011 and specifies the geographical regions of France that were affected. Therefore, we were able to know which watersheds suffered from extreme low-flow periods according to their geographical localisation. Finally, we used a different method to highlight humid hydrological years as we considered a year was "humid" when cumulated observed discharge of a given watershed is 50% higher than the 10-years mobile average cumulated discharge of this watershed. We think that using this method to highlight the other climatic anomalies would have been a better solution, but we suffered from a huge lack of time and because of the missing data for climatic variables (P; ETP; Temperature) in many watersheds. This is a limit to our study, and it would be interesting to improve this method to define the climatic anomalies that impacted each watershed in future research.

Parameters	**Unit**	**Dataset**
Drainage intensity	%	Agreste (RGA)
Physicochemical data (Nitrate concentration)	mg/l	Naiade
Climate - Temperature - Precipitations - Evapotranspiration	- °C - mm/day - mm/day	Safran (Delaigue et al., 2020)
Hydrology (Discharge)	mm/day	Banque Hydro (Delaigue et al., 2020)
Agricultural yields	100kg/ha	API-AGRO
Climatic anomalies - Droughts - Heatwaves - High winter temperatures - Low-flow periods	-	- Soubeyrou et al., 2012 - Soubeyrou et al., 2016 - Meteo France & INRAE - Caillouet, 2016

Table 2: Database used for the statistical analysis.

2.2 Cross tabulation of data

We used QGIS 3.12.0 to attribute different spatial characteristics to each studied area/watershed according to their location. This geographic information system application was used on the selected watersheds to characterize the location, surface, land cover (based on the Corine Land Cover, reference year 2018) and soil occupation of each selected watershed, and the location of their corresponding Naiade-station and Hydro-station.

The merging of the different variables and characteristics of each watershed was performed using Rstudio. Our objective was to produce a unique dataset for each watershed gathering all the daily hydroclimatic variables and water quality measurements recorded by the corresponding monitoring station. Then, we computed a yearly "*neutral mean*" for agricultural yields, NO3 concentration and discharge recorded in each watershed (Figure 5). It is a mobile mean giving an accurate picture of their long-term variations and "business-as-usual" situation. This is particularly true for agricultural yields, for which we observed a sharp increase between the beginning and the end of our records (1951-2016). We computed this neutral mean according to two different scenarios depending on the nature of the variables:

- Case 1 (hydrological and climatic variables): $mobile\ mean_y$ is equal to the mean of the cumulative values recorded during the period between the two preceding years and the seven following years.
- Case 2 (agricultural yields and water quality variables): $mobile\ mean_y$ is equal to the mean of the cumulative values recorded during the period between the two preceding years and the two following years.

Finally, we calculated the annual deviation from these neutral means (in %) to measure the positive or negative anomalies recorded each year. For each year "y", we calculate these anomalies with the following ratio: $Yearly\ mean_y \Big/ Neutral\ mean_y$

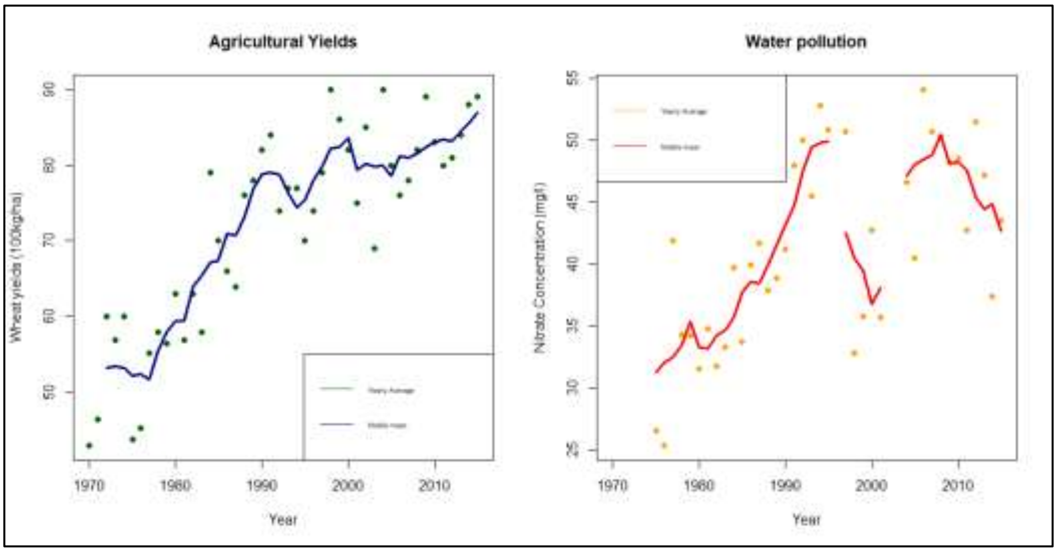


Figure 5: Variation of yearly mean and neutral mean for agricultural yields and NO3 concentration in the watershed of Mélarchez. Points: Yearly mean. Line: Neutral mean.

Once this process has been completed successfully, we produced an "identity sheet" for each watershed summarizing the different characteristics mentioned above. Thanks to this document, it was easier for us to describe the studied area and point the watersheds for which we have a lot of missing hydrological and physicochemical data. An example of these “identity sheets” is available in Annexe 1.

2.3 Spatial analysis

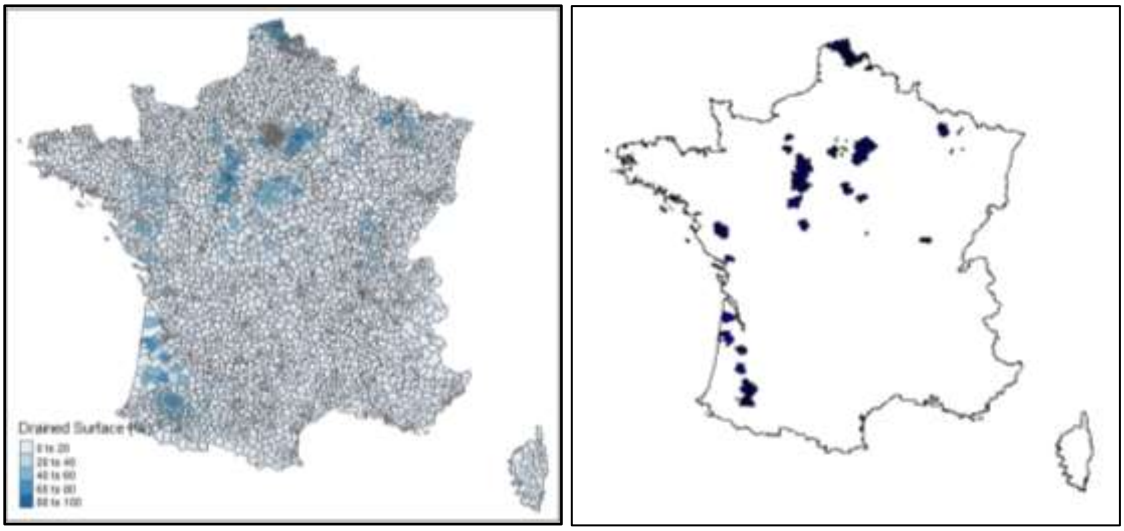
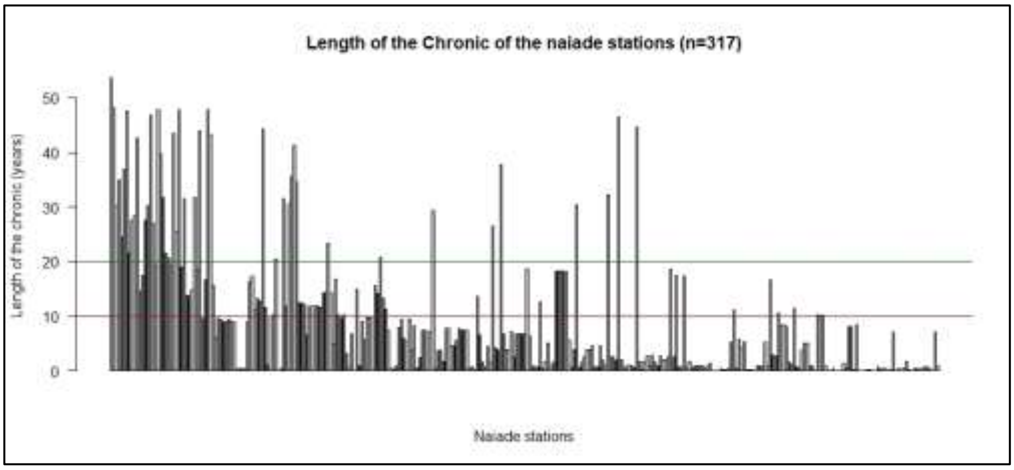


Figure 6: Variation of drainage intensity (% of drained UAA) among French cantons (A); and localisation of French cantons with more than 50% of drained UAA

Selecting the most relevant watersheds was one of the biggest operations of our work. Drainage intensity, i.e. the share of drained UAA, was the main characteristics we used for this selection in order to keep watersheds and monitoring stations that are strongly influenced by agricultural drainage. We highlighted French cantons with a high drainage intensity, i.e. more than 50% of drained UAA (Figure 6). We kept 317 Naiade stations that were located within these cantons. As we mentioned previously, a large majority of these stations have extremely poor data on Nitrates concentration, i.e. low frequency, and short period of measurements. Consequently, we kept only the Naiade stations that operated measurements during a period longer than 10 years and with an average frequency of more than 3 measurements per year (Figure 7) to end up with a number of 61 Naiade stations fulfilling these requirements.



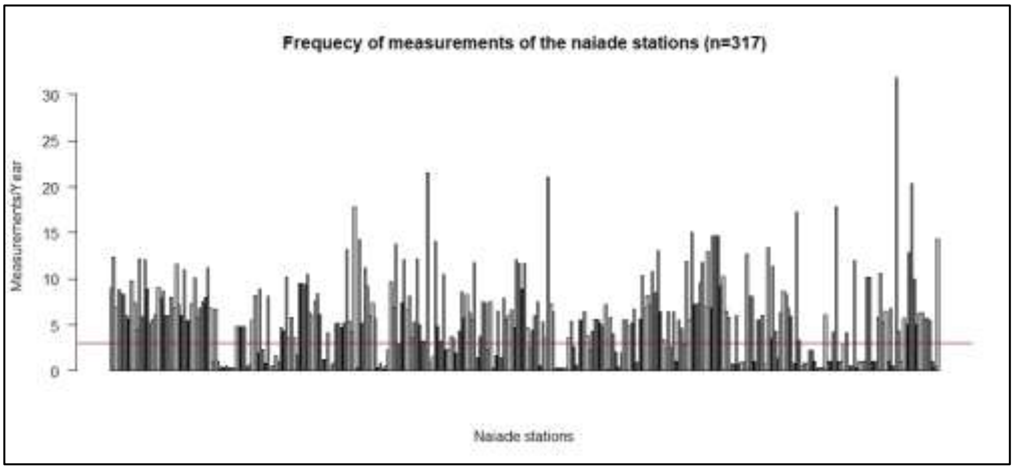


Figure 7: Length of monitoring period (A) and average number of measurements (B) of the 317 Naiade stations located in cantons with drained SAU higher than 50%

These 61 Naiade stations were then manually connected to a Hydro station and a corresponding watershed from the Banque Hydro. Each Naiade station is linked manually to the closest Hydro station located downstream to be included in the corresponding watershed. Five exceptions were made for Naiade stations that we connected to similar watersheds located nearby (closer than 10km) because we assumed that discharge and climate would be similar. Three Naiade stations could not be joined to any watershed, which gives us 58 Naiade stations joined to 42 different Hydro stations. Five watersheds were removed from this list because they lack hydroclimatic data. Our final selection leaves us with a total of 37 watersheds that include 49 Naiade stations. All the different steps of this selection are detailed in the Figure 8 below and were performed using QGIS 3.12.0. We tested the selected watersheds with SIDRA-RU in order to verify if this model is able to simulate discharge at the outlet of these catchments and their drained surface.

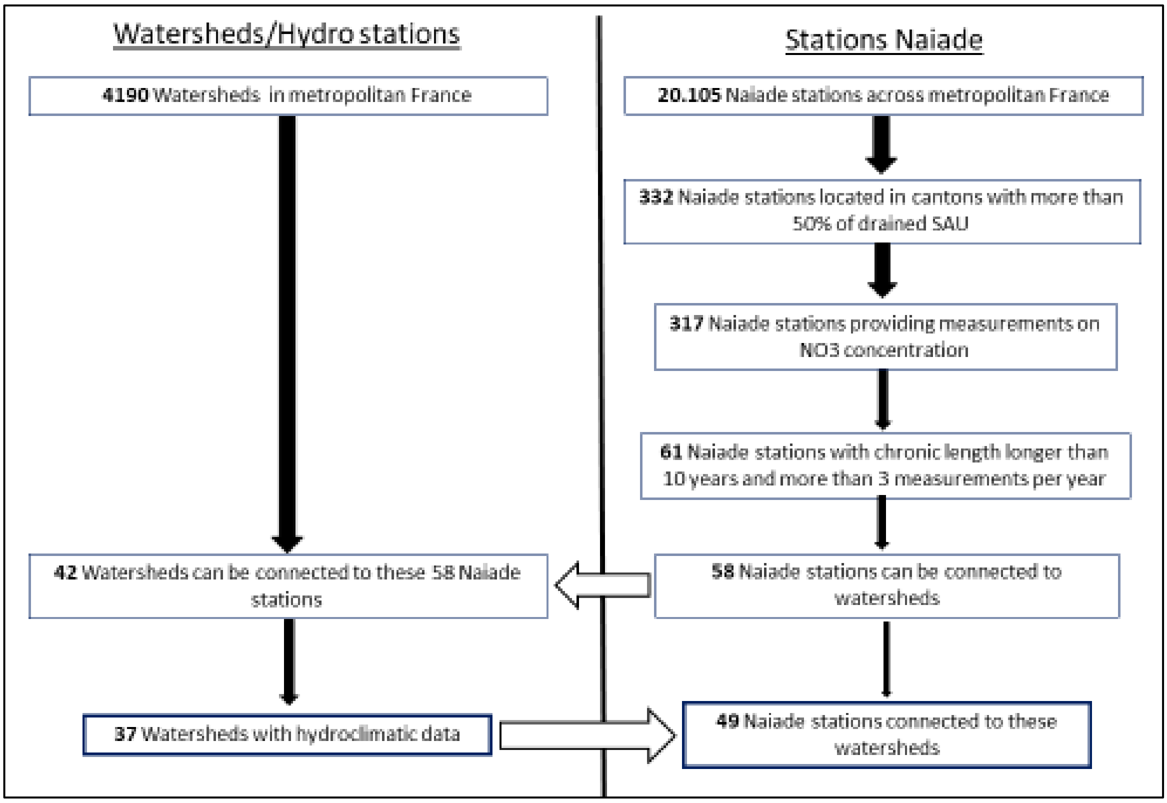


Figure 8: Summary of the different steps for the selection of the relevant watersheds and monitoring stations (Hydro and Naiade)

Statistical processing of data

- Preparation of the final dataset

A table containing the different variables has been built for each selected watershed. It combines data on climate, hydrology, agricultural yields, water quality and climatic anomalies that we collected in the different databases. Table 3 provides the list of all these variables and their timescale.

Variables	Timescale	Unit/Value
Year	$Civilian\ year_y$	-
Watershed	-	Watershed Reference (Banque Hydro)
Hydrology - Q_{sim} - Q_{obs} - Mobile mean of Q_{obs} - Deviation from mobile mean	Hydrological year $(Oct_{y-1}$ - $Sept_y)$	mm/year
Climate Precipitations: - Precipitations - Mobile mean of precipitation - Deviation from mobile mean ETP: - ETP - Mobile mean of ETP - Deviation from mobile mean	Hydrological year $(Oct_{y-1}$ - $Sept_y)$	mm/year
Water quality Annual NO3 concentration: - Mean annual concentration - Mobile mean of annual concentration - Deviation from mobile mean NO3 concentration at flow resume: - Mean NO3 concentration at flow resume - Mobile mean of NO3 concentration at flow resume - Deviation from mobile mean	- $Civilian\ year_y$ - $Nov_y + Dec_y + Jan_{y+1}$	mg(NO3)/l
Agricultural yields	$Civilian\ year_y$	100kg/ha
Climatic anomalies	$Civilian\ year_y$	Yes/No

Table 3: General description of variables used for the statistical analysis.

This table deals with cumulated variables, i.e. aggregations of daily values for each year. For hydrological and climatic variables, we summed the daily observed discharge, modelled discharge (SIDRA-RU), precipitations and ETP during each hydrological year, which is slightly offset from civilian year. This means that for a given civilian year "y" the cumulative values of these variables correspond to the sum of daily values from the 1st of October of the previous year "y-1" to the 31st of September of year "y". This method is better to assess the hydrological state of the watersheds. We included an additional indicator to evaluate water quality, i.e. mean NO3 concentration (in mgNO3/l) during the three months when drainage restarts after the dry season. We made this choice because drainage discharge is usually almost null until the month of November since the water table is too low in drained agricultural plots. Consequently, we assumed that the RNBW cannot be exported before this period but is transported by water at the outlet of the catchments when waterflow finally resumes at the beginning of following wet season. This indicator corresponds to the mean NO3-concentration recorded during the months of November and December of the year “y” and January of year “y+1” for each year and each watershed. There is room for improvement as this indicator could have been adapted to each specific case (watersheds and months during which waterflow resume after the dry season) in further research.

- Statistical Treatment

The different relations between the different variables that we gathered were evaluated for the watershed of Mélarchez and the selected watersheds of the Banque Hydro. This evaluation was only possible for periods during which we have data on discharge and water quality at the same time. Unfortunately, this was not the case for 18 of our selected watersheds for the Banque Hydro, so we were forced to remove them from the list. After we calculated the yearly relative deviation from mobile mean for each quantitative variable, we performed Anova statistical tests on R studio to assess the relations between climatic anomalies, agricultural yields, and water quality. We tested different H_0 hypotheses to assess the impact of climate, yield, and water quality anomalies on each other:

- Impact of climatic anomalies on agricultural yields ➔ H_0: “Climatic anomalies do not impact yield anomalies”.
- Impact of agricultural yields on water quality ➔ H_0: “Yield anomalies do not impact NO3 anomalies”.
- Impact of climatic anomalies on water quality ➔ H_0: “Climatic anomalies do not impact NO3 anomalies”.

We tested these hypotheses for the watershed of Mélarchez and our selection of 15 watersheds to assess if they are true or false. If they are rejected (p-value=<0.1), this means that we validate the corresponding opposite hypothesis H_1 that implies a relation between the variables.

Results

1. Mélarchez

1.1. Assessment of the hydrological behaviour of this watershed

We obtained satisfying results for the watershed of Mélarchez after the calibration of SIDRA-RU, with a KGE coefficient of 0.69. Figure 6 provides the hydrograph showing the variation of observed and simulated discharge at the outlet of the catchment. In addition, the outcome of calibration gives us the following values for the five parameters:

- Permeability (k) = 0.94 m/d
- Porosity (µ) = 0.06
- S_i = 115.02mm
- SSDI = 5mm
- Simulated drained surface = 763ha

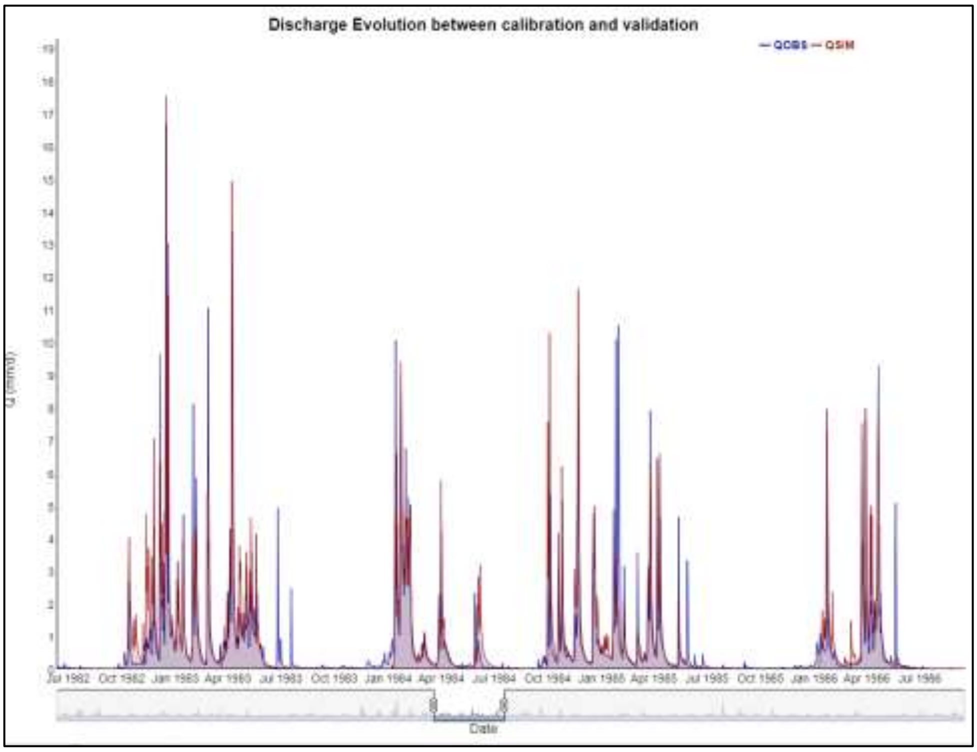


Figure 9: Daily variation of observed and simulated discharge (mm/day) at the outlet of the watershed of Mélarchez between July 1962 and July 1966.

The actual drained surface of this watershed is 709ha and seems slightly overestimated by the model. This might be attributed to an agricultural drain that collects water from a neighbouring catchment. Nevertheless, we obtained a good overall performance of the model (KGE coefficient), an accurate simulation of the discharge and a decent estimation of the drained surface (overestimation of only 7%).

1.2. Impact of climate on agricultural yields

We found a significative negative effect of climatic anomalies on wheat yields, as yields anomalies (deviation from neutral mean) were 6,72% lower during years when climatic anomalies occurred (p-value= 0.002; R^2= 0.2; Figure 10). Heat waves and abnormally high winter temperatures were the only extreme climate events with a significative impact on agricultural yields. During years affected by heat waves and high winter temperatures, we observed that wheat yields anomalies were 9% (p-value = 0.001; $R^2 = 0.22$) and 6% (p-value = 0.08; $R^2 = 0.08$) lower, respectively. No impact of the other climatic anomalies (droughts, low-flow periods, humid years) on yields was found in the watershed of Mélarchez. In addition, no correlations between climatic variables (Q, ETP, P) and wheat yields anomalies was found during our study. This could mean that wheat yields in this watershed are more affected by extreme climate events than softer variation of temperature or precipitation.

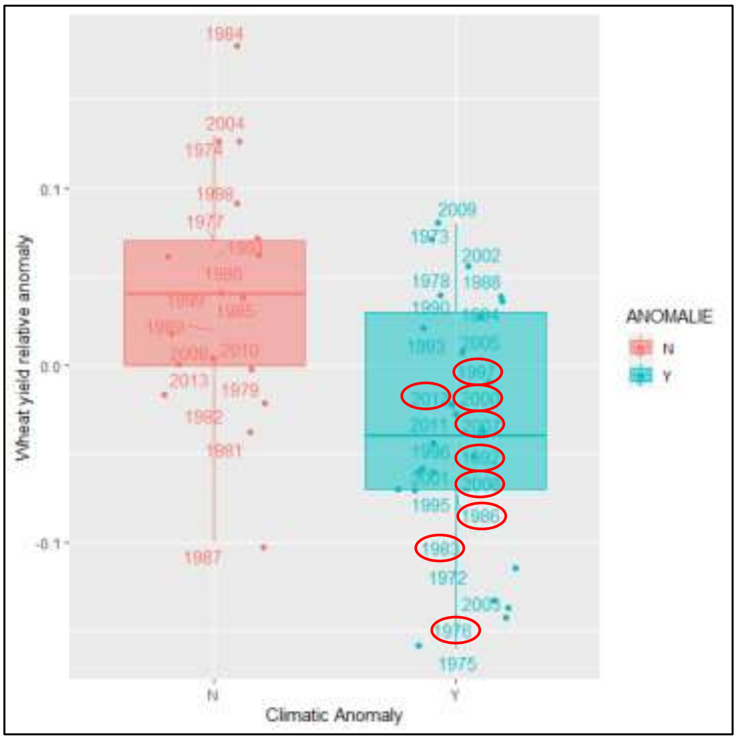


Figure 10: Impact of Climatic anomalies on agricultural yields in the watershed of Mélarchez. Blue = Years affected by at least one extreme climate events; Red = Years without any climatic anomaly. Years within red circles are the nine *critical years* (see part 1.3).

1.3. Impact of agricultural yields on Nitrate pollution

We did not find any influence of agricultural yields on yearly mean NO3 concentration during the corresponding year, but we observed a slight significative impact of Wheat yields on NO3 concentration during the beginning of the next hydrological drainage season (called next). Nitrate concentration in November, December, and January seems to be higher when wheat yields were low during the previous harvest. Figure 11 shows this small influence of agricultural yields on Nitrate pollution during the restart of drainage in the watershed of Mélarchez, but it also highlights years, called "*critical years*" that provide an interesting combination of loss of yield and higher NO3 concentration during the months of November, December, and January: 1976; 1983; 1986; 1992; 1997; 2000; 2006; 2007; 2012. These years are interesting for us because they seem to correspond to situations during which our assumption is validated: When agricultural yields are low, RNBW increases, thus leading to higher Nitrate concentration when drainage restarts and exports the Nutrients that were not taken by plants. All of these years experienced climatic anomalies and it would be interesting to assess if we find the same results in our selected watersheds.

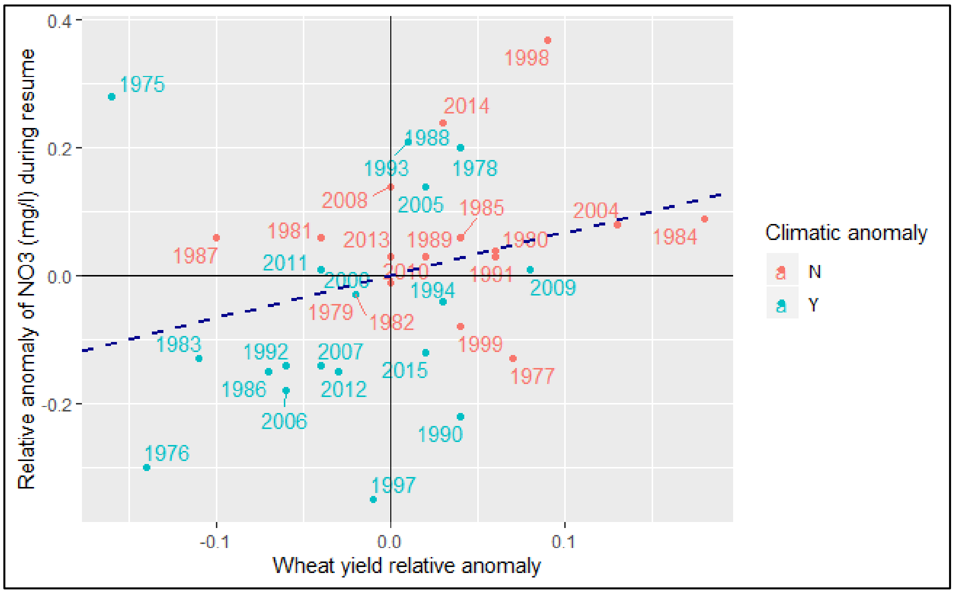


Figure 11: Influence of yearly wheat yield anomalies on average NO3 concentration recorded between the following months of November and January in the watershed of Mélarchez ($y = 0{,}68x$).

1.4. Impact of climate on Nitrate pollution

Taken all together, we did not find any impact of climatic anomalies on yearly average NO3 concentration. Moreover, none of the different climatic anomalies has an individual impact on this variable. However, average Nitrate concentration in November, December and January was significatively higher after these extreme climate events, since deviation from neutral mean NO3 concentration during these months is equal to -10,3% after years that experienced at least one of them (p-value = 0.05; R^2 = 0.11) compared to normal years. Droughts are the only climatic anomaly with a statistically significative impact on Nitrate concentration when drainage resumes. NO3 Anomaly is on average 12,6% lower for years affected by this anomaly (p-value=0.02; R^2=0.15; Figure 12).

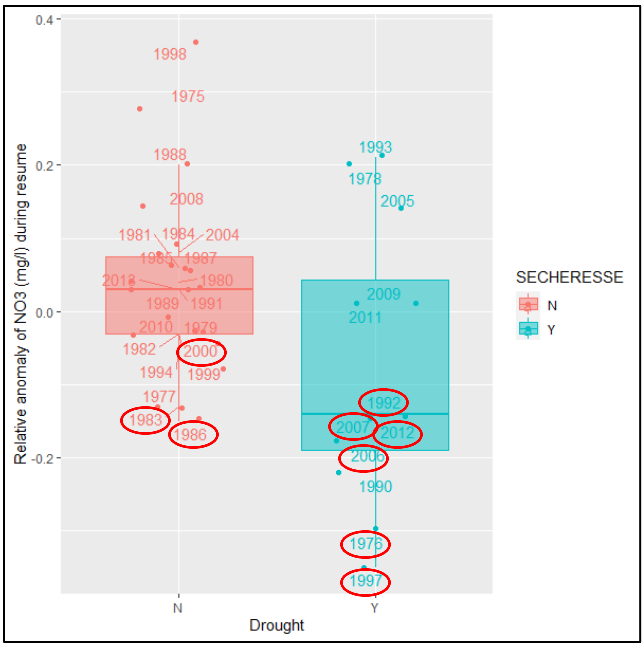


Figure 12: Impact of severe droughts on average Nitrate concentration between November and January in the watershed of Mélarchez. Blue = Years affected by drought; Red = Years without drought. Years within red circles are the nine *critical years*.

2. At National Scale

2.1. Selected watersheds and monitoring stations

Figure 13 gives the location of the 37 watersheds and 49 Naiade-stations we selected previously (cf: Materials and Method). They cover the main agricultural regions of France with high drainage intensity: Western and Eastern Parisian basin; Northern France; the Poitevin marshlands; and the Landes. This is positive for the geographical diversity of our exploratory study. We lack selected watersheds located in the Southern part of the Parisian basin and near the Sarthe-river, but these regions do not include Naiade-stations with decent records on water quality.

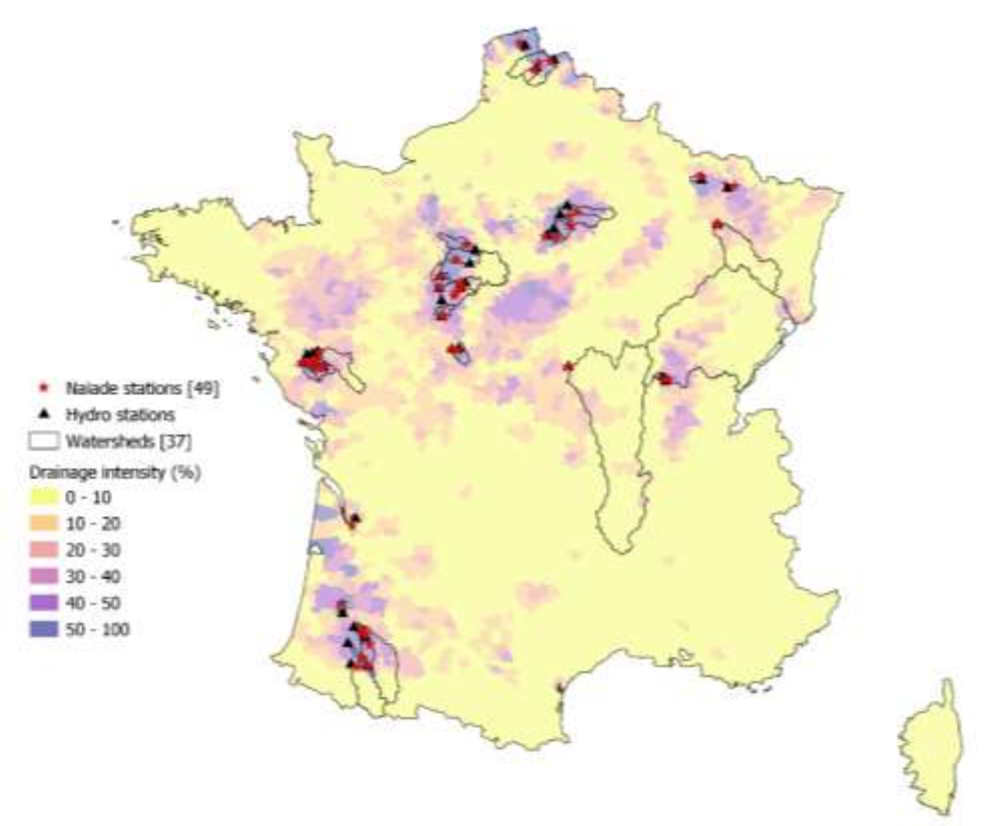


Figure 13: Limits of selected catchments and location of their monitoring stations.

The surface of our selected watersheds ranges from 24.6km² to 21017.43km² with mean and median values of 1788.36 km² and 402.15 km², respectively. Figure 14 below shows how this surface is distributed among the 37 selected watersheds. We can clearly see that most of the studied watershed have comparable surface areas, with two exceptions covering 17640.14km² and 21017.43km².

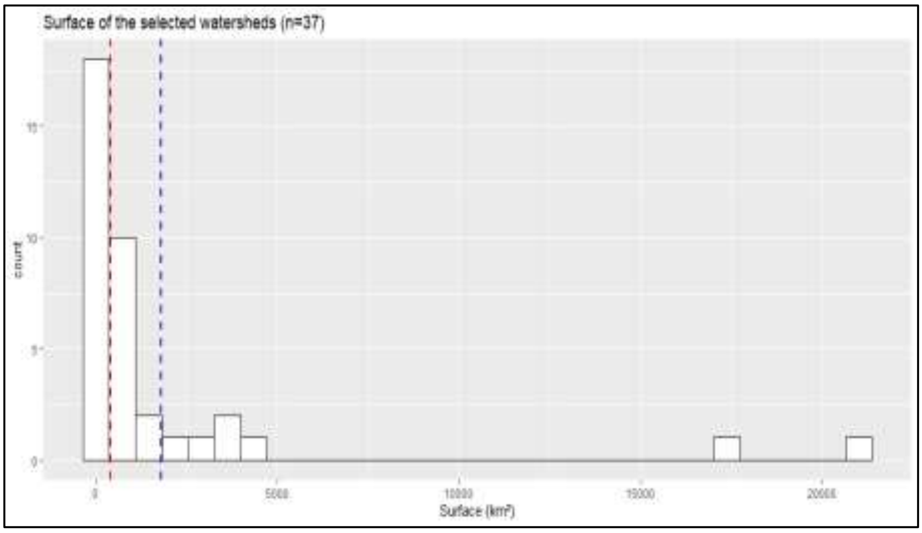


Figure 14: Surface distribution of the 37 selected watersheds in km². Red dotted line = median surface area (402.15km²); Blue dotted line = mean surface area (1788.36km²).

2.2. SIDRA-RU

2.2.1 Performance of the model

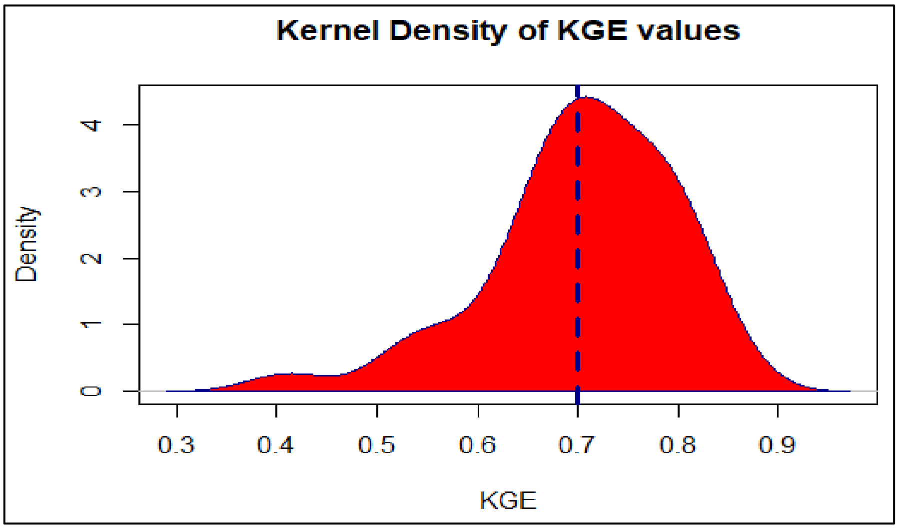


Figure 11: Distribution of KGE values obtained by SIDRA-RU among our selected watersheds.

SIDRA-RU ran successfully for the 37 selected watersheds, with very satisfying performances of the model. The value of the KGE coefficient ranges from 0.41 (Aigre-river at Romilly s/ Aigre) to 0.85 (Sèvre-river at Clisson) with an average value of 0.7 among the 37 tested watersheds.

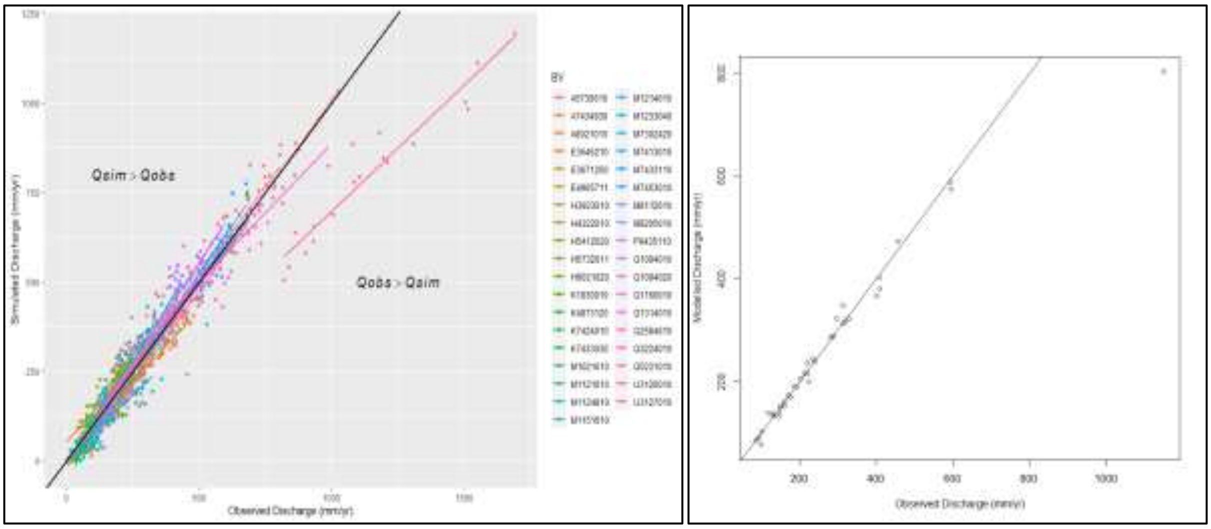


Figure 12 Comparison of yearly cumulative discharge at the outlet of the 37 selected watersheds between observation and simulation from SIDRA-RU (in mm/year). A (left): yearly observed and simulated of each watershed; B (right): average yearly discharges.

The model was particularly good at simulating discharge leaving the outlet of each catchment and we globally have efficient simulations of daily and yearly discharge. Annexe 2 provides two concrete examples of hydrographs comparing observed discharge and discharge simulated by SIDRA-RU for two catchments during three hydrological years. However, we observed that it is difficult for the model to explain some hydrological behaviours of some watersheds. We can see it during periods when simulated and observed discharge are not matching. For example, SIDRA-RU is not very efficient to simulate discharge during summer, probably because it does not happen in drained agricultural plots. In addition, it underestimates discharge during short specific periods when it is remarkably high. This issue can be attributed to the fact that SIDRA-RU is not used to work on watersheds of this surface. Nevertheless, the outcome of this model gives us accurate simulations of yearly discharge (in mm/yr) for every single selected catchment. Figure 12 above shows that yearly simulated and observed discharge are proportional for almost each watershed as the ratio ${Yearly\ average\ discharge_{Observed}}/{Yearly\ average\ discharge_{simulated}}$ ranges from 0,8 to 1,44, with a median value of 1,03.

2.2.2 Parameters' calibration

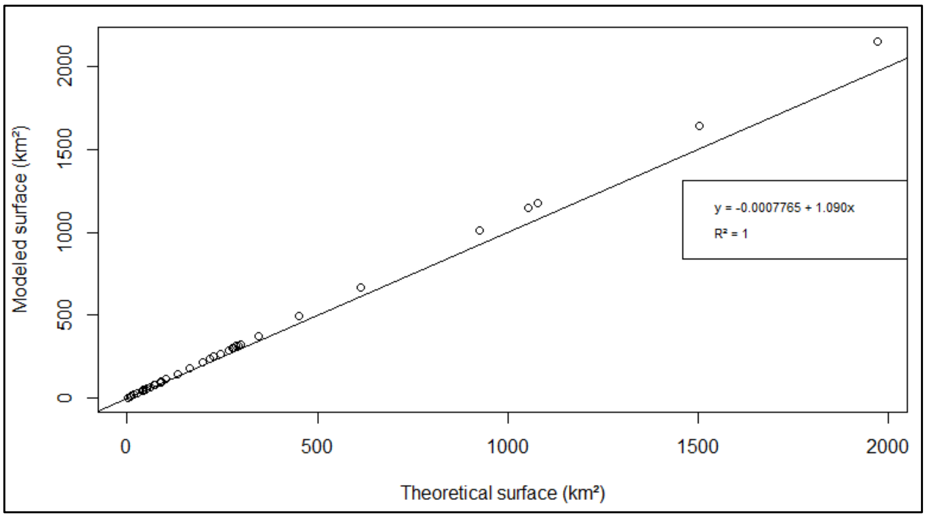


Figure 13: Yearly simulated vs observed discharge of the 37 selected watersheds.

SIDRA-RU managed to attribute the five calibrated parameters to each watershed. We were positively surprised by the drained surface calibrated by the model since it is very close to the theoretical surface that we computed for each watershed using our data on drainage intensity and agricultural surface (Figure 13). The model just slightly overestimates this parameter by 9%, but we found a perfectly linear relation between the theoretical and simulated drained surface as expressed by the following expression: $Drained\ Surface_{sim}$= 1.09 x $Drained\ Surface_{th}$ (R^2=1). The outcome was more "disappointing" for the four other parameters because many watersheds have a calibrated value equal to one of the limit-ranges we set previously (cf: Table 1) for at least one parameter. Indeed, 25 of the 37 catchments have at least one calibrated parameter that is equal to one of its corresponding limit-values (Table 4). Porosity is the most affected parameter, which is not surprising because this characteristic varies a lot from one watershed to another depending on their size of drainage networks or surface.

Parameter	Watersheds "hitting" the limit-range
Permeability	6/37
Porosity	17/37
S_i	10/37
SSDI	7/37
Drained surface	0/37
Total	**25/37**

Table 4: Number of selected catchments whose SIDRA-RU's calibrated value is equal to one of the limit-ranges for each parameter.

2.3. Climatic anomalies / agricultural yields

Climatic anomalies affected agricultural yields in the studied area of Mélarchez, and we observed a similar relation between extreme climate events and yields in the 15 watersheds we tested. Deviation from neutral mean was on average equal to -6,1% during years when climatic anomalies occurred (p-value= $4*10^{-9}$; R^2= 0.08) for agricultural yields, although this relation is lacking predictivity. Heatwaves, droughts, and high winter temperatures are significatively impacting agricultural yields as they provoke a decrease of yields anomalies by 5% (p-value= $3*10^{-5}$; R^2= 0.05), 3,6% (p-value= $6*10^{-4}$; R^2= 0.03), and 3,6% (p-value= $1,75*10^{-8}$; R^2= 0.07), respectively.

2.4. Water quality and Nitrate pollution

Concerning the influence of agricultural yields on water pollution, we found opposite results compared to those obtained for the watershed of Mélarchez. Yearly average Nitrate concentration at the outlet of the catchments was significatively higher when agricultural yields are low (p-value = 0.006; R^2 = 0.02), but this relation has an extremely weak R^2. This relation between yields and water pollution is a bit stronger and is less variable when we focus only on years affected by climatic anomalies, as we observed the following linear relation:

$NO3\ Anomaly_{year}$= 0.03 + 0.33*$Yield\ Anomaly$(p-value = $4,4*10^{-5}$; R^2 = 0.07).

However, yields do not have any impact on average NO3 between November and January in our selected watersheds.

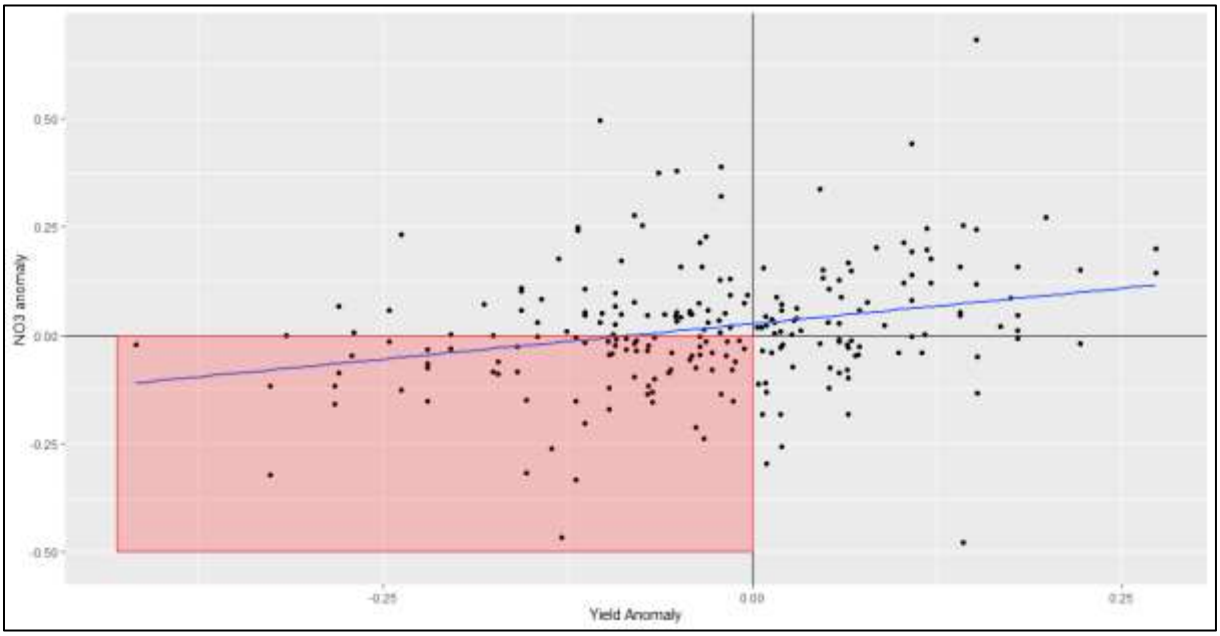


Figure 14: Influence of yearly yield anomalies on yearly average NO3 concentration (y = 0,03 + 0,33x).

Finally, all climatic anomalies had no significative impact, neither on yearly NO3 concentration, nor on average Nitrate concentration between November and January. This does not correspond to the initial hypothesis we made. We still wanted to investigate the level of Nitrate pollution and agricultural yields during the nine critical years we highlighted in Part 1.3, but this was very difficult because very few watersheds provided records on these variables before the 90's. Therefore, the quality of our dataset is extremely bad, especially for the years 1976, 1983, and 1986. In addition, none of these particular years experienced general decrease of agricultural yields and increase of Nitrate concentration.

Discussion

1. Assessment of drainage influence on hydrological behaviour of our selection of watersheds

The purpose of the SIDRA-RU model during this research was to investigate if our selection of watersheds behaves like drained agricultural plots or "giant lysimeters", i.e. systems where total net water inputs (Precipitation-ETP) leaves the system under the form of surface water thanks to agricultural drainage. This model is functional for agricultural plots (Hénine et al., 2020), but we were surprised to see that it is also working very efficiently for the 37 watersheds of our selection, plus the watershed of Mélarchez. The performance of the calibration and simulation performed by SIDRA-RU was tremendous as we obtained KGE values above 0.4 for all watersheds. This means that for all of them, we managed to simulate discharge using just Precipitation and ETP and SIDRA-RU, which is a model created to simulate the hydrological behaviour of drainage. This result seems to validate our assumption that agricultural drainage is strongly contributing to discharge in these watersheds. Figure 12 - which gives the ratio between simulated and observed discharge - also strengthens this idea since the ratio $^{Qobs}/_{Qsim}$ is extremely close to 1 for almost each watershed (all hydrological years and average yearly discharges). This ratio ranges between 0.8 and 1.2 and seems constant for each watershed among the different hydrological years, which seems to mean that drainage contribution to annual discharge remains constant. The watershed U3120010 is the only exception where $Qobs$ and $Qsim$ are significatively different, as its ratio is approximately equal to 1.4 with $Qobs > Qsim$. That particular case tends to show that drainage in this watershed is also influenced by groundwater contribution, which is logical as this is the biggest watershed of our selection, with a surface of 21.017km².

Globally speaking, we can conclude that our assumption of drainage contribution to hydrological behaviour of selected watersheds was successful and that a big share of water flow leaving the outlet of the watersheds can be attributed to drainage. These results validate our assumption that drained watersheds behave like giant lysimeters exporting water and nutrients to the rivers as a function of climate (Precipitation and ETP). Consequently, water sampled by the different monitoring stations was influenced by agricultural drainage, which gave us access to monitoring effect of agriculture on water quality. Therefore, this reasoning can be used by scientists trying to assess water quality in drained areas.

Regarding the calibration of the five parameters by the model, the results are bit more confusing, because a large proportion of selected watersheds are "hitting" one of the limit-ranges imposed to the model. We initially explained this phenomenon by assuming that SIDRA-RU tries to adapt generate a situation that "sticks" closer to data of observed discharge even though they do not correspond streamflow measurements of fully drained areas. However, our final interpretation of this result is that SIDRA-RU is a model create for drained agricultural plots with a limited surface, and we used it to assess the hydrological behaviour of watersheds that cover a much larger surface and a multitude of parameters influencing hydrology that are usually not considered by the model (land-cover, forests, different types of soil, etc.). The fact that many watersheds have a calibrated value equal to one of the limit-ranges for at least one parameter does not mean that SIDRA-RU is inaccurate, and that the hydrology of these watersheds are not influenced by drainage. It can be explained by characteristics of the watersheds - e.g. surface, size of drains – that are unusual for the model but does not affect the good performance of the model.

2. Water quality at national scale and impact of agricultural drainage

In addition to the assessment of the relations between climate, yields and Nitrate concentration, we tried to investigate the bad reputation of agricultural drainage to see if it was so strongly increasing water pollution in France. We initially thought that it would be a nice opportunity to take advantage of the Naiade database, which collects Nitrate concentration measurements from monitoring stations that are evenly distributed in the French territory. We used the mean NO3 concentration by each of the 20.105 Naiade stations of metropolitan France to create Figure 15 and highlight the areas that suffered the most from Nitrate pollution since the beginning of Naiade records in 1962. This Figure created with QGIS by kriging the mean values of NO3 concentration recorded by each Naiade station also includes spatial information on the repartition of drainage intensity in France. This Figure is not accurate due to the heterogeneity of measurements (frequency and chronic length) among the different Naiade stations but is spatially and temporally large. This Figure It does not show any clear homogeneity and correlation between agricultural drainage and water pollution. Further, a main finding emerges from this observation: even though agricultural drainage is often being targeted for its negative impact on water quality (Williams et al., 2015; Strock et al., 2018; Castellano et al., 2019), it is not the only key variables and should not be stigmatized for being the only contributor to water quality degradation. The whole agricultural seems to be – logically – the most important source of water contamination by Nitrate.

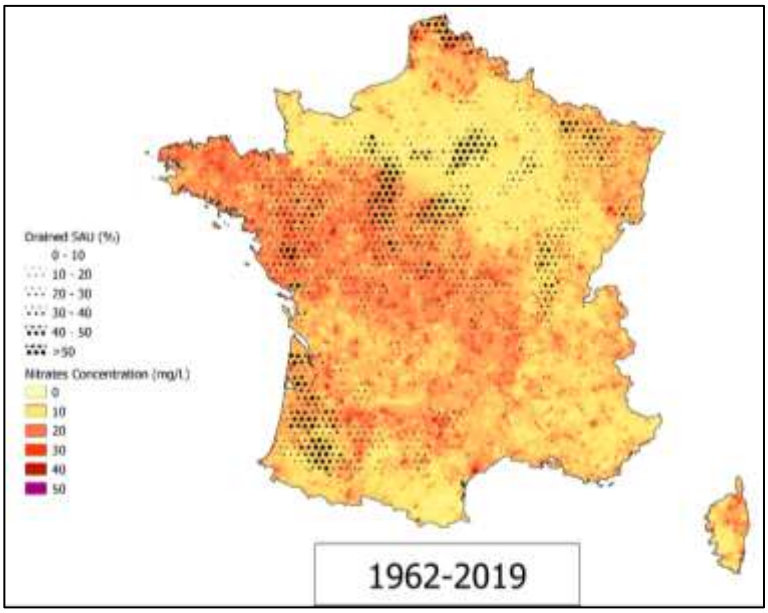


Figure 15: Geographical variation of mean NO3 concentration recorded by Naiade stations and drainage intensity.

However, we observed some relatively important water pollution issues in French watercourses: we did not see any Naiade station with higher average NO3 concentration above the drinkable limit (set at 50mgNO3/l), but the level of Nitrate contamination remains strong in several areas where average Nitrate concentration exceeds 30mgNO3/l over the 1962-2019 period. This means that Nitrate contamination might reach the critical limit at some periods, when a bigger quantity of reactive N is exported. We found similar results for the 49 selected Naiade stations as some of them experienced period with NO3 concentration levels exceeding the drinkable limit (Figure 16). Therefore, improving water quality should remain a source of concern for French authorities.

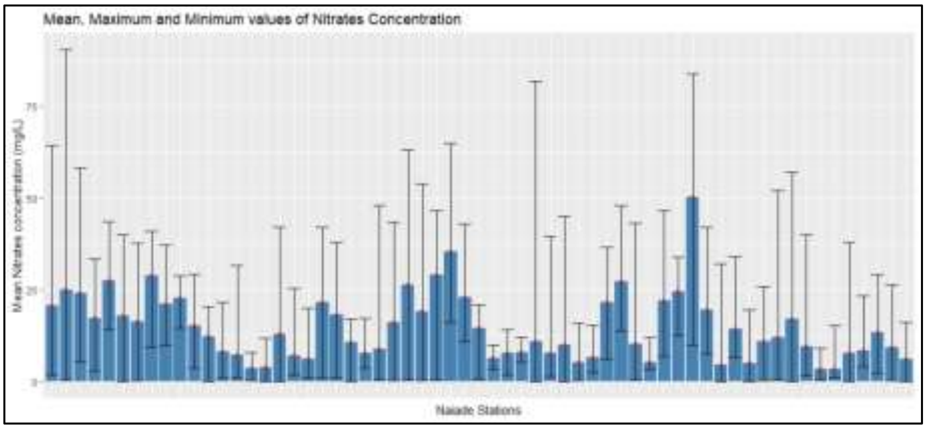


Figure 16: Mean, minimum and maximum NO3 concentration measured by the 49 selected Naiade stations. Values of mean NO3 concentration are represented by vertical bars; Error bars show the maximum and minimum values of NO3 concentration recorded by each Naiade station.

3. Impact of climate and agricultural yields on drainage water quality

We could not observe any clear relations between climatic anomalies, agricultural yields, and nitrate pollution as we observed different results for the watershed of Mélarchez and the selection of watersheds from the database “Banque Hydro”. In both cases, climatic anomalies have a negative impact on agricultural yields. In Mélarchez and the selection of watersheds, these extreme climate events lead to an average yield deviation of -6,72 and -6,1%, respectively. This means that agricultural yields after a climatic anomaly are significatively lower than the 4-years neutral mean attributed to these given years. In Mélarchez, heatwaves and high winter temperatures are the only climatic anomalies having a significative negative impact on agricultural yields. In our selection of watersheds, these two kinds of climate events are also decreasing yields, but severe droughts as well. This is plausible and matches with the previous findings on the assessment of effects of climate events on agricultural yields (Vogel et al., 2019). This loss can be attributed to lack of water creating unfavourable conditions for crop development and growth following heatwaves and droughts. High winter temperatures can also favour the development of crop pests or diseases, leading to higher rates of leaf senescence and decreasing yields (Ben Ari et al., 2018).

The effects of yield losses on nitrate pollution remains uncertain in this study. In Mélarchez, lower agricultural yields provoked higher Nitrate concentration between the following months of November, December, and January, i.e. when drainage resumes. No similar relation was found for the selected watersheds we tested with the same statistical test as NO3 concentration during the same period was not influenced by yield deviations. Similar results were observed regarding the impact of climatic anomalies on water pollution. Extreme climate events led to higher climate events between November and January during the 1976-2015 period in the watershed of Mélarchez, but such impact was not seen in the selected watersheds.

Our results obtained in the watershed of Mélarchez tend to validate our main hypothesis: climatic anomalies create unfavourable conditions for crop growth and development, thus leading to agricultural yields. As a result, N uptake by plants decreases and a bigger quantity of reactive N is available to be exported by drainage during the first months of the next humid season, when drainage restarts next season. It seems that this situation happened during nine different years of the 1976-2015 period that provide a combination of negative yield deviation and higher rates of NO3 concentration at the outlet of tile drains between the following months of November, December, and January. Moreover, in our selection of 49 Naiade stations, December and January were the months with the highest average NO3 concentration for 17 and 15 of them, respectively. We believe that it shows the importance of available NO3 content in soil at the beginning of winter driving Nitrate export at the outlet of watersheds, since Nitrate exported during these months resulted from reactive-N that has not been taken by crops during the previous growing season.

"Unfortunately", we were not able to validate this finding with our selection of drained watersheds since any statistical impact of agricultural yields and climate on Nitrate concentration was found. This disappointing result does not negate the findings we obtained in the watershed of Mélarchez and can be explained to several factors:

- We were lacking data for these watersheds as our datasets on hydrology and nitrate concentration were not matching for a large number of years, especially before the 90's. 22 watersheds had to be removed from the selection for the statistical test because of this reason. This poor quality of data might have decreased our ability to find relations between agricultural yields and water pollution during years affected by climatic anomalies.
- More specifically, we were not able to analyse the interesting years. We did not have physicochemical data on NO3 concentration for the year 2003 in Mélarchez, while a severe drought and heatwave occurred. The selected watersheds from the "Banque Hydro" did not provide solid datasets for several interesting years we highlighted in Mélarchez: 1976, 1983, and 1986.
- Similarly, it would be interesting to investigate the level of Nitrate pollution in drainage water recorded for 2016 and 2020 as these years experienced extremely severe yield losses due to climatic anomalies (Ben Air et al., 2018). Unfortunately, we did not have recent data to perform this study.
- The surface of watersheds might play a big role in NO3 exports. This would explain why our hypothesis are validated in the watershed of Mélarchez (7km^2) but does not work at bigger scale for larger watersheds. Indeed, the watershed of Mélarchez is fully dedicated to drained agriculture, which facilitate the validation of our assumptions. On the contrary, the selected watersheds have different land covers, leading to different retention rate of reactive N. For instance, the share of surface area covered by forests varies between 0% and 84% among our selection of watersheds. Indeed, forests and semi-natural areas are useful to increase denitrification and N retention within the biomass, which leads to a decrease of nitrate pollution (Passy et al., 2012 & Legeay et al., 2016). This example shows that additional parameters need to be incorporated in future assessments of water pollution in drainage water and its origin.

Our final interpretation is that the effects of climatic anomalies on agricultural yields and water pollution vary among the French catchments because the intensity and magnitude of the different extreme climate events is not the same in every region. We also conclude that this relation seems to work at small scale for watersheds under a certain surface and with a sufficient intensity of agriculture and drainage. However, at bigger scale – for larger watersheds - this relation might be diluted by several watershed's characteristics driving nutrient exports. The low values of the coefficient of determination R^2 for the different Anova tests operated in the watershed of Mélarchez also tend to show the weak proportion of the variance in the dependent variables (yields and NO3 concentration) that is predictable from the independent variables (climatic anomalies and yields) and that other factors are involved in the variations of yields and Nitrate pollution.

As a conclusion, this result is not disappointing. This report is an exploratory study, which needs to be improved, that showed the impact of climatic anomalies on agricultural yields and the impact of RNBW for Nitrate export by watersheds when drainage restarts during the winter season.

This relation could be identified at the small scale with a watershed supervised by a French public research observatory providing daily data but was more complex at bigger scale with more heterogeneous data. This highlights the benefits of these research observatories and their regular monitoring of water pollution for research.

4. Limits of our explanatory study and room for improvements

Despite our efforts to realize a rigorous and qualitative scientific research, we have been struggling with different aspects of this exploratory study. Consequently, report includes several limits and room for improvements, which can be considered for further research on this topic.

Lack of data

One of our main findings during this research was the extremely poor quality of French data on water quality, especially Nitrate concentration. A huge majority of watercourses are not properly controlled at a regular basis, which is a public health issue. This issue is also a handicap for research studies that try to analyse the processes involved in water pollution and its origin. For example, in our case, we were obliged to keep Naiade stations that performed measurements of water quality for a period longer than 10 years and with more than 3 measurements per year. However, this threshold is not sufficient as Nitrate is highly soluble in water (Billen et al., 2013) and can be exported very quickly in case of high discharge. This is why we think having daily values on N03 concentration in water would have been a huge benefit for this study, because with just several measurements per month/year, the measurements collected by Naiade might have missed the critical periods when Nitrate is flushing and NO3 concentration reaches its peak.

Choice of indicators monitoring water pollution

We chose to use daily and monthly values of NO3 concentration to assess water pollution in this report, and this choice is probably not the most relevant. Measuring the quantity of Nitrate (in kg) leaving the outlet of different watersheds might be a better solution in order to avoid errors caused by the dilution because discharge can vary a lot. This indicator will probably give a better picture of the impact of climate and yields on water pollution, but also the amount of nutrients polluting the ecosystems.

Improvement of methodology to define years affected by climatic anomalies

Using scientific report giving a record of ancient climatic anomalies was probably not the most rigorous method, but we chose it due to lack of time. Future research on the same topic could use observed daily climatic data from SAFRAN (if possible, for each year) to target years affected by climatic anomalies.

Better definition of the period when drainage restarts

Drainage does not always restart between the months of November and January. We empirically chose to set this period after looking at the hydrographs created by SIDRA-RU, as it seemed that observed and simulated discharge were increasing sharply during this period (after the dry season) for most of our selected watersheds. However, future research should improve this method and define a shorter period – just a few days - for each watershed. It should be possible to use hydrological data (Q) to define when drainage restarted and select rigorously the first observed concentration closer to the date of drainage restart following hydrological season.

5. Further reflexions to improve water quality from drained agricultural plots

Our findings show that small watersheds with intensive and drained agriculture are exposed to higher Nitrate leaching during the first months of the following hydrological year from drainage to surface watercourses after extreme climate events affecting agricultural yields. This raises concerns for agricultural regions that rely a lot on N-fertilizers and drainage, as more frequent and damaging episodes of water contamination by Nitrate could occur in the future, as Nitrogen inputs to the environment will likely increase in most of regions of the planet in the next decades (Seitzinger et al., 2010). Additionally, the frequency of extreme climate events, such as droughts and heatwaves, are also expected to increase as well because of the effects of climate change (Seneviratne et al., 2012), leading to more variable and hazardous agricultural yields. It seems crucial to implement different measures aiming at improving water quality and facing future issues related to contamination of drainage water by Nitrate. To fulfil this objective, two main strategies are possible to decrease Nitrate export by drained agricultural surfaces (Passy et al., 2012):

- Preventive measures: farming practices reducing the rate of fertilisation or excess fertilisation over crop uptake (Ravier et al., 2018). Innovative and reasonable fertilization methods based on regular monitoring of crop N-nutrition and simulation of short-term soil N-availability with a crop model can be implemented to reduce N-surplus available in agricultural soils.
- Restauration measures: implement appropriate hydraulic installations catching NO3 leaching from drainage and improving downstream water quality (Castellano et al., 2019). These measures for sustainable drainage favour Nitrogen retention thanks to three major processes: uptake by vegetation, sedimentation, and denitrification. They include ponds restauration; retention basins; buffer and vegetative filter strips; or reactive barriers (Strock et al., 2010).

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Annexe 1: Example of watershed's "Identity Sheet"

Watershed M7433110; Naiade station n°4172030

Localisation :

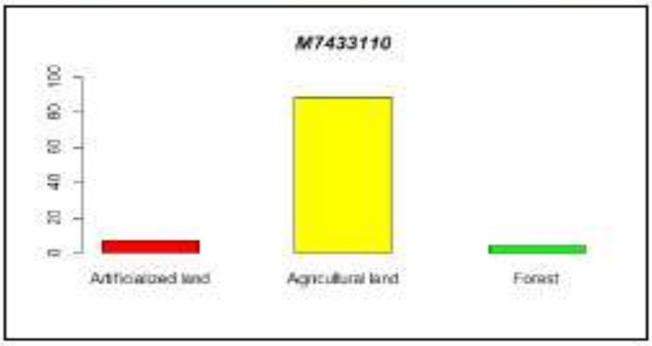
General information (Banque Hydro):

Surface : 191.78 km²

Drained SAU: 46.25 %

Soil Occupation:

- Agricultural land = 88.9 %
- Forest and semi-natural areas = 4%



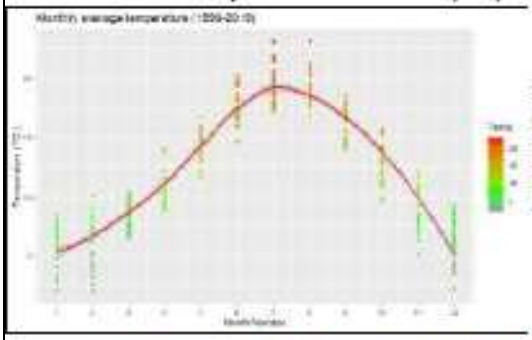
Climatic data (Safran):

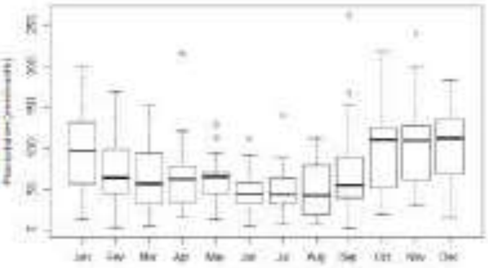
Mean Temperature = 11.87 °C

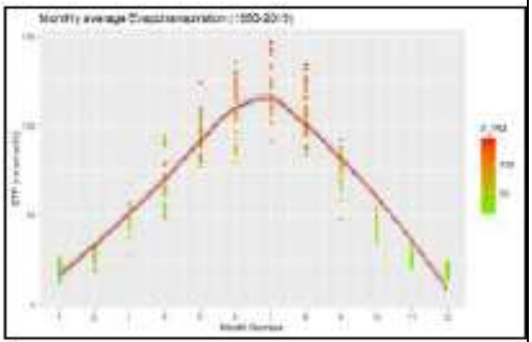
Mean Precipitation = 2.35 mm/day

Mean Evapotranspiration = 2 mm/day

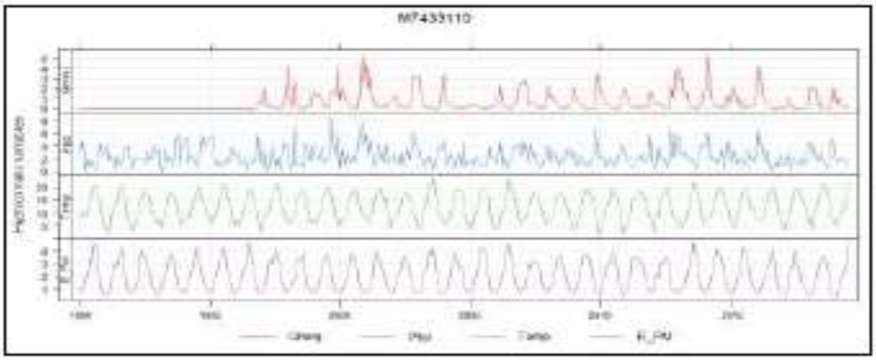
Period of measurements: 01/08/1958 – 31/07/2019







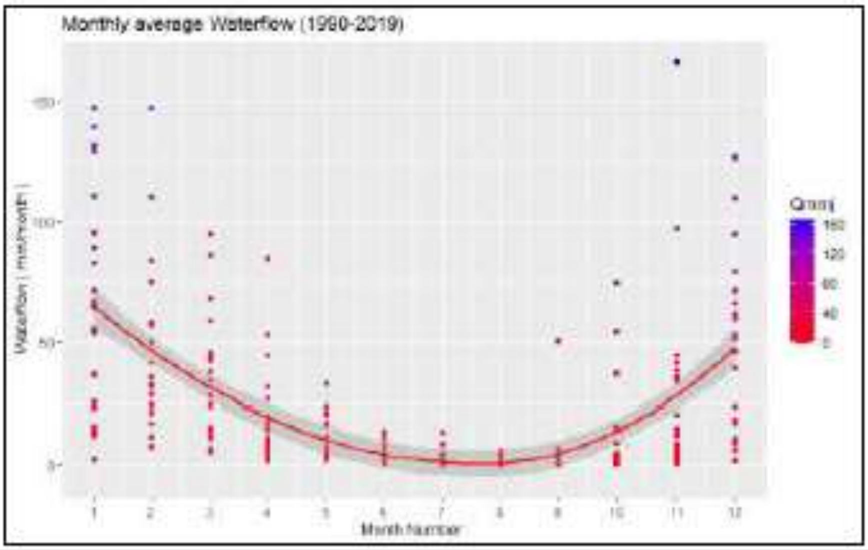
Variation of hydroclimatic variables (1990-2019)



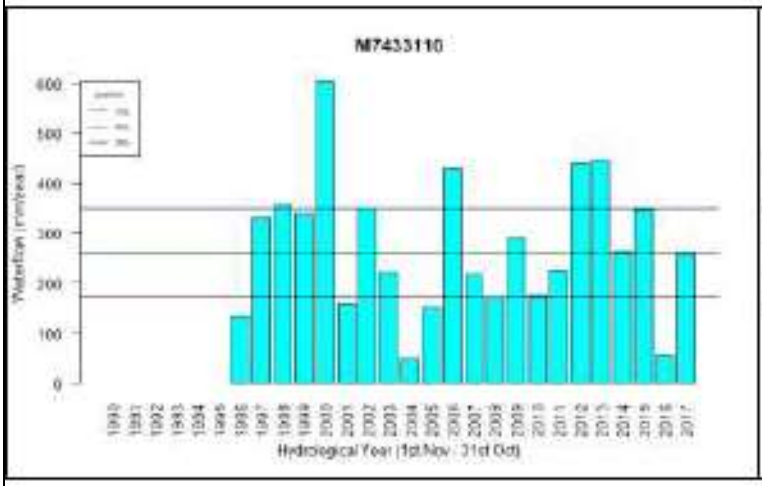
Hydrological data (Banque Hydro):

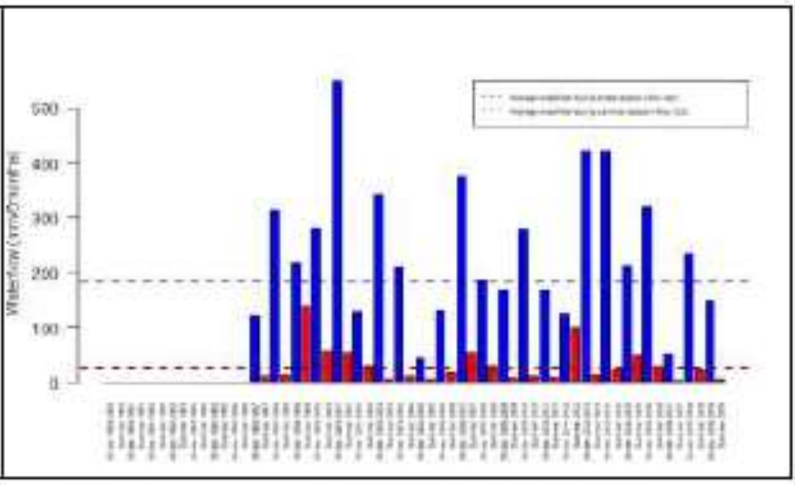
Mean waterflow values (1958-2019):

- 1647.7 l/s
- 0.74 mm/day



Seasonal hydrological regimes (Banque Hydro):

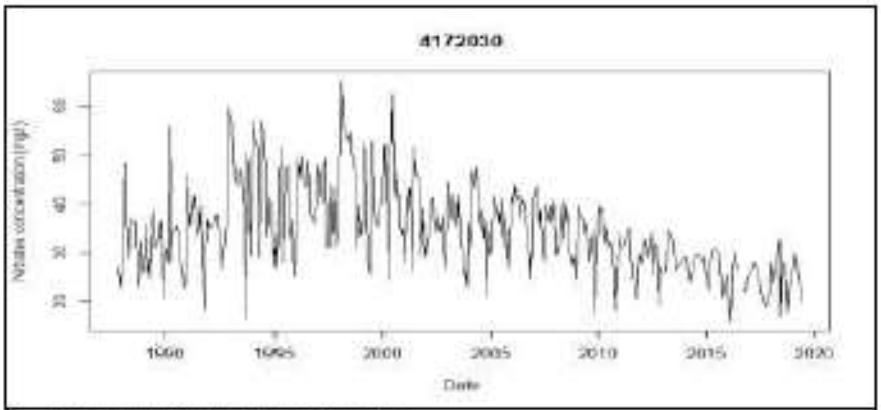


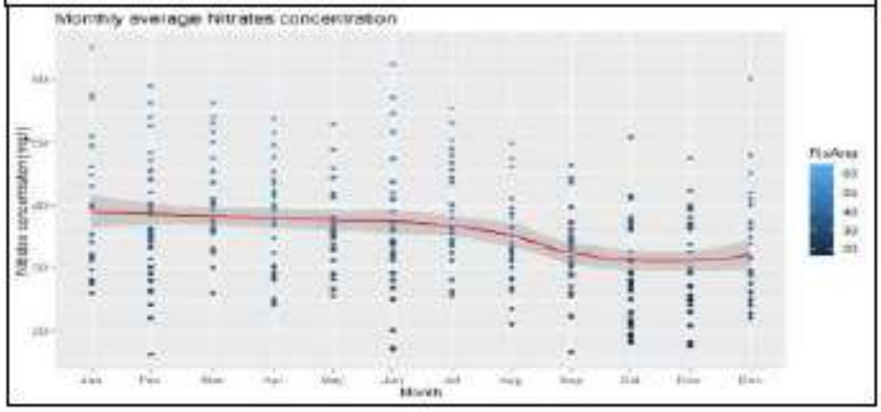


Winters (1st Nov – 30 Apr) and Summers (1st May – 31th Oct)

Physicochemical data (Naiade):

Month	Mean Nitrates concentration recorded by month (mg/l)
Jan.	38.74
Feb.	37.83
Mar.	40.93
Apr.	36.4
May	36.16
Jun.	37.5
Jul.	38.8
Aug.	34.41
Sep.	32.89
Oct.	28.7
Nov.	30.6
Dec.	32.84

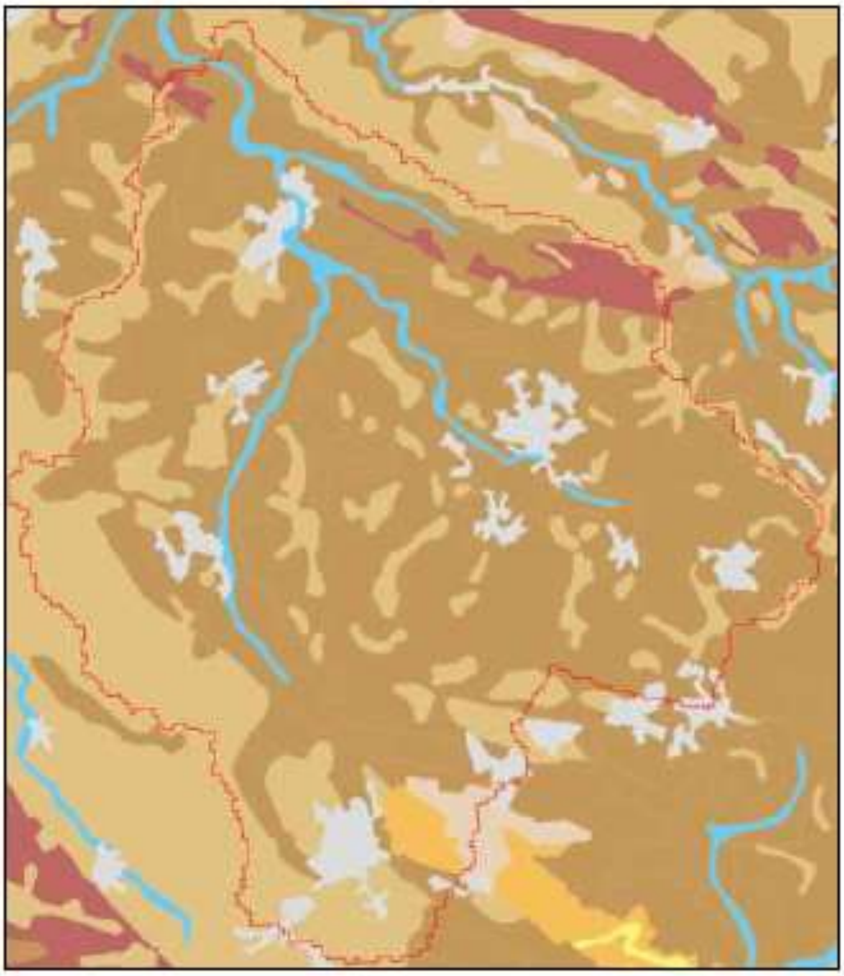




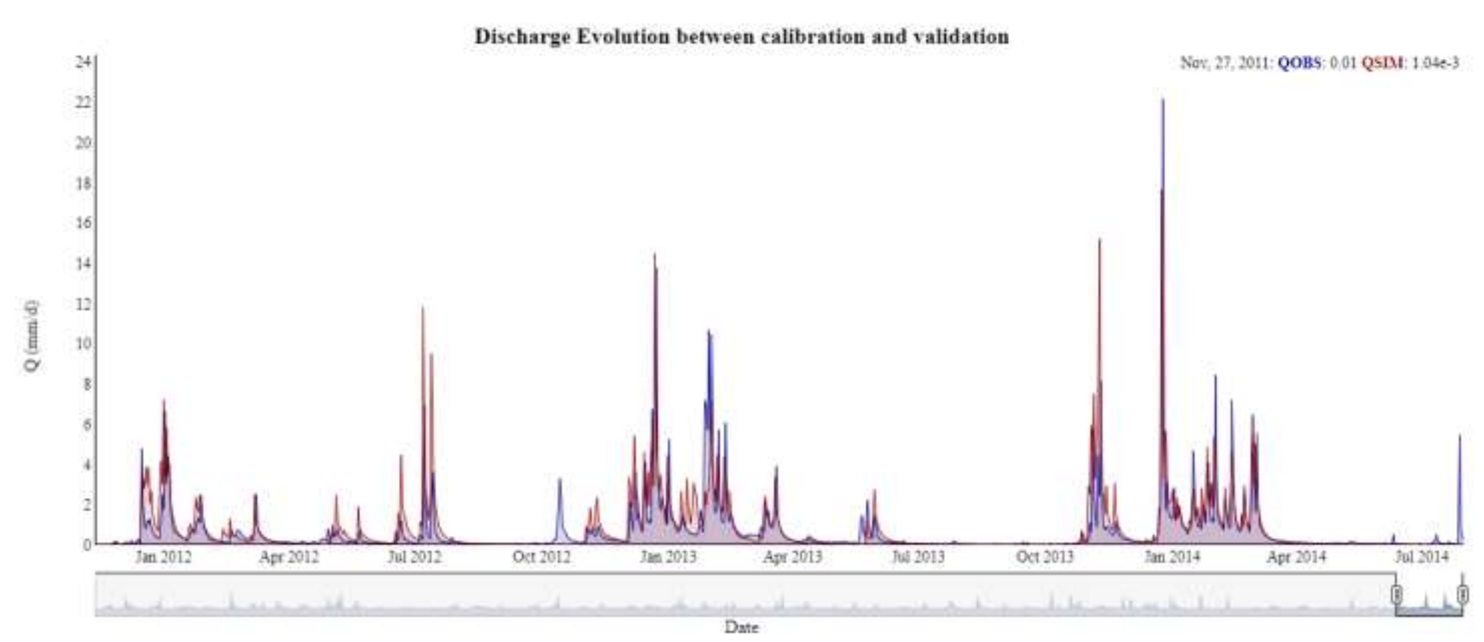
Soil information (GeoPortail):

Main types of soil:

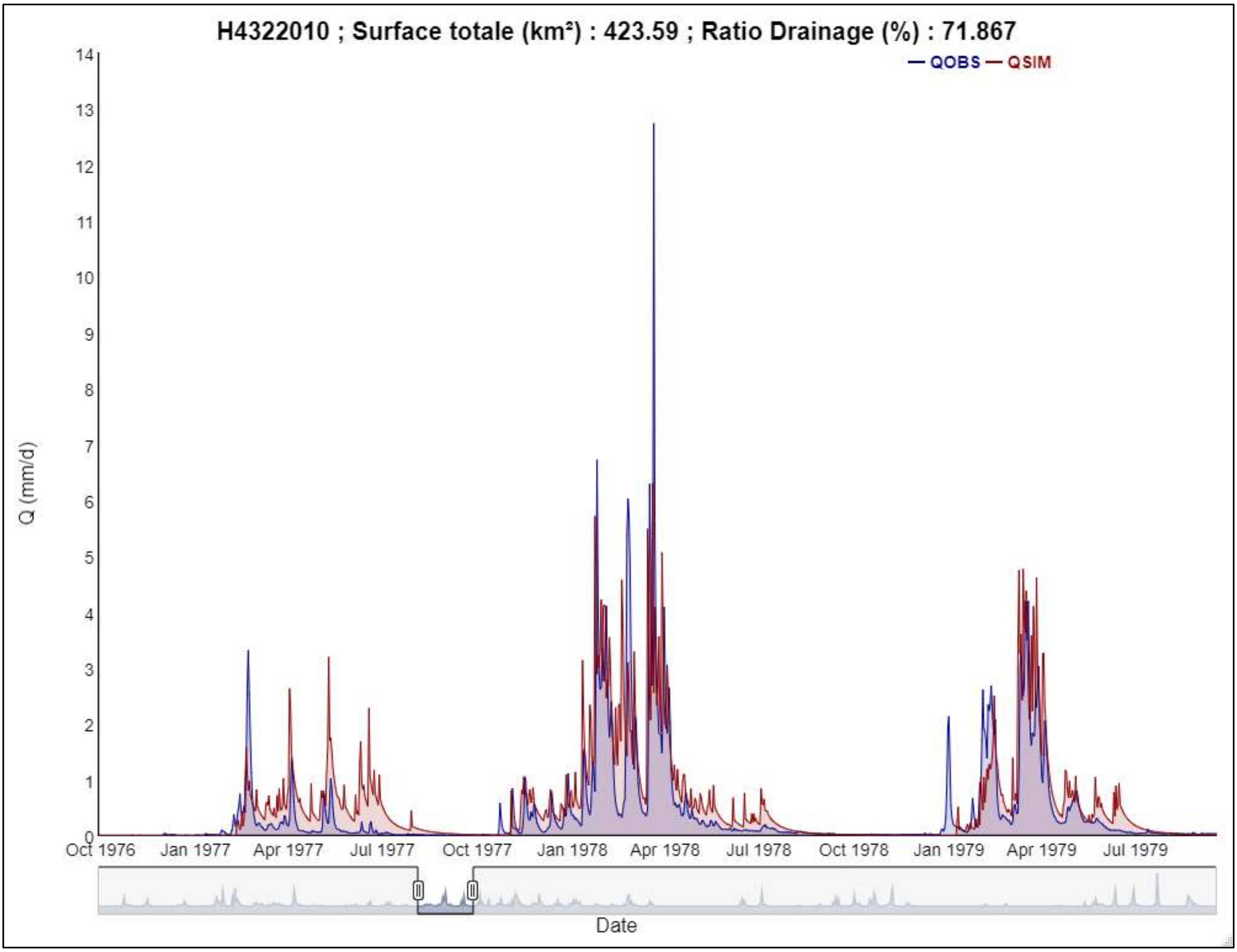
- Darkbrown: Brunisols; argileux à limono-argileux; hydromorphe
- Lightbrown: Luvisols-Rédoxisols; limon à limon sableux ; souvent hydromorphes
- Red : Néoluvisols-Rédoxisols; limoneux à argilo-limoneux ; hydromorphes



Annexe 2: Examples of hydrographs obtained with SIDRA-RU for two watersheds after their calibration



Annexe 2.1: Hydrograph of the watershed of Mélarchez with simulated and observed discharge from January 2012 to July 2014.



Annexe 2.2: Hydrograph of the watershed H4322010 (Yerres river at Courtomer) with simulated and observed discharge from October 1976 to September 1979.

Annexe 3: Rscript of SIDRA-RU model (calibration and performance)

```
#---------------------------------------------------------------------------
# Title              :
# Author             : Matthieu Descout : matthieu.descout@inrae.fr
# Date               : 18/06/2020
# Description        :
# Data requirements    :
# Packages requirements :
#---------------------------------------------------------------------------
PACKAGES <- c("hydroGOF","zoo","manipulate","graphics","reshape",
"reshape2","sensitivity","lubridate","dismo","rgl",
          "htmlwidgets",
"dygraphs","shiny","xts","foreach","doSNOW","progress","RColorBrewer","htmltools")
if(PACKAGES != c("")){
  isIn = PACKAGES %in% .packages(all = T)           # Test si packages deja charges, renvoit
vecteur de bouleens
  if(!all(isIn)){install.packages(PACKAGES[!isIn])}   # Si pas charge, on charge
  lapply(PACKAGES, library, character.only = T)
}
WKspace      <- "C:/Data/SIDRA/"
# WKspace_DATA  <- paste0(WKspace,"01_DATA/02_USE/")
WKspace_DATA  <- "C:/Data/Bases de
données/SAFRAN/HYDRO_SAFRAN_Selection2/HYDRO_SAFRAN"
# WKspace_CODES <-
paste0(WKspace,"02_CODES/CALAGE/CALIBRATION_MICHEL/CALAGE_SEQ/DIR_ORIGINAL/"
)
# WKspace_CODES <- paste0(WKspace,"02_CODES/CALAGE/CALIBRATION_MICHEL/V10/")
WKspace_CODES <- "C:/Data/SIDRA/V10/V10/"
WKspace_OUT   <- paste0(WKspace,"RESULTATS_CAL/")
```

```
# Fichier principal : informations sur toutes les simulations

# par_inT      <- read.table(file = paste0(WKspace_DATA,"SAFRAN-
HYDRO/PARAM_BV_HYDRO.csv"),

#                         sep = ";", header = TRUE)

par_inT      <- read.table(file = paste0(WKspace,"PARAM_BV_HYDRO.csv"),

                         sep = ";", header = TRUE)

# LISTE_SITES   <- read.table(file =
paste0(WKspace_DATA,"ANALYSES_STATISTIQUES/LISTE_SITES.csv"),

#                         sep = ";", header = TRUE)

# ------------------------------------------------------------

# Import functions

# source(file = paste0(WKspace,"02_CODES/CHARGER_CODES.R"))

source(file = paste0(WKspace,"CHARGER_CODES.R"))


# file <- FUN_Kc_LIST[1]

CHARGER_PACKAGE_FUNCTIONS(file = paste0(WKspace_CODES,"/CODES_UTILES/"))


# ------------------------------------------------------------

# STATS_X <- data.frame(read.table(file =
paste0(WKspace_DATA,"SENSIBILITE/STATS_DISTRI_X.csv"), sep = ";", header = TRUE))

STATS_X <- data.frame(read.table(file = paste0(WKspace,"STATS_DISTRI_X.csv"), sep = ";",
header = TRUE))



# ------------------------------------------------------------

# Calage site par site

SITES         <- as.character(par_inT$SITES)

for(site in SITES){
```

```
  # DATA_TEST      <- read.table(file = paste0(WKspace_DATA,"SAFRAN-HYDRO/",site,"_HYDRO_SAFRAN.txt"),
  #                          sep = ";", header = TRUE)
  DATA_TEST      <- read.table(file = paste0(WKspace_DATA,"/",site,"_HYDRO_SAFRAN.txt"),
                           sep = ";", header = TRUE)
  DATA_TEST$Date <- as.POSIXct(as.character(DATA_TEST$Date), format = "%Y%m%d", tz = "UTC")

  DATE_DEB       <- substr(DATA_TEST$Date,1,10)[head(which(substr(DATA_TEST$Date,6,10) == "08-01"),1)]
  DATE_FIN       <- substr(DATA_TEST$Date,1,10)[tail(which(substr(DATA_TEST$Date,6,10) == "07-31"),1)]
  n_annees       <- floor(as.numeric((difftime(time1 = as.Date(DATE_FIN), time2 = as.Date(DATE_DEB), units = "days")+1)/365))

  DATA_TEST      <- DATA_TEST[,c("Date","Ptot","E_PM","Qmmj")]; colnames(DATA_TEST) <- c("Date","Pluie","ETP","Q_Obs")

  # Conversion du débit
  DATA_TEST$Q_Obs[DATA_TEST$Q_Obs %in% c("NaN",-99)] <- NA
  # On remplace les valeurs négatives par 0
  DATA_TEST[as.numeric(as.character(DATA_TEST$Q_Obs)) < 0 & !is.na(as.numeric(as.character(DATA_TEST$Q_Obs))),"Q_Obs"]  <- 0
  DATA_TEST$Pluie     <- as.numeric(as.character(DATA_TEST$Pluie))
  DATA_TEST$ETP       <- as.numeric(as.character(DATA_TEST$ETP))
  DATA_TEST$Date      <- as.Date(as.character(DATA_TEST$Date), format = "%Y-%m-%d")

  par_in              <- par_inT[as.character(par_inT$SITES) == site,] # On ne garde que les paramètres de la Jaillière

  # ------------------------------------------------------------
  # Lecture des parametres hydrodynamique du modele RU et SIDRA dans le fichier Param_in
```

```
 PARAMETRES_INI        <- list()

 PARAMETRES_INI$SIDRA$S          <- as.numeric(as.character(par_in$Surface.ha))*10000
 # PARAMETRES_INI$SIDRA$S          <- NA
 PARAMETRES_INI$SIDRA$l          <- as.numeric(as.character(par_in$demi_Ecartement))
 PARAMETRES_INI$SIDRA$K          <- as.numeric(as.character(par_in$K))
 PARAMETRES_INI$SIDRA$mu         <- as.numeric(as.character(par_in$mu))
 PARAMETRES_INI$SIDRA$a1         <- as.numeric(as.character(par_in$a1))
 PARAMETRES_INI$SIDRA$a2         <- as.numeric(as.character(par_in$a2))
 PARAMETRES_INI$SIDRA$Pdrain     <- as.numeric(as.character(par_in$Pdrain))

 PARAMETRES_INI$SISWHOC$SSDI     <- as.numeric(as.character(par_in$SSDI))
 PARAMETRES_INI$SISWHOC$S_inter   <- as.numeric(as.character(par_in$Si))
 PARAMETRES_INI$SISWHOC$Beta     <- as.numeric(as.character(par_in$Beta1))
 PARAMETRES_INI$SISWHOC$Kc_Max    <- 1



 PARAMETRES_INI$SIDRA            <- as.data.frame(PARAMETRES_INI$SIDRA)
 PARAMETRES_INI$SISWHOC          <- as.data.frame(PARAMETRES_INI$SISWHOC)

 # ------------------------------------------------------------
 # Choix de la texture pour extraction des données de calibrations
 sol <- as.character(par_in$Texture_Defaut_2)


 # ------------------------------------------------------------
 # Setting input data and run period
 DATE_DEB      <- substr(DATA_TEST$Date,1,10)[head(which(substr(DATA_TEST$Date,6,10)
== "08-01"),1)]
 DATE_FIN      <- substr(DATA_TEST$Date,1,10)[tail(which(substr(DATA_TEST$Date,6,10) ==
"07-31"),1)]
```

```
  DATA_TEST     <- DATA_TEST[which(as.character(DATA_TEST$Date) ==
DATE_DEB):which(DATA_TEST$Date == DATE_FIN),]


  # ------------------------------------------------------------
  ## preparation of elements for CalibOptions object
  # SearchRanges     <- matrix(data =
c(unlist(LISTE_SITES[as.character(LISTE_SITES$SITE_NOM) == site,
  #                                         grep(pattern = "MIN", colnames(LISTE_SITES))]),0,0.5,
  #                               unlist(LISTE_SITES[as.character(LISTE_SITES$SITE_NOM) == site,
  #                                         grep(pattern = "MAX", colnames(LISTE_SITES))]),1,2.0),
  #                        nrow = 2, ncol = 6, byrow = TRUE)
  # SearchRanges     <- matrix(data = c(unlist(STATS_X[as.character(STATS_X$TEXTURE) ==
sol,
  #                                         grep(pattern = "MIN", colnames(STATS_X))][1:4]),0,298/2,
  #                               unlist(STATS_X[as.character(STATS_X$TEXTURE) == sol,
  #                                         grep(pattern = "MAX",
colnames(STATS_X))][1:4]),1,298*2),
  #                        nrow = 2, ncol = 6, byrow = TRUE)
  SearchRanges     <- matrix(data = c(0.1,0.01,060,005,0,par_in$Surf_DRAIN_Th/10,
                                 1.0,0.10,300,300,1,par_in$Surf_DRAIN_Th*10),
                         nrow = 2, ncol = 6, byrow = TRUE)
  SearchRanges[,6] <- SearchRanges[,6] * 1000000 # Pour tansformer la surface de l'hectare
au m²
  Moyennes_DIST    <- c(unlist(STATS_X[as.character(STATS_X$TEXTURE) == sol,
                                grepl(pattern = "MEAN", colnames(STATS_X))]),NA,NA)
  EcartType_DIST   <- c(unlist(STATS_X[as.character(STATS_X$TEXTURE) == sol,
                                grepl(pattern = "SD_", colnames(STATS_X))]),NA,NA)
  # On tente une liste de distribution de paramètres en entrée
  # pas = 0.0835*2
  # pas = 0.05
  pas = 0.10
```

```
 PROBAS          <- seq(from = pas, to = 1, by = pas)[seq(1, length(seq(from = pas, to = 1, by =
pas)), 2)]

 StartParamDistrib <- matrix(data = as.matrix(do.call(rbind,lapply(X = PROBAS, FUN =
function(proba) return(rep(proba,6))))),

                      ncol = 6, byrow = FALSE)

 FixedParam       <- c(NA,NA,NA,NA,1/3,NA)

 # FixedParam       <- c(0.49,0.05,149.16,5,1/3,NA)

 # ---------------------------------------------------------

 # CALAGE

 # ---------------------------------------------------------

 # ANNEE_CHAUFFE    <-
DATA_TEST[1:head(which(substr(as.character(DATA_TEST$Date),6,10) == "07-31"),1),]

 # DATES_THEORIQUES <- substr(seq(from =
as.POSIXct(paste0(as.numeric(substr(ANNEE_CHAUFFE$Date[1],1,4))-1,"-08-01"),

 #                                  format = "%Y-%m-%d", tz = "UTC"),

 #                        to   =
as.POSIXct(paste0(as.numeric(substr(ANNEE_CHAUFFE$Date[nrow(ANNEE_CHAUFFE)],1,4))-
1,"-07-31"),

 #                                  format = "%Y-%m-%d", tz = "UTC"),

 #                        by   = "d"),

 #                     1,10)

 # if(sum(substr(DATES_THEORIQUES,6,10) == "02-29") > 0){

 #   DATES_THEORIQUES <- DATES_THEORIQUES[-
c(head(which(substr(DATES_THEORIQUES,6,10) == "02-29"),1))]

 # }

 # if(sum(substr(ANNEE_CHAUFFE$Date,6,10) == "02-29") > 0){

 #   ANNEE_CHAUFFE    <- ANNEE_CHAUFFE[-c(which(substr(ANNEE_CHAUFFE$Date,6,10)
== "02-29")),]

 # }

 #

 # ANNEE_CHAUFFE$Date <- substr(as.character(DATES_THEORIQUES),1,10)

 # DATA_TEST$Date     <- substr(as.character(DATA_TEST$Date),1,10)
```

```
 # DATA_TEST         <- rbind(ANNEE_CHAUFFE,DATA_TEST)
 # DATA_TEST$Date     <- as.Date(as.character(DATA_TEST$Date), format = "%Y-%m-%d")
 #
 #
 InputsModel <- CreateInputsModel_A(FUN_MOD = SIDRA_SISWHOC,
                          DatesR  = as.POSIXlt(DATA_TEST$Date),
                          Precip  = as.numeric(as.character(DATA_TEST$Pluie)),
                          PotEvap = as.numeric(as.character(DATA_TEST$ETP)))


 Ind_Warm_UP <- c(1: head(which(substr(DATA_TEST$Date,6,10) == "07-31"),1))


 Ind_Run     <- c((Ind_Warm_UP[length(Ind_Warm_UP)]+1):nrow(DATA_TEST))
 # -----------------------------------------------------------
 ## preparation of RunOptions object
 RunOptions <- CreateRunOptions_A(FUN_MOD = SIDRA_SISWHOC,
                         InputsModel = InputsModel, IndPeriod_Run = Ind_Run,
IndPeriod_WarmUp = Ind_Warm_UP)


 # -----------------------------------------------------------
 # Calibration des paramètres K et mu


 InputsCrit <- CreateInputsCrit_A(InputsModel = InputsModel,
                         RunOptions = RunOptions, Qobs = DATA_TEST$Q_Obs[Ind_Run],
                         alpha = 1, CRIT = "KGE", transfo = "",
                         SEQ_CALAGE = FALSE)


 CalibOptions <- CreateCalibOptions_A(FUN_MOD = SIDRA_SISWHOC_CM,
                           Moyenne_DIST = Moyennes_DIST,
                           EcT_DIST = EcartType_DIST, SearchRanges = SearchRanges,
```

```
                              OtherPARAMS = PARAMETRES_INI, StartParamDistrib = 
StartParamDistrib,
                              FixedParam = FixedParam, exe_TRANS = TRUE)


  # InputsModel  = InputsModel
  # RunOptions   = RunOptions
  # InputsCrit   = InputsCrit
  # CalibOptions = CalibOptions
  # Moyenne_DIST = Moyennes_DIST
  # EcT_DIST     = EcartType_DIST
  # FUN_MOD      = SIDRA_SISWHOC_CM
  # FUN_CRIT     = ErrorCRIT_SIDRA_RU
  # FUN_TRANSFO  = TransfoParam_SIDRA_RU
  # verbose      = TRUE


  OutputsCalib  <- Calibration_Michel_A(InputsModel = InputsModel, RunOptions = 
RunOptions,
                               InputsCrit = InputsCrit, CalibOptions = CalibOptions,
                               Moyenne_DIST = Moyennes_DIST, EcT_DIST = EcartType_DIST,
                               FUN_MOD = SIDRA_SISWHOC_CM, FUN_CRIT = ErrorCRIT_SIDRA_RU, 
FUN_TRANSFO = TransfoParam_SIDRA_RU,
                               verbose = TRUE)




  CRITERE_CAL   <- round(OutputsCalib$CritFinal,3)
  JEUX_CAL      <- OutputsCalib$ParamFinalR
  JEUX_CAL[6]/1e6
  SIMU_CAL      <- SIDRA_SISWHOC_CM(InputsModel = InputsModel, RunOptions = 
RunOptions,
                             Param = JEUX_CAL, PARAMETRES = PARAMETRES_INI)
  # InputsModel = InputsModel
```

```
# RunOptions  = RunOptions
# Param       = JEUX_CAL
# PARAMETRES  = PARAMETRES_INI

# ---------------------------------------------------------
# Evaluation Calage
NSE_CAL     <- NSE(sim = SIMU_CAL$Qsim, obs = DATA_TEST$Q_Obs[Ind_Run])
KGE_CAL     <- KGE(sim = SIMU_CAL$Qsim, obs = DATA_TEST$Q_Obs[Ind_Run])
RESULTS <- data.frame("DatesR"     = InputsModel$DatesR[RunOptions$IndPeriod_Run],
                      "anneehydro" = SIMU_CAL$anneehydro,
                      "Qobs"       = DATA_TEST$Q_Obs[RunOptions$IndPeriod_Run],
                      "Qsim"       = SIMU_CAL$Qsim,
                      "h"          = SIMU_CAL$h,
                      "Stock"      = SIMU_CAL$Stock,
                      "ETR"        = SIMU_CAL$ETR,
                      "ETP"        = SIMU_CAL$ETP,
                      "Pluie"      = SIMU_CAL$Pluie)

TAB_RECAP <- data.frame("SITE"             = site,
                        "TEXTURE"          = sol,
                        "CRIT_CAL"         = round(CRITERE_CAL,3),
                        "K_CAL"            = round(JEUX_CAL[1],2),
                        "mu_CAL"           = round(JEUX_CAL[2],2),
                        "Si_CAL"           = round(JEUX_CAL[3],2),
                        "SSDI_CAL"         = round(JEUX_CAL[4],2),
                        "SURFACE_CAL"      = round(JEUX_CAL[6],2),
                        "SMAX"             = round(JEUX_CAL[3],2) + round(JEUX_CAL[4],2),
                        "KGE_CAL"          = round(KGE_CAL,3),
                        "NSE_CAL"          = round(NSE_CAL,3),
```

```
                    "PERIODES"          = paste0(substr(RESULTS$DatesR[1],1,4),"-
",substr(RESULTS$DatesR[nrow(RESULTS)],1,4)))
  # # --------------------------------------------------------------
  # # Save RESULTS
  # # --------------------------------------------------------------
  if(!dir.exists(paste0(WKspace_OUT,site,"/"))){dir.create(paste0(WKspace_OUT,site,"/"))}
  # saveRDS(object = RESULTS, file =
paste0(WKspace_OUT,site,"/CHRON_Q_TEST.RDS"))WKspace
  write.table(x = RESULTS, file = paste0(WKspace_OUT,site,"/CHRON_Q_TEST.csv"),
            sep = ";", col.names = TRUE, row.names = FALSE)
  write.table(x = TAB_RECAP, file = paste0(WKspace_OUT,site,"/TAB_PARAM.csv"),
            sep = ";", col.names = TRUE, row.names = FALSE)
}


CHRON_Q  <- xts(RESULTS[,c("Qobs","Qsim")],
             order.by=RESULTS$DatesR)


colnames(CHRON_Q) <- c("QOBS","QSIM")
CHRON_Q  <- dygraph(data = CHRON_Q,
                main = "Discharge Evolution between calibration and validation",
                xlab = "Date", ylab = "Q (mm/d)") %>%
  dyOptions(colors = c("darkblue","darkred"))%>%
  dyOptions(axisLineWidth = 1.5, fillGraph = TRUE, drawGrid = FALSE)%>%
  dyRangeSelector(dateWindow =
c(c(as.POSIXct(as.character(RESULTS$DatesR[1])),as.POSIXct(as.character(RESULTS$DatesR[n
row(RESULTS)])))))
# CHRON_Q
saveWidget(widget = CHRON_Q,
         file = paste0(WKspace_OUT,"CALAGE/",site,"/CHRON_Q.html"),
         selfcontained = TRUE, libdir = NULL,
         background = "white", knitrOptions = list())
```