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# Freshwater fish and climate change
## Current situation and adaptation strategies

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# Freshwater fish and climate change Current situation and adaptation strategies

Florence Baptist, Nicolas Poulet
& Nirmala Séon-Massin (coordinators)

# Foreword

The reality of climate change is no longer an issue. According to the annual climate statement by the World Meteorological Organisation, 2013 tied with 2007 as the sixth hottest year ever recorded worldwide, thus confirming the observed long-term warming trend. Temperatures were not unusual in continental France, however, a number of exceptional climatic events occurred such as the heavy snow and rain fall that led to flooding in the south-western section of France and the storms Christian and Dirk. As for 2014, it also confirmed the reality of climate change in that the month of May was the hottest ever since the start of records in 1880 (according to the U.S. National oceanic and atmospheric administration (NOAA)). In addition, the Intergovernmental panel on climate change (IPCC) recently increased to 0.6°C its estimate of the average surface temperature rise for the period 1951 to 2010.

The experts agree that the causes are anthropogenic, notably due to emissions of greenhouse gasses. It would seem obvious that this rapid and significant change in the climate will have an impact on all ecosystems and the dependent organisms, as well as on the ecosystem services that human beings count on. The organisation by France of the upcoming conference of the parties to the U.N. Framework convention on climate change (COP21/CMP11) that will be held in Paris from 30 November to 11 December 2015 is ample proof of the importance placed on the topic by France. The objective is that all countries, both developed and developing, accept a universal and binding agreement on the climate.

Lakes, rivers and marshes cover only 0.01% of the surface of the planet. In spite of this very small surface area, they are home to a vast number of species representing 9% of all animal species identified to date. They are also highly vulnerable to climate change if only because it has a direct impact on the water cycle. In addition, a majority of aquatic species are cold-blooded, which makes them even more sensitive to even the slightest modifications in the temperature of their environment. Finally, the climatic disturbances are simply another of many pressures, including excessive captures, water pollution, invasive species, etc. Climate change, whether in the form of increased temperatures or modifications in hydrological regimes, is thus fully capable of significantly altering the functioning of ecosystems.

That is why Onema supports research efforts to improve our knowledge on the effects of climate change, notably concerning hydrology and hydrogeology on the one hand, and fish populations on the other. Examples are the studies on the long-term changes in low-flow levels and groundwater levels, carried out by Irstea and

BRGM, respectively. Concerning fish, Onema has funded and contributed to various research projects such as those at Irstea on diadromous fish throughout Europe, those at the Université Paul-Sabatier (Toulouse III) on recent changes in the ranges of freshwater fish, those at the Université de Lorraine on the impact of warming on fish reproduction and the Explore 2070 project launched by the Ecology ministry. A great deal of the new information exited the ivory towers of academia and was discussed with water managers. This information also provided significant technical assistance in formulating the National plan for adaptation to climate change (PNACC) in 2011.

The overall objective of this book is to inform on current knowledge concerning the observed and projected modifications in the climate and hydrology, and the impact of these modifications on fish communities. Fish are particularly useful in determining the degree of change now under way in aquatic environments as well as the capacity of organisms to adapt (acclimatisation or migration). They live in virtually all surface waters, integrate the various anthropogenic pressures and constitute excellent indicators in the work to assess the ecological quality of aquatic environments. Finally, they play an essential role for human populations as a food source and in an array of socio-economic activities including commercial fishing, recreational fishing, aquaculture, etc. As a result, contrary to a majority of aquatic taxa, a mass of data (ecological knowledge, population monitoring, etc.) are available that are essential to understanding the processes involved.

Fish are the indispensable "indicator" species needed to both understand the modifications caused by climate change and implement the most suitable preservation policies for aquatic environments.

**Philippe Dupont**
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# Abstract

## Freshwater fish and climate change Current situation and adaptation strategies

This book is divided into four chapters. The first presents the current knowledge on observed and projected modifications in temperature, precipitation and river hydrology in a context of climate change. The different types of models producing the projections are discussed. The second describes the impacts of climate change already observed on the physiology, phenology and ranges of freshwater fish over the past few decades. The discussion takes into account both experimental and empirical studies. Three geographical areas are examined in detail, namely the Rhône and Seine basins and Lake Geneva. The third chapter discusses the existing models attempting to assess the vulnerability of freshwater fish in the future. Statistical distribution models are precisely described to put readers in a position to identify the data required to use the models, the correct scale for data interpretation and the uncertainties inherent in the models. Finally, the last chapter provides information on the adaptation strategies that can be implemented to reduce the vulnerabilities of fish in the future. The discussion will demonstrate that the recommended measures are largely compatible with existing laws and regulations.

## Chapter 1 - Understanding the impact of climate change on water resources

The global climate has always fluctuated over time under the direct and indirect influence of various phenomena (orbital forcing, change in global albedo, disturbances in atmospheric currents, feedback loops). However, human activities releasing greenhouse gasses (GHG) and aerosols have clearly caused changes in the climate since the end of the 1800s, resulting in increases in air temperatures and the average sea level, as well as a reduction in snow-covered surfaces and ice caps. In continental France, analysis of long data series has produced estimates of average increases of approximately 1°C in air temperature and 1.6°C in water temperature over the last century. Loss of snow cover at medium altitudes is a further factor confirming that climate change is effectively under way. Other parameters, such as precipitation, evapotranspiration and surfacewater/groundwater hydrology, are also affected but the trends are not as clear given the difficulties in distinguishing between the effects of climate change and those of direct human activities.

To assess changes in the climate and in the various components of the water cycle (precipitation, evapo-transpiration, surface water, groundwater), climate models coupled with hydrological models have been formulated and calibrated for the various GHG emissions scenarios. For continental France over the coming decades, all climate projections (whatever the greenhouse-gas (GHG) emissions scenario) foresee warming between 1.5 and 3°C. Longer term, the projections diverge widely depending on the scenario and are much less reliable. They indicate warming from 2°C to more than 4.5°C by 2100. Concerning water resources, the projections for precipitation, evapotranspiration and discharges are more uncertain and differ depending on the model. However, evapotranspiration is expected to increase in the south-western section of France. Monthly mean discharges in rivers should decrease and low-flow levels should worsen over large parts of the country, particularly in the southern half. Finally, groundwater recharging may drop along with piezometric levels. Human activities will most likely reinforce the effects of climate change on water resources, notably due to increases in abstractions for drinking water and agriculture.

Consequently, even though there are numerous uncertainties concerning these projections, the potential impact of climate change on water resources in continental France should be considerable with a clear trend toward a reduction in those resources. Aquatic environments and fish in particular will be heavily impacted in the above scenarios.

## Chapter 2 - Changes in fish communities in a context of climate change

The physiology, biological rhythms and distribution of fish depend on environmental factors such as temperature, hydromorphological conditions and water quality (dissolved oxygen, pollutant concentrations, etc.). Climatic disruptions impact these factors and thus constitute a major source of change for fish species.

Though it is very difficult in the freshwater context to distinguish between the effects of climate change and those of local anthropogenic pressures, a number of studies have revealed the impact of temperature increases on fish communities. Changes in certain physiological characteristics in response to an increase in water temperature have in turn resulted in changes in reproduction, growth and seasonal rhythms. In addition, some species have moved up river, extending their range when movement is not blocked by other factors such as weirs and dams. These movements have led to changes in the composition of communities with as a consequence modifications in species richness and in the number of dominant species.

Even though the signs are still not very clear in some rivers and interpretation is difficult due to anthropogenic pressures, the consequences of climate change are observable over France as a whole. They contribute to the impact of human activities in rivers (dams, reservoirs, sealing of banks, abstractions for various uses, release of polluted water, etc.) and can in certain cases reinforce the ecological modifications.

Unfortunately, the lack of long data series and the change in the sampling strategy for the surveillance-monitoring network limit the possibilities in terms of studying current changes in communities in the context of climate forcing. What is more, there is still a significant gap between ecological theory and on-site observations that requires in-depth research in this field.

## Chapter 3 - Anticipating the impact of climate change on fish communities

Over the past few years, numerous tools have been developed to assess the impact of climate change on living organisms. Among those tools, statistical distribution models play an important role because they are based on simple assumptions and can project the potential habitat changes of a given species in response to different climate-change scenarios. In that certain ecological processes are not taken into account in these models, other tools, namely mechanistic models, have been developed in parallel. They are more powerful and robust, however they require much more knowledge on species biology. That is why their application to a large number of species has remained limited.

Even though the many underlying assumptions limit the possibilities of transposing the results locally, the projections produced by the distribution models reveal trends that can be used to assess the vulnerability of each species and any changes in the richness and composition of communities.

Generally speaking, all the models foresee a shift in the ranges of cold-water species upstream. The ranges of species living exclusively at the heads of river basins would be reduced to high-altitude refuge zones and the risks of their local extinction would be increased in certain lower-lying basins. Conversely, the conditions for species located in intermediate zones or downstream, such as cyprinids and centrarchids, would improve. On the community scale, an increase in species richness and greater uniformity of communities is expected in all rivers. In other words, the communities will be richer, but more similar to each other, resulting in a loss of diversity.

The vulnerability of species to climate change depends on the ecological requirements of each species and some of these requirements are currently not taken into account in the models for freshwater fish in continental France (dispersal capabilities, anthropogenic pressures, adaptive and evolutionary processes, etc.). A quantitative approach in conjunction with a critical analysis of the results based on expert knowledge would now appear to be a solution to refine the potential distribution maps for each species in the context of climate forcing.

In the future, the formulation of hybrid models combining both statistical and mechanistic models should make it possible to refine the projections produced by the distribution models, on the condition that the necessary data are available. The development of these models should proceed in parallel with the many research projects already under way to understand the pressure-impact relations (thermal pollution, minimum discharge, invasive species, etc.) that are factors in defining adaptive measures. Use of data series spanning long time periods, for both biological and environmental data, e.g. discharges, water temperature, etc., is also essential. In addition, it would appear that knowledge on species' ecology, even that of the most common species, is far too fragmentary and insufficient for mechanistic models. Filling in the gaps is a further priority. Finally, too few studies address time periods spanning the next decades, which are nonetheless an intermediate target of great importance for management. A great amount of work must be put into all the above topics.

## Chapter 4 - Taking action to reduce the vulnerability of fish communities

Adaptation to climate change is a complex phenomenon that is already well under way in continental France. The National plan for adaptation to climate change (PNACC) laid the foundation in 2011 and produced a number of incentive and regulatory measures such as the Regional plan for climate, air and energy (SRCAE) and the Territorial climate-energy plan (PCET). In the water field, however, no new binding measures have been undertaken. That being said, the information presented in this chapter makes clear that the WFD measures already implemented constitute a highly effective tool in reducing the vulnerability of fish populations in a context of climate change. The increases in minimum discharges, the development of indicators such as the target low-flow discharge and efforts to reduce water consumption as stipulated by the PNACC are all important steps forward in the quantitative management of water resources. The restoration of ecological continuity, implemented country wide for all holobiotic (living their entire life in the same environment) and diadromous (alternating between freshwater environments and the sea) species will enable them to reach more favourable areas in the future in as much as the available habitat conditions (hydrology, physical-chemical parameters, etc.) are still favourable. Further imperative conditions are an improvement in water quality and the restoration of rivers, which will impact positively on the survival of fish in a changing environment. In spite of the uncertainties surrounding climatic and hydrological projections, climate change should be seen as a further argument to implement measures to attenuate pressures and thus enhance the resilience and adaptive capacity of environments and organisms.

Research programmes will provide knowledge on essential aspects such as the thermal and/or hydromorphological "preferences" of fish, their movements in rivers and their capacity to adapt or to acclimate. The relative impact of anthropogenic pressures compared to climate forcing and the links between water quality, water temperature and fish populations are further issues that require the attention of researchers. Finally, the uncertainties inherent in distribution models must be reduced in order to produce robust projections on smaller scales (e.g. the river-basin scale) in order to enable their operational use.

The continued operation and development of the observatories and measurement networks will be key factors in the future in both monitoring change and in assessing the effectiveness of the measures implemented. In the final analysis, it is important, on the one hand, to pursue and immediately amplify all types of work to restore and preserve correct functioning of aquatic environments. Their good health will make them more resilient to modifications resulting from climate change and thus reduce the vulnerability of species. On the other hand, it is important to continue the accumulation of data and research results in order to better understand, over the mid term, the phenomena involved and to improve the responses to those phenomena. The two approaches are essential because they complement each other.

# Contents

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1

# Understanding the impact of climate change on water resources

# Defining climate and the influential factors

According to the World Meteorological Organisation, the climate may be defined as the mean conditions prevailing in a given place (temperature, precipitation, etc.) and calculated on the basis of observations over at least 30 years. A climate is characterised by mean values, but also by variations in values and by extremes. For the planet as a whole, the climate is the result, over space and time, of a vast series of interactions between the elements making up the following compartments:

- atmosphere;
- lithosphere (crust of the Earth);
- hydrosphere (all seas, oceans, lakes and rivers on the planet);
- cryosphere (surfaces covered with snow and ice);
- biosphere (all living things).

The balance of the energy exchanges between these compartments depends on a number of factors.

The first is the quantity of solar energy reaching the Earth. The planet is subject to periodic variations of its axis and orbit that modify its position with respect to the sun and consequently the quantity of solar irradiance received (see Figure 1). These variations are called the Milankovitch cycles and they explain in part the progressive shifts in glacial-interglacial cycles that have characterised climate regimes over the past several million years (Lisiecki and Raymo, 2005; Jouzel *et al.*, 2007). These cycles is consequently very long, ranging from 10 000 to 100 000 years.

However, orbital forcing explains only part of the climate variations. The properties of the various compartments, e.g. atmosphere, oceans, cryosphere, and their complex interactions play the dominant role in the amplitude and frequency of the glacial-interglacial cycles (Sigman and Boyle, 2000; Jouzel *et al.*, 2007), notably by influencing the fraction of the solar irradiance reflected by the planet. This fraction, which varies depending on the darkness of the planet surface, is called albedo. The factors contributing the most to albedo are, in the atmosphere, clouds and aerosols (particles suspended in the air), and, in the lithosphere, the type of terrestrial surface (bare ground, vegetation, ice). The climate also depends on the concentration of the greenhouse gasses (GHG) present in the atmosphere (see Figure 1). GHGs, i.e. water vapour, $CO_2$, ozone, methane and nitrous oxide, are naturally present in the atmosphere. They absorb part of the radiation emitted by the Earth (causing the lower layers of the atmosphere to warm) and re-emit part of the radiation to space. When the concentration levels of GHGs increase, a greater percentage of the infrared radiation is trapped in the lower layers of the atmosphere, resulting in low-altitude warming.

Figure 1

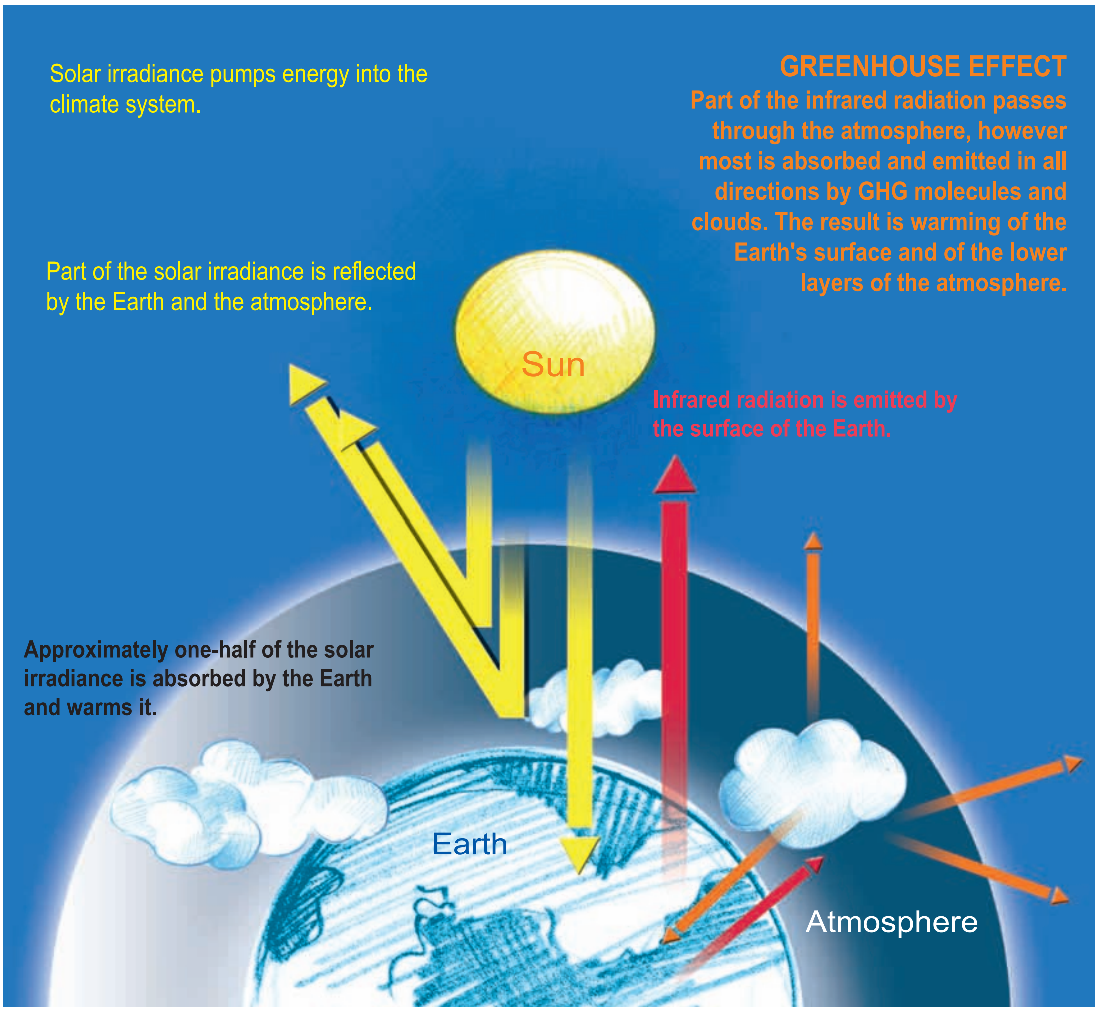


*Diagram showing the functioning of the greenhouse effect as part of the radiation balance in the climate system (according to IPCC, 2007).*

Other phenomena also influence the climate. Examples are El Niño and La Niña, two phenomena caused by disturbances in the atmospheric circulation between the poles and the equator, themselves caused by variations in ocean temperatures. El Niño occurs when the precipitation zones move eastward in the Pacific Ocean and block the current of cold water that otherwise moves north along the coast of South America. Conversely, La Niña occurs when the trade winds in the Pacific Ocean strengthen and push the warm surface waters away from the coast of South America, thus reinforcing the current of cold water. In both cases, these atmospheric phenomena cause severe cyclones and dry periods on either side of the Pacific Ocean and even on the global scale. In the same manner, the large-scale cyclical variations in the atmospheric and ocean currents of the Atlantic Ocean also influence the climate. Two are of particular importance, the North Atlantic Oscillation[1] and the Atlantic Multidecadal Oscillation[2].

Major ocean currents also affect the climate by contributing to the redistribution of heat. For example, the Gulf Stream is a current that starts in the region between Florida and the Bahamas and travels northward to Greenland. It play a role in regulating winter temperatures in Western Europe. However, in recent years, its importance has been downplayed by scientists (Seager *et al.*, 2002).

1. The North Atlantic Oscillation (NAO) index is based on the difference of normalised sea level pressure (SLP) between two meteorological stations, Gibraltar and Reykjavik.
2. The Atlantic Multidecadal Oscillation (AMO) index is calculated by averaging sea-surface temperatures in the Atlantic Ocean north of the equator.

Finally, the climate is influenced both directly and indirectly by feedback phenomena that can amplify or attenuate the initial effects of the phenomena mentioned above. One example of a positive (amplifying) feedback is that occurring when rising temperatures melt snow and ice. The worldwide reduction in snow-covered areas means there is an increase in darker surfaces (land and water) that trap more of the heat emitted by the sun (see Figure 2). Water vapour is also involved in a positive feedback loop. The increase in temperatures augments the quantities of water vapour in the atmosphere, which in turn increases the greenhouse effect. Finally, liquid water, notably that contained in clouds, can contribute to both cooling the atmosphere by reflecting solar rays back out to space (primarily high cloud formations) and to warming the atmosphere by trapping the infrared radiation rising from the surface (primarily low cloud formations).

**Figure 2**

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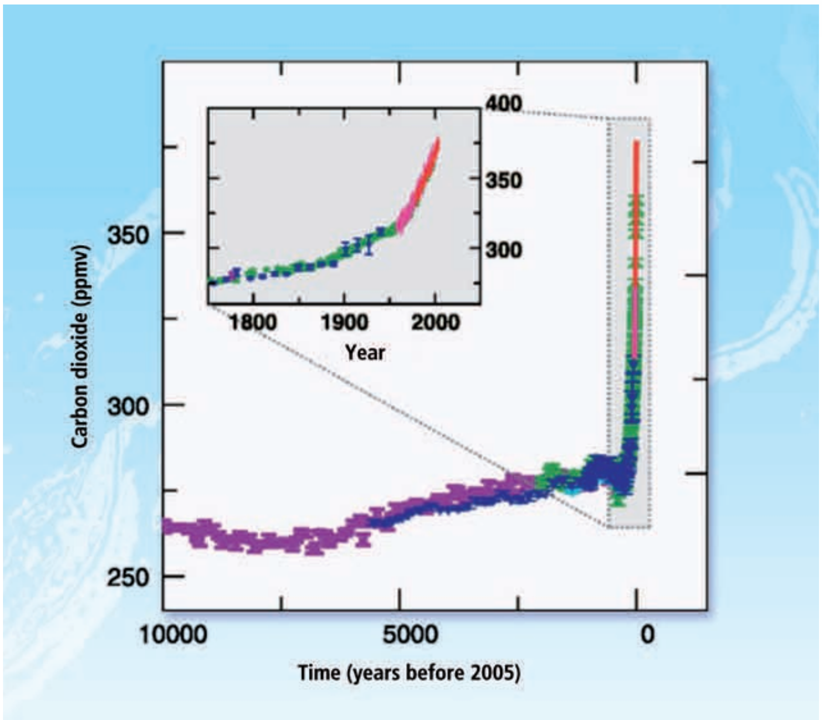
*Dark surfaces revealed by melting snow trap more heat and accelerate the melting process.*

# Causes and consequences of climate disruption

Human activities are the cause of growing emissions of greenhouse gasses (GHG). Over the past millennia, $CO_2$ concentrations in the atmosphere stood at approximately 280 ppmv (parts per million by volume), then jumped from 280 to 385 ppmv between 1800 and the years just after 2000 (see Figure 3).

**Figure 3**

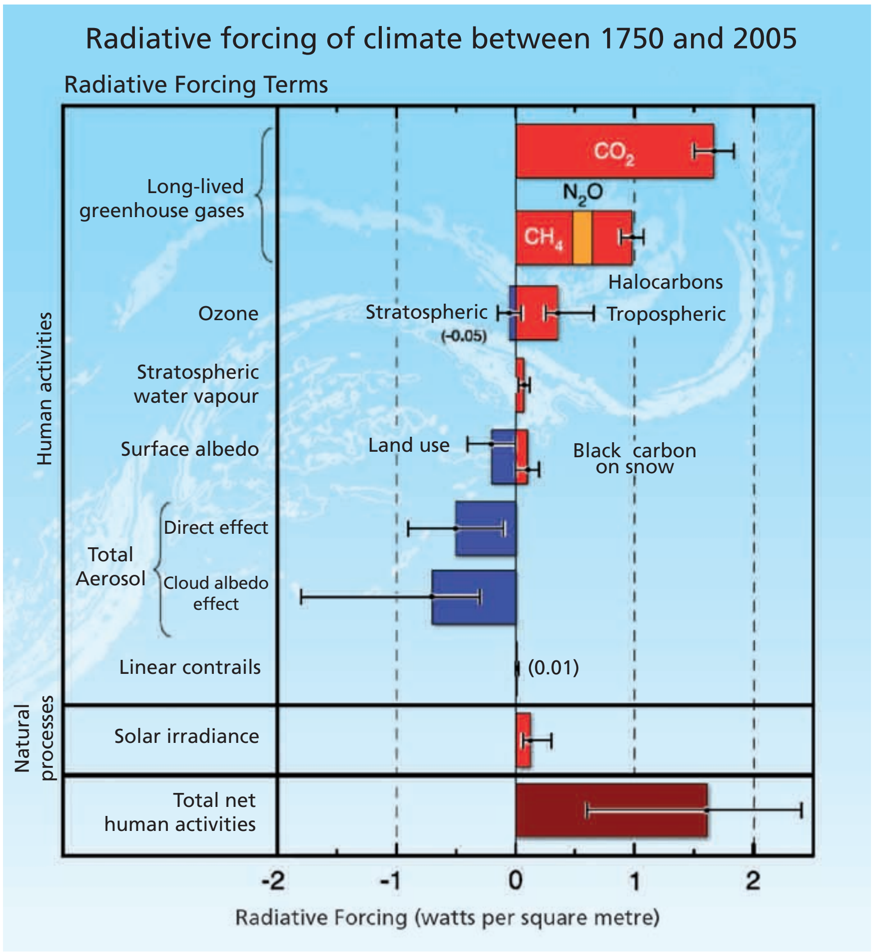



*Atmospheric concentrations of $CO_2$ over the past 10 000 years (large graph) and since 1750 (detail). The data are drawn from ice cores (the different colours represent different studies) and from direct atmospheric measurements (red lines) (IPCC, 2007).*

Transportation and industry (including the production of halogenated compounds) are the main human activities releasing GHGs, however agriculture (clearing of forests, nitrous oxide from nitrogen fertiliser, methane from the digestion of ruminants) also contributes non-negligible quantities (see Figure 4).

As explained in the previous section, the increase in GHG concentrations modifies the radiation balance in the atmosphere (see Figure 4), which in turn, strictly according to the laws of physics, results in an increase in atmospheric temperatures and changes in evaporation rates, in atmospheric humidity and in condensation processes.

Figure 4



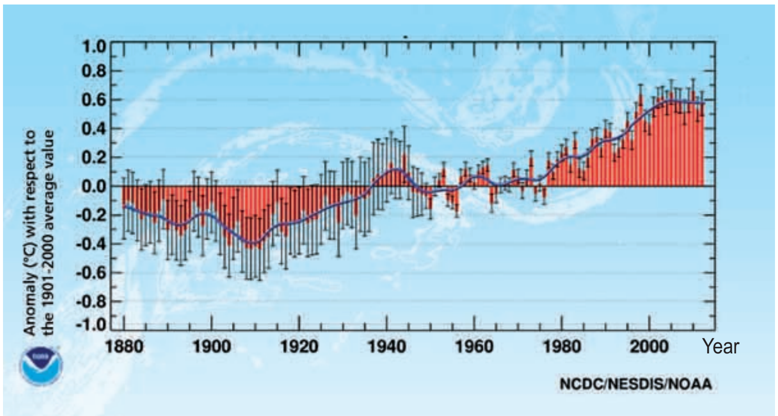

*Summary of the principal components of the radiative forcing of climate change (IPCC, 2007). Positive forcings lead to warming of the climate and negative forcings to cooling. Note that black carbon is produced by incomplete combustion of solid or liquid substances such as fossil fuels, biofuels and biomass. When it lands on snow, the black carbon modifies the albedo and more heat is drawn from the solar irradiance. Linear contrails are the long, thin lines of condensation that sometimes form behind aircraft. They reflect solar irradiance and absorb infrared rays. By increasing cloud cover, they are the cause of slightly positive radiative forcing.*

Observation of climate variables (temperature, precipitation) over the past decades has revealed major changes of the types mentioned above that have affected the water cycle (evapotranspiration, runoff, groundwater) and water quality (temperature, chemistry).

## Observed impact on atmospheric temperatures

Over the past century, the globally averaged surface temperature has risen rapidly, as shown by the terrestrial temperature measurements carried out over the past 150 years (see Figure 5). Between 1951 and 2010, the globally averaged temperature rose 0.6°C (IPCC, 2007). The average speed of the temperature rise over the past 50 years was virtually double that of the past 100 years. As a result, the last 12 years (2001-2012) were among the 14 hottest years ever recorded since 1880 (NOAA, 2012).

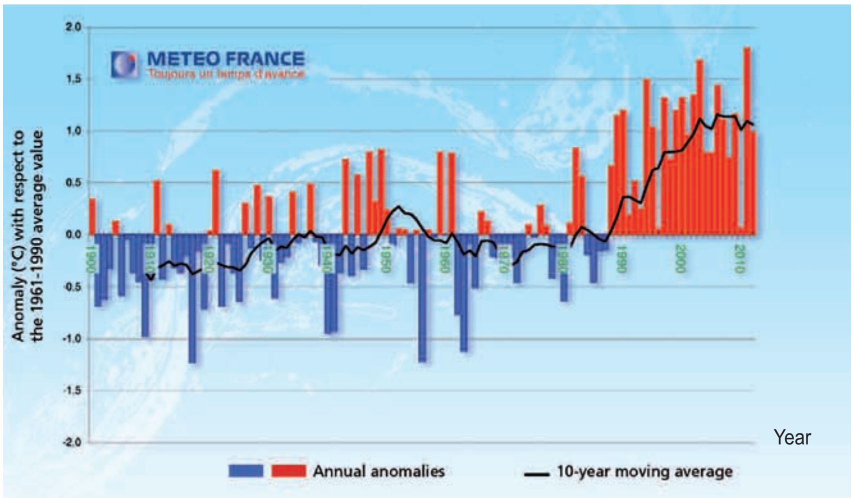
Figure 5




*Change in the globally averaged surface temperature, on the basis of data compiled by the National Oceanic and Atmospheric Administration (NOAA), © NCDC: Global Surface Temperature Anomalies. The Y-axis shows the difference in °C over the period 1880 to 2012, with respect to the long-term average value calculated for the period 1901 to 2000.*

The change in temperature has also been noted on a more local scale. Over the last century, the average air temperature in continental France increased by approximately 1°C, the increase being greater in the southern than in the northern section of the country (Soes, 2011; see Figure 6).

Figure 6




*Change in the anomaly of the averaged annual temperature in France over the 1900s, with respect to the long-term average value calculated for the period 1961 to 1990. The averaged annual temperature is defined as the average of the averaged annual values of the daily minimum and maximum temperatures. The anomaly is calculated by comparing the averaged annual temperature to the 1961-1990 value. Negative anomalies are shown in blue, positive anomalies in red. This graph was plotted using homogenised data series spanning the 1900-2012 period and distributed over continental France (Météo-France, 2012).*

The increases in the minimum temperatures (1.2°C) are greater than those in the maximum values (0.6°C) (Moisselin *et al.*, 2002). Analysis of the data series by Météo-France for the period 1951 to 2000 also revealed higher temperatures during the day and at the end of the night, as well as a reduction in the number of days with freezing temperatures (Dandin, 2007).

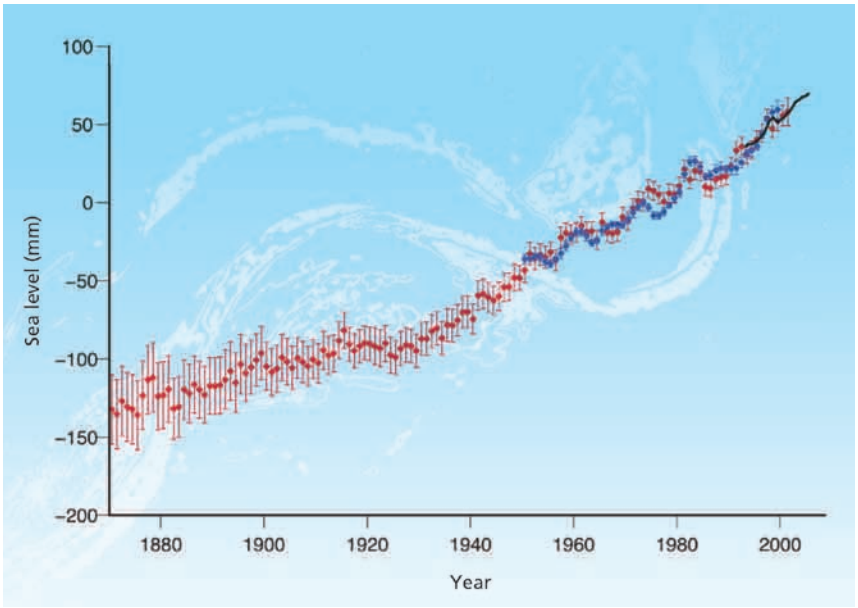
## Observed impact on precipitation, the cryosphere and sea levels

Climate change impacts precipitations in two distinct manners. The rise in temperatures means the air can hold more humidity which in turn has an influence on the frequency and intensity of precipitation. Secondly, because the rise in atmospheric temperatures is greater at the higher latitudes, the thermal gradient between the poles and the equator is reduced, which modifies atmospheric circulation, winds and the entire hydrological cycle.

These hypotheses have been confirmed globally by an analysis of the data series covering the second half of the last century. Subtropical zones now tend to be dryer whereas an increase in precipitation has been observed at the low latitudes.

In addition, surface areas covered with snow and ice have decreased year after year (again due to the increase in temperatures). Snow-covered areas in the northern hemisphere decreased by 7.5% over the 1992 to 2005 period, following a sudden and sharp transition between 1986 and 1988 (Brown, 2000). Similarly, satellite data (since 1978) have revealed that the averaged annual surface area of the Arctic Ocean covered by ice has dropped by approximately 2.7% per decade, with even sharper decreases of 7.4% during the summer period (Comiso, 2002, 2003). Melting of the ice pack has led to an increase in the average sea level, up 1.8 mm per year on average since 1961 and 3.1 mm per year since 1992 (Church and White, 2006; see Figure 7).

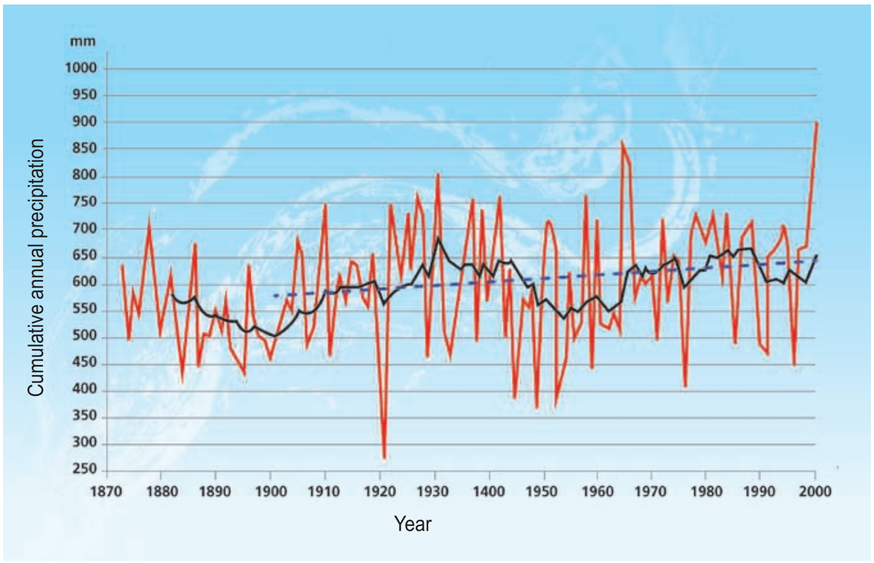
**Figure 7**




*Globally averaged annual sea level based on reconstructed zonal data (red), tide-gauge data (blue) and satellite data since 1992 (black). Sea levels are measured in millimetres and compared to the 1961-1990 average value. The error bars are set to 90% of the confidence intervals (IPCC, 2007).*

In France, the trend is not always clear and may be contradicted by data from the southern section of the country, however on the whole, there is an increase in annual precipitation (Moisselin *et al.*, 2002; Dubuisson and Moisselin, 2006; see Figure 8).

**Figure 8**




*Cumulative annual precipitation (in mm, red line) in Paris from 1873 to 2000 (Moisselin* et al. *2002). The black line is a 15-year moving average. The dotted blue line is the trend from 1901 to 2000.*

An increase in seasonal differences and greater regional diversity have also been observed. For example, in the northern section of France, precipitation has tended to increase in the winter and to decrease in the summer (Dandin, 2006, 2007). In addition, dry periods during the summer are increasingly frequent and intense (Dubuisson and Moisselin, 2006).

On the other hand, no clear trends in extreme events have been detected due to the lack of long data series on the subject and the great spatial variability of precipitations in France. The indices characterising events producing high daily precipitation values do not all point in the same direction. However, it has been noted that the number of days with heavy precipitation (> 10 mm) has risen over the two northern thirds of France (Dubuisson and Moisselin, 2006) due to the increase in atmospheric humidity, similar to the rest of the planet.

## Potential impact on evapotranspiration

Evapotranspiration[3] is one of the fundamental components in the hydrological cycle and must be studied in any effort to assess the consequences of an increase in temperature on the hydrological balance of a region or river basin. However, the importance of this variable contrasts with the fact that there are very few direct measurements of effective evapotranspiration[4] for all land masses (Boé, 2007), in spite of a few initiatives such as the Fluxnet[5] network. Variations in evapotranspiration are caused not only by the level of humidity, but also by the available energy, surface winds and $CO_2$ concentrations (i.e. their impact on plant transpiration). Generally speaking, greater evapotranspiration may be expected in regions where water stress does not increase (e.g. tropical forests and zones where precipitation increases).

## Observed impact on runoff and extreme situations

Even though a vast number of studies have been carried out on the impact of climate change on river discharges, no clear trends on the planetary scale have been noted (Bates, 2008). This is due primarily to the fact that it is very difficult to distinguish between the effects of climate change and those caused by human activities (changes in land use, creation of reservoirs, etc.). In addition, the sparse spatial distribution of data-collection points makes it particularly difficult to obtain a clear signal. This is true for France as well. Analysis of over 200 data series on daily discharges did not reveal any general changes over the past century (Grésillon *et al.*, 2007). In a limited number of cases, significant downward trends in the interannual mean discharge of rivers not influenced by anthropogenic factors (see Box 1) have been noted over the past 40 years in the southern section of France and more precisely in the Pyrenees and the Cévennes (Giuntoli, 2012). It is however difficult to establish a causal link with climate change due to the Atlantic multidecadal oscillation (see footnote n° 2) (Boé and Habets, 2014).

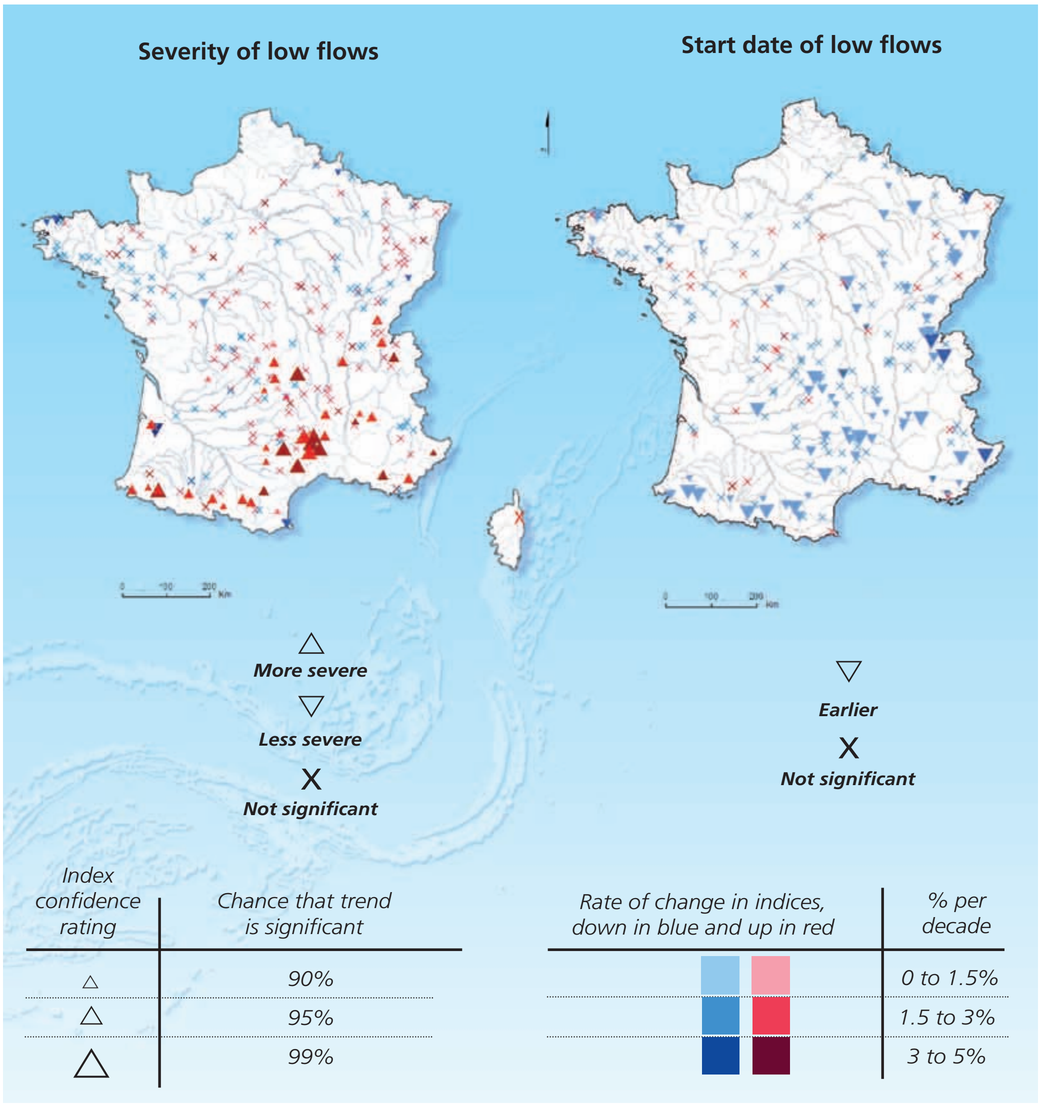
Similarly, most studies conclude that no significant and general trends are detectable in flood volumes since the middle of the last century (Renard *et al.*, 2006; Renard, 2006). This lack of a clear trend is due to high regional variability. That being said, more frequent extreme flooding has been noted in the Alps over the past 20 years due to increases in the discharges of rivers supplied by glaciers (Bard *et al.*, 2012). Also, in some places, earlier peak spring flooding has been noted due to earlier melting of snow packs (OsCC, 2011).

3. Quantity of water entering the atmosphere due to evaporation from the soil and transpiration by plants.
4. For this reason, one does not speak of observed impact, but of the potential impact of climate change on this variable.
5. http://fluxnet.ornl.gov/introduction

Concerning low-flow levels, no significant changes have been observed in the northern section of France or in nival rivers (Giuntoli and Renard, 2010; Giuntoli *et al.*, 2012). Of interest, however, is a study on two nival rivers, the Chéran and Isère Rivers, which noted a reduction of over 35% in their discharges at the beginning of the summer season (OsCC, 2011). It would also appear that the low-flow period occurred earlier during the summer, however no trend has yet been confirmed (see Figure 9).

Finally, in the southern section of France, the severity and duration of low-flow periods would appear to have increased from 1968 to 2007, though it is difficult to determine the origin of this phenomenon (measurement problems, cyclical variations in atmospheric and ocean currents in the Atlantic, global warming due to the increase in GHGs).

**Figure 9**




*Trends detected over the period from 1968 to 2007 concerning the severity (on left) and the timing (on right) of low-flow periods, on the basis of 236 hydrometric monitoring points in continental France. The low-flow period occurred earlier in the year at 32% of the monitoring points (diagrams modified, originally from Giuntoli and Renard, 2010; Giuntoli* et al.*, 2012).*

### Common hydrological variables

The discharge of a river is the volume of water flowing through the cross-sectional area of the river per unit of time. Discharge is expressed in cubic metres per second ($m^3/s$). The following discharges are commonly used.

- Daily mean discharge. Ratio between the volume of the flow for a full day (0-24 hours) and the corresponding duration. The volume is calculated using the record of instantaneous discharges.
- Monthly, annual and interannual mean discharge. Mean value, for the given period, of the daily mean discharges. The interannual mean discharge is the mean value of the annual mean discharges.
- Natural discharge. Discharge that would occur in the absence of a hydraulic structure modifying the river regime at the monitoring point. Values are calculated only for monthly and annual discharges.
- Influenced discharge. Discharge of a river disturbed by human activities, but such that flows retain their general characteristics.
- Annual minimum monthly discharge with a five-year return period (QMNA5). Monthly discharge that has an 80% chance of being exceeded each year. This variable is used to characterise a calender month with low hydraulic conditions.
- Low-flow discharge. Minimum discharge in a river calculated over a given time period when water levels are at their lowest in the year. For a given year, one may speak of the daily low-flow discharge, the low-flow discharge over x consecutive days or the minimum monthly discharge (the average of the daily discharges during the month of least discharge).

Low-flow discharges may also be expressed as averages over several consecutive days. For example, the period may be the month with the least discharge (QMNA, annual minimum monthly discharge), the three days with the least discharge (VCN3, minimum mean discharge over three consecutive days) or any number of days (VCNx). Similarly, the floods during a year may be characterised using the maximum instantaneous discharge (QIX) or the maximum daily discharge (QJX).

Finally, the return period of floods and low-flows is commonly mentioned. This term characterises the frequency of the phenomena and corresponds to the reciprocal of the probability that the event in question will occur or be exceeded each year. For example, a flood with an annual frequency of 0.1 has a ten-year return period and one speaks of a "ten-year flood". Such a flood has a 10% chance of occurring or being exceeded each year.
*Source: www.hydro.eaufrance.fr/glossaire.php*

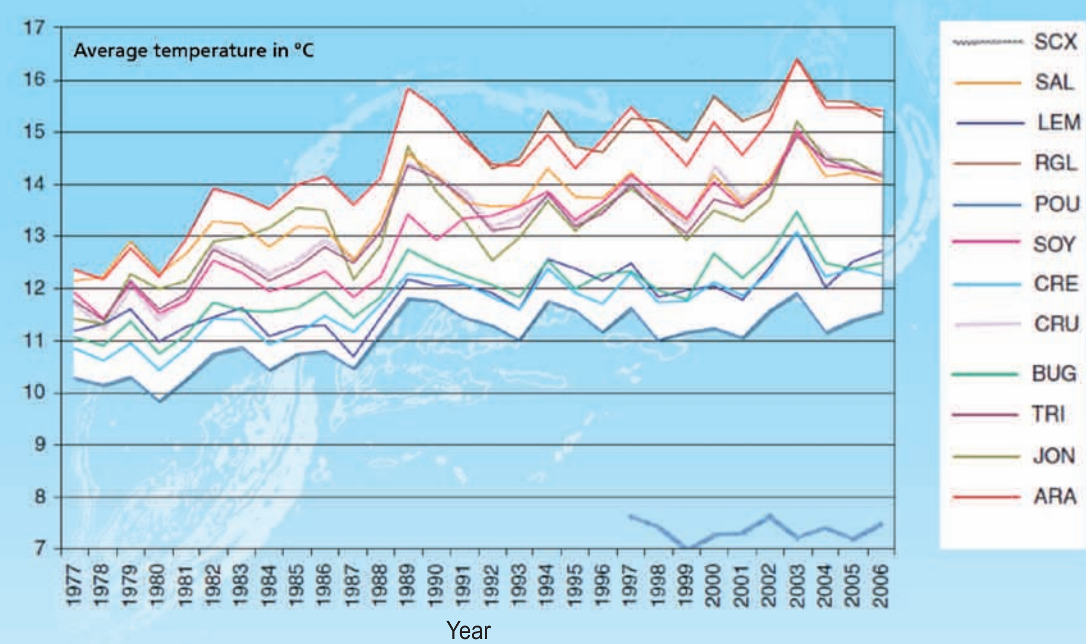
## Observed impact on groundwater

Groundwater levels depend heavily on the distribution of precipitation between evapotranspiration, surface flows and infiltration to groundwater. It follows that climate change will necessarily have an impact on groundwater reserves. However, to date, no general trends, either temporal or spatial, have been detected in continental France. The results by Vernoux and Seguin (2011) indicate that the available data series are too short, the spatial distribution of monitoring points is too heterogeneous and there are too many confounding factors, notably human activities and the Atlantic multidecadal oscillation.

## Observed impact on water temperatures

Over the last decades, the increase in air temperatures has gone hand in hand with a rise in water temperatures in rivers and lakes. Poirel (2008) notes for example a general upward trend in the Rhône River and its tributaries between 1977 and 2006. The increase is almost 1°C in the Saône, it rises to 1.5°C in the Ain and in the Rhône downstream of the Bugey and even 2°C downstream of the Isère (see Figure 10).

**Figure 10**




*Monitoring points*
*SCX = upstream of Lake Geneva*
*LEM = downstream of Lake Geneva*
*POU = 25 km downstream of Lake Geneva*
*CRE = upstream of Creys-Malville power plant*
*BUG = upstream of Bugey power plant*
*JON = downstream of Ain/Rhône confluence*
*SAL = upstream of Saint Alban power plant*
*RGL = upstream of Isère/Rhône confluence*
*SOY = downstream of Isère/Rhône confluence*
*CRU = downstream of Drôme/Rhône confluence, upstream of Cruas-Meysse power plant*
*TRI = upstream of Tricastin power plant*
*ARA = downstream of Durance/Rhône confluence*

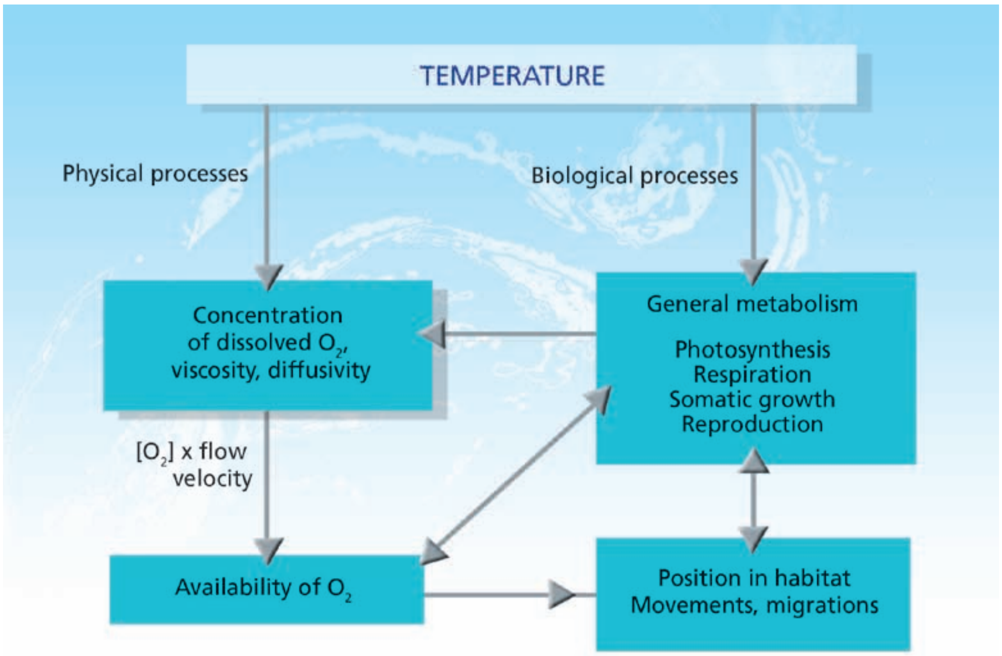
*Averaged annual water temperatures along the Rhône River (Poirel* et al.*, 2008).*

Similar to the Rhône, study of temporal data series for the mid-Loire River revealed an average annual temperature rise of 1.2°C between the first and last decade of the 32-year period from 1977 to 2008. The primary reason is a rise in air temperatures and the second is a decrease in discharges (Floury, 2012). These results are in line with previous observations by Moatar and Gailhard (2006) on the Loire from 1976 to 2003, as well as with data from other major European rivers, e.g. an increase of 1.4 to 1.7°C over the last century for the Danube and its tributaries (Webb and Nobilis, 2007). The same trends have been noted for lakes. Measurements carried in Lake Bourget, at a depth of two metres over the period from 1984 to 2011, signal an average increase of 1.1°C, with the highest values noted in 2003 and 2011 (OsCC, 2012). However, caution is advised when interpreting these results because the time span of the data series underlying the analysis is generally less than 40 years. In addition, other factors explaining the phenomena must be taken into account, for example human activities and cyclical variations in atmospheric and ocean currents in the Atlantic, notably the Atlantic multidecadal oscillation (Sutton and Hodson, 2005; Sutton and Dong, 2012; Boé and Habets, 2014).

## Potential impact on water chemistry

Water temperatures directly and indirectly impact many chemical (concentration of dissolved oxygen, viscosity, diffusivity) and biological functions (plant and animal metabolisms) (see Figure 11). An increase in temperature could modify the balance between oxygen availability and metabolic needs (Dumont *et al.*, 2007), thus increasing the risks of trophic imbalances (Fabre, 2012). However, no studies on the subject are currently available.

**Figure 11**




*Links between temperature and oxygen availability, and the impacts on aquatic ecosystems (according to Dumont* et al.*, 2007). Note that the maximum concentration of dissolved oxygen in water decreases as the temperature rises. For example, at 10°C, the maximum concentration of dissolved oxygen is 11 mg/L, but at 30°C, the maximum concentration is only 7 mg/L.*

## Conclusion

The observed changes in climate and hydrology are in line with the expected consequences of the increase in GHGs emitted by human activities over the past two centuries (IPCC, 2007; Cook *et al.*, 2013). The trend data for air temperatures are fairly clear and consistent worldwide, however it is more difficult to detect a trend in the qualitative and quantitative changes in water resources over the past century. In addition, when trends are observed, it is often difficult to establish a causal link with climate disruptions due to the existence of many confounding factors (human activities, the Atlantic multidecadal oscillation, etc.).

The next section is a presentation of the models used to project changes in water resources in view of assessing the possible consequences of climate change. The uncertainties inherent in these models are also noted.

# Modelling tools to project changes in the climate and in water resources

Digital models are required to assess the degree of climate change, anticipate the impacts and take adaptive measures. Such models, based on equations governing fluid mechanics and energy conservation, were first developed in the United States starting in 1960 and became increasingly complex in order to produce more precise and robust projections of the future climate.

Climate change is a function of GHG emissions, which explains why GHG-emissions scenarios were proposed by the IPCC and are used by climatologists as input data for climate models. The climate scenarios produced by the models are in turn used in impact models that simulate the effects of climate on hydrology and ecosystems.

## Emissions scenarios for greenhouse gasses

Scenarios on the future composition of the atmosphere, also called SRES (Special Report on Emissions Scenarios) scenarios, were devised on the basis of socio-economic projections (demographics, life styles, new technologies, etc.) (Nakićenović and Swart, 2000). Four basic scenarios were formulated (see Figure 12).

■ **Scenario A1.** Convergence between North and South, economic development similar to the current situation. This scenario is divided into three groups describing different energy strategies. A1FI corresponds to intensive use of fossil fuels, A1T calls on non-fossil energy resources and A1B corresponds to a balance across all sources.

■ **Scenario B1.** Convergence between North and South, economic development taking environmental concerns and sustainability into account.

■ **Scenario A2.** Heterogeneous situation, economic development similar to the current situation. This scenario most closely corresponds to the present situation.

■ **Scenario B2.** Heterogeneous situation, economic development taking environmental concerns and sustainability into account.

As mentioned above, the GHG concentrations estimated using these scenarios served until recently as input data for models simulating the future climate.

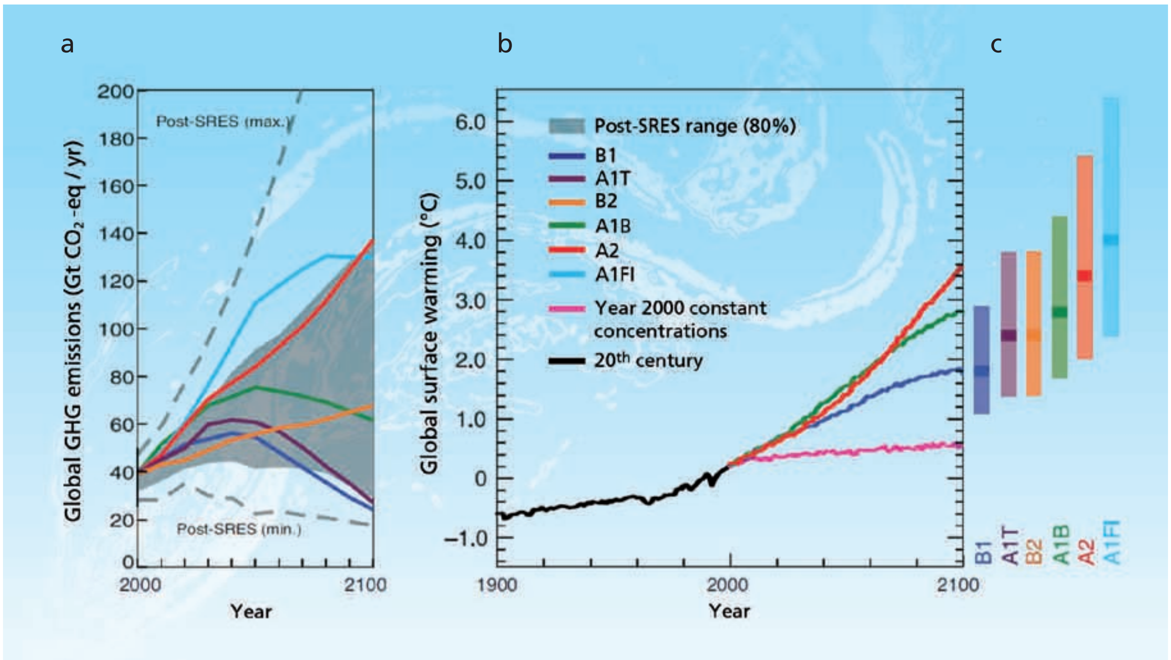
Starting with the preparation of the Fifth IPCC assessment report, parts of which started to be published in 2013, a different approach was adopted in order to encourage the emergence of adaptation scenarios. This time, to assess the evolution of the climate in the future, the IPCC experts defined *ex anti* four trajectories for GHG emissions and concentrations, called Representative Concentration Pathways (RCP) (Moss *et al.*, 2008, 2010). The RCPs are used by the various teams of experts (climatologists, hydrologists, agronomists, economists, etc.)

that all worked in parallel for the first time. On the basis of the RCPs, climatologists produce global and regional climate projections. Economists devise scenarios, called Shared Socio-Economic Pathways (SSP), used to define worldwide socio-economic conditions that are compatible with the various RCPs.

Four families of RCPs have been developed.

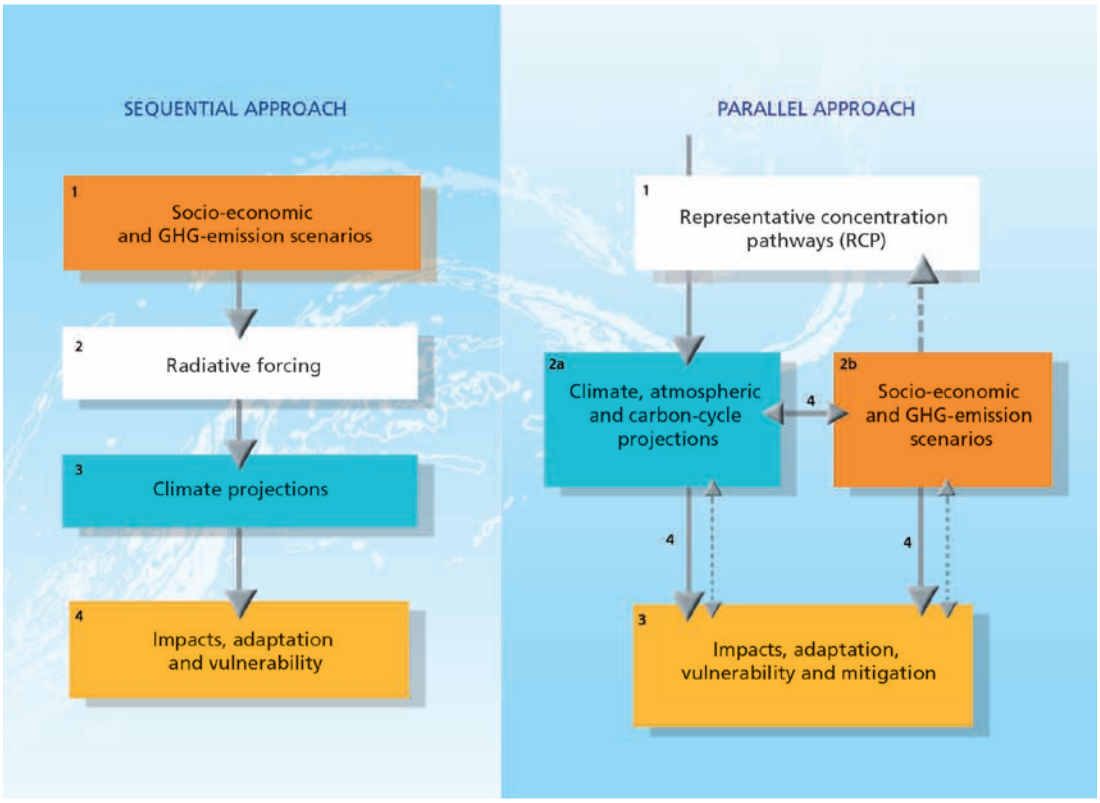
- **RCP 8.5.** In the year 2100, radiative forcing reaches 8.5 W/m², which corresponds to a $CO_2$-equivalent concentration of approximately 1 370 parts per million by volume (ppmv). Radiative forcing continues to increase strongly in 2100.
- **RCP 6.** In the year 2100, radiative forcing reaches 6 W/m², which corresponds to a $CO_2$-equivalent concentration of approximately 850 ppmv. Radiative forcing stabilises after 2100.
- **RCP 4.5.** In the year 2100, radiative forcing reaches 4.5 W/m², which corresponds to a $CO_2$-equivalent concentration of approximately 650 ppmv. Radiative forcing stabilises after 2100, but stabilisation begins around 2060.
- **RCP 2.6.** Radiative forcing reaches a peak of 3 W/m² ($CO_2$-equivalent concentration of approximately 490 ppmv) before 2100 and decreases subsequently. In the year 2100, it is approximately 2.6 W/m². This scenario is also called RCP 3-PD, i.e. 3 W/m² and peak decline. It is the only scenario in which the rise in global temperatures remains below 2°C.

**Figure 12**




*Scenarios for GHG emissions from 2000 to 2100 and projections of surface temperatures.*
*a. Global GHG emissions in the absence of climate policies. Six illustrative SRES marker scenarios (coloured lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (grey shaded area). Dashed lines show the full range of post-SRES scenarios.*
*b. Solid lines are multi-model global averages of surface warming for scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. The pink line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values.*
*c. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099.*
*All temperatures are relative to the period 1980-1999 (IPCC, 2007).*

Figure 13




*Presentation of the sequential (SRES) and parallel (RCP and SSP) approaches. The numbers correspond to the different steps, where steps 2a and 2b are carried out simultaneously. The solid arrows signal information transfers, the thick dotted arrow corresponds to RCP selection and the thin dotted arrows indicate information integration for the assessment of impacts and the formulation of mitigation and adaptation strategies (diagrams modified, originally from Moss* et al.*, 2008).*

The correspondence between RCPs and SRES scenarios is not always obvious because a given RCP may be compatible with several SRES scenarios. That is the case for RCP 4.5 which may be compatible with three of the SRES scenarios (A2, B1 and B2). Conversely, a given set of SRES scenarios may be compatible with several RCPs.

## General circulation models

All the compartments of the climate system and their interactions must be taken into account in climate models. The digital models currently used, called Global Circulation Models (GCM), are in fact sets of interlinked modules (atmosphere, oceans, sea ice, etc.). The complexity and quantity of the necessary calculations require enormous computer resources and budgets. For these reasons, the horizontal resolutions of global models are, for the time being, fairly low (grid size of approximately 200 km for the finest resolutions).

Such low resolutions may have a major impact on simulations, notably for precipitations that are generally highly dependent on the local context. France is a good example of this problem. Given its complex topography, climate regimes can vary significantly over short distances. For this reason and to improve modelling results, regionalisation methods have been developed.

## Regionalisation of climate scenarios

There are several ways to enhance the spatial-temporal resolution and correct the biases (poor representation of relief, poor integration of marine influences, physical errors) of climate models. These methods, called downscaling, regionalisation and spatial disaggregation, can be used to reveal detailed information on local conditions that are consistent with the observed values.

There are two main approaches to increasing the spatial-temporal resolution of climate models.

■ Dynamic downscaling, i.e. improving the resolution of the global models. There are three families of models:

- high-resolution global models covering the entire planet that require long calculation times and large budgets;
- variable-resolution global models start with a uniform grid covering the entire planet, but the grid can be modified to achieve higher spatial resolution for the studied zone. The ARPEGE-Climat (Météo-France) and LMDZ (IPSL LMD) models are of this type (Gibelin and Déqué, 2003) and are capable of zooming in to resolutions of a few dozen kilometres;
- regional models covering only a part of the planet (e.g. Europe) and having data ranges limited by global models with lower resolutions. This method can be used to achieve high spatial resolutions (10 to 20 km) required to realistically simulate the local climate (relief, land-sea contrast, complex coast lines) and to take into account regional physical processes.

■ Statistical downscaling, based on defining a statistical relation between low-resolution global variables and high-resolution local surface variables. There are numerous statistical methods to project global variables to the local level and each has application limits specific to its internal structure.

Note that statistical corrections are often required to avoid significant distortion of the results, whatever the type of downscaling employed.

## Hydrological models

Following climate modelling, the resulting projections are fed into hydrological models to assess their impact on different local hydrological variables (interannual mean discharge, flood discharge, low-flow discharge, etc.). There are two main types of models:

■ the first type attempts to reproduce the observed physical processes, for example in a river basin. They are called mechanistic (or explicit) models, one example being the SAFRAN-ISBA-MODCOU models coupled as SIM[6] (Habets *et al.*, 2008);

■ other models are said to be conceptual, e.g. the GR4J and GARDENIA models (Perrin *et al.*, 2003; Thiéry, 2003). They attempt to precisely reproduce the observations, but without taking into account all the physical processes.

Conceptual models often produce excellent results over the period covered by the data, but they are theoretically not designed to react well outside of the situation for which they are calibrated, e.g. for a change in land cover. Conversely, physical models require good characterisation of the environment, e.g. soil and vegetation. This data is generally difficult to acquire and these models often do not offer the same level of performance as conceptual models over recent time periods. However, they are thought to be more robust in situations where the climate and environmental conditions are modified.

6. The Safran-Isba-Modcou coupled model was developed in a partnership between CNRM-GAME and the Geosciences centre at Mines ParisTech.

## Uncertainty at every step

Considerable uncertainty accompanies climate and hydrological projections and must be taken into account in studies attempting to predict the impact of climate change on human populations and the environment (see Figure 14).

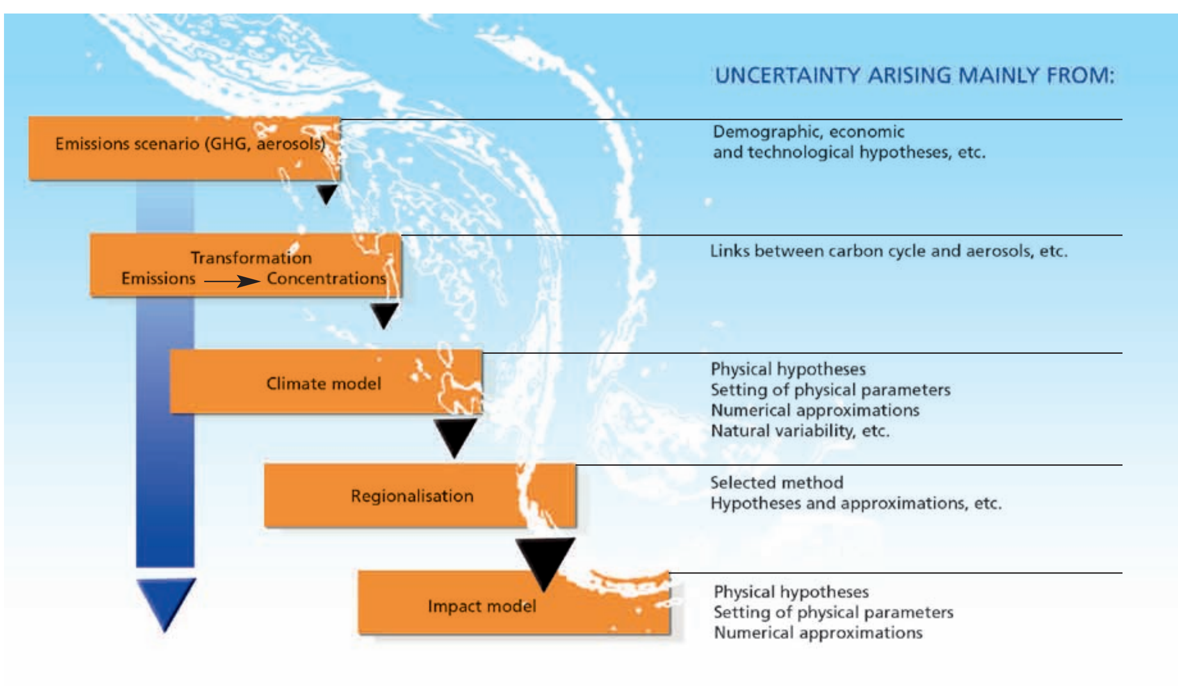
Concerning GHG emissions scenarios, the uncertainty is due to the hypotheses selected as well as to changes in society.

Concerning the models themselves, their design and the resolution methods employed raise a number of questions. These questions are amplified by downscaling, the complexity of the phenomena involved, the interactions between variables and feedback loops.

The translation of the projections resulting from the climate models into hydrological terms, particularly concerning extreme conditions, is also a source of significant uncertainty. This is because current models are primarily based on the stationarity hypothesis[7] which, in the field of climate change, is widely debated.

In addition, hydrological models still do not take into account certain variables (Fabre, 2012). For example, the influence of vegetation is not explicitly integrated in conceptual models (land cover). Similarly, human factors, such as abstractions and dams, are rarely taken into account, which limits the capacity to clearly distinguish between the effects of climate change and anthropogenic pressures.

**Figure 14**




*Cascading uncertainty when carrying out a study on climate change (according to Boé, 2007).*

7. Average climate values and their variability are considered constant. But the climate is obviously not stationary. It has evolved greatly since the beginning of the Earth and will continue to do so in the future.

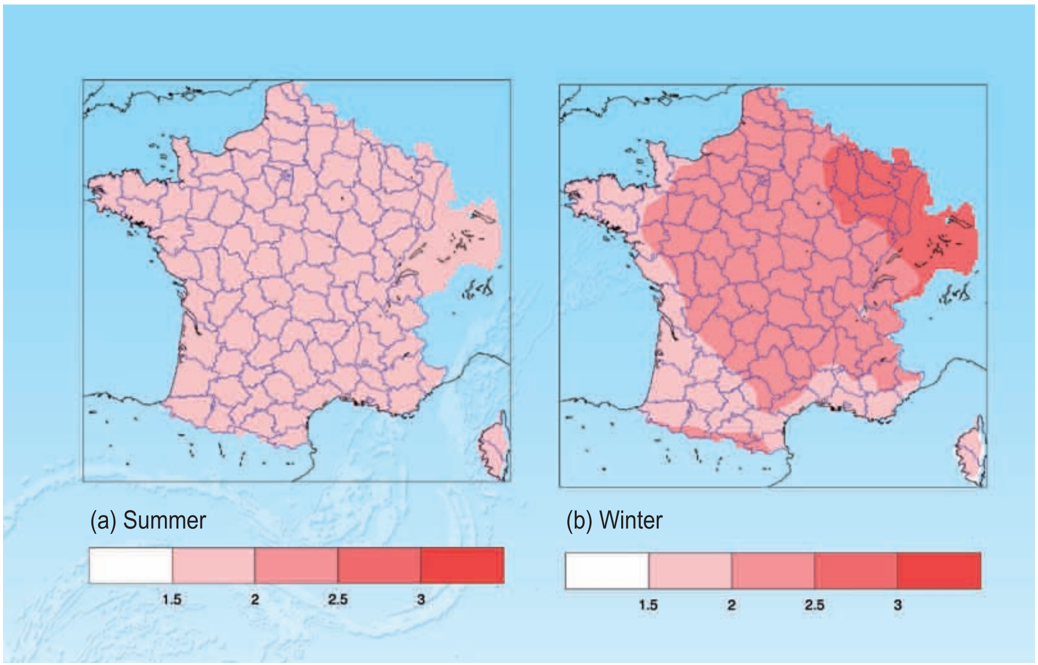
# The future climate and water resources in continental France

Over the past few years, the scientific community has worked intensively on the issues of climate change and its effects on society. The models described above made possible multi-disciplinary projects that quantified the expected impacts on water resources. This section presents the results for France concerning a certain number of climate and hydrological variables (all the results presented here are drawn from the studies based on CMIP3 / IPCC AR4).

## Projected impact on air temperatures

For France as a whole, all the scenarios project an increase in air temperatures ranging from 1.5 to 3°C by 2050. The results of simulations up to the year 2100 are less clear and project an increase of approximately 2 to 4.5°C compared to current temperatures (Déqué *et al.*, 2005) (see Figure 15). Extreme events such as heat waves in the summer should also be more frequent (Déqué, 2007).

**Figure 15**

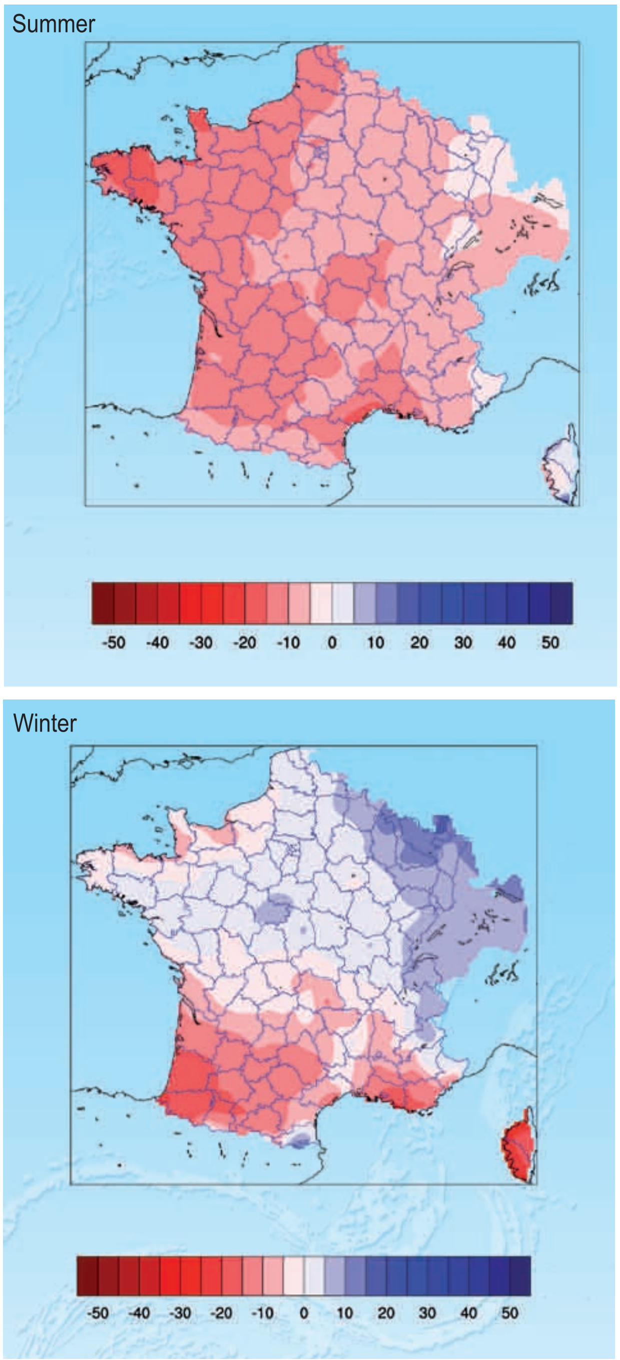



*Multi-model averages of temperature anomalies (in °C) during (a) the summer period (June, July, August) and (b) the winter period (December, January, February), for the years 2046 to 2065, compared to the 1961-1990 averaged value. Results drawn from 15 IPCC and 7 ARPEGE V4 simulations (Pagé and Terray, 2011).*

## Projected impact on precipitation

Regionalised projections based on scenario A1B used in 15 IPCC and 7 ARPEGE simulations (Météo-France model) comparing the periods 2046-2065 and 1961-1990 indicate that summer precipitations will decrease in virtually every part of the country (Boé, 2007; Pagé and Terray, 2011; see Figure 16). For the winter, the simulations project an increase, notably in the Centre region and the north-eastern section of the country, but a decrease in the south-western section (Boé, 2007). Any change would be limited in the spring (Drias; Météo-France data; CERFACS; IPSL, 2013). Finally, the simulations do not detect any clear trends for the fall (Drias; Météo-France data; CERFACS; IPSL, 2013).

**Figure 16**




*Multi-model averages of precipitation anomalies (in mm/year) during the summer period (June, July, August) and the winter period (December, January, February), for the years 2046 to 2065, compared to the 1961-1990 averaged value. Results drawn from 15 IPCC and 7 ARPEGE V4 simulations (Pagé and Terray, 2011).*

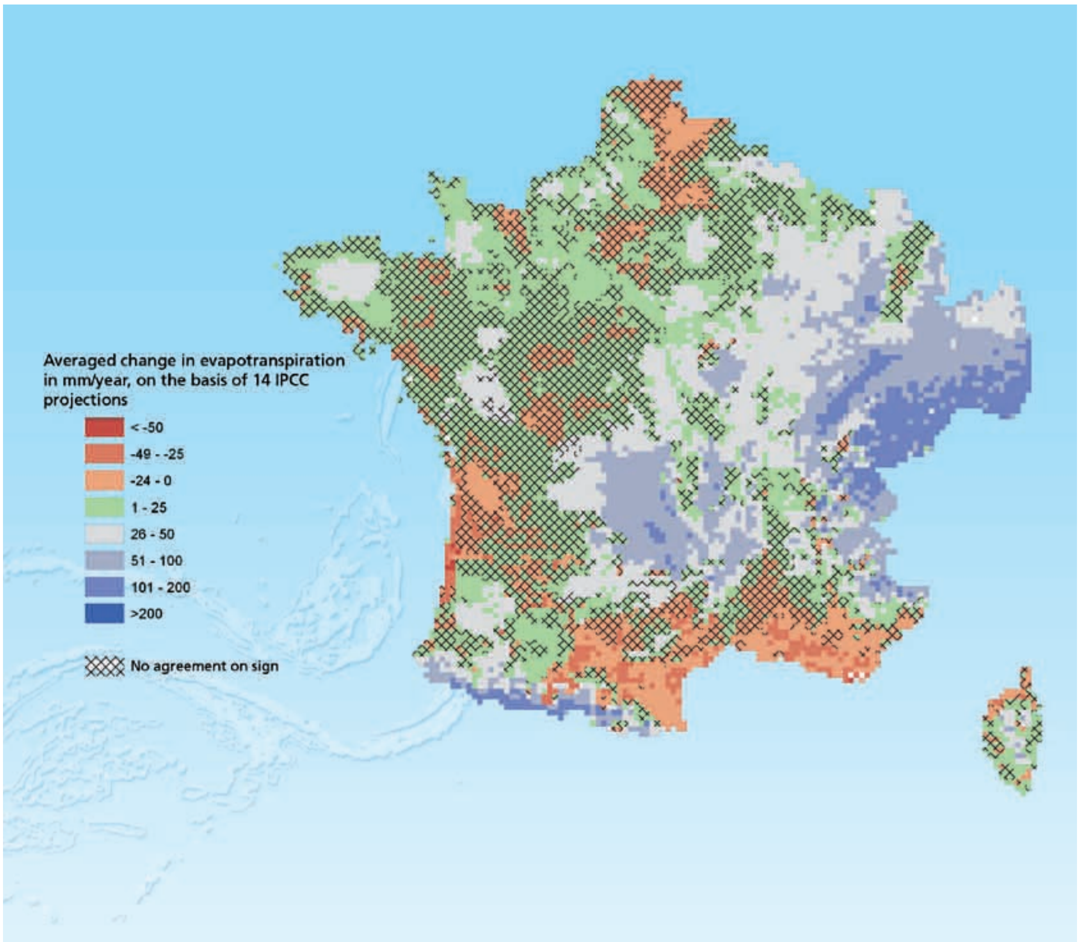
Concerning extreme events, the projections made for Europe using high-resolution global models indicate an increase in heavy rainfall during the winter and, conversely, an increase in the duration of dry periods during the summer (Déqué, 2007).

Finally, concerning snowfall, all the models focussing on the Alps and the Pyrenees predict a major reduction in snowfall at lower altitudes and a less significant reduction at higher altitudes (Beniston, 2005; Lopez-Moreno *et al.*, 2009).

## Projected impact on evapotranspiration

Boé (2010) ran a study on France specifically to quantify the possible variations in effective evapotranspiration. The simulations, using a physical model (SIM) and 14 disaggregated climate projections according to scenario A1B, signal a sharp reduction in evapotranspiration on the Mediterranean and Atlantic coasts, but an increase in the eastern section of the country and at higher altitudes (see Figure 17). Note that depending on the climate and hydrological models used, the projected changes in effective evapotranspiration are particularly heterogeneous (Habets *et al.*, 2013).

Figure 17

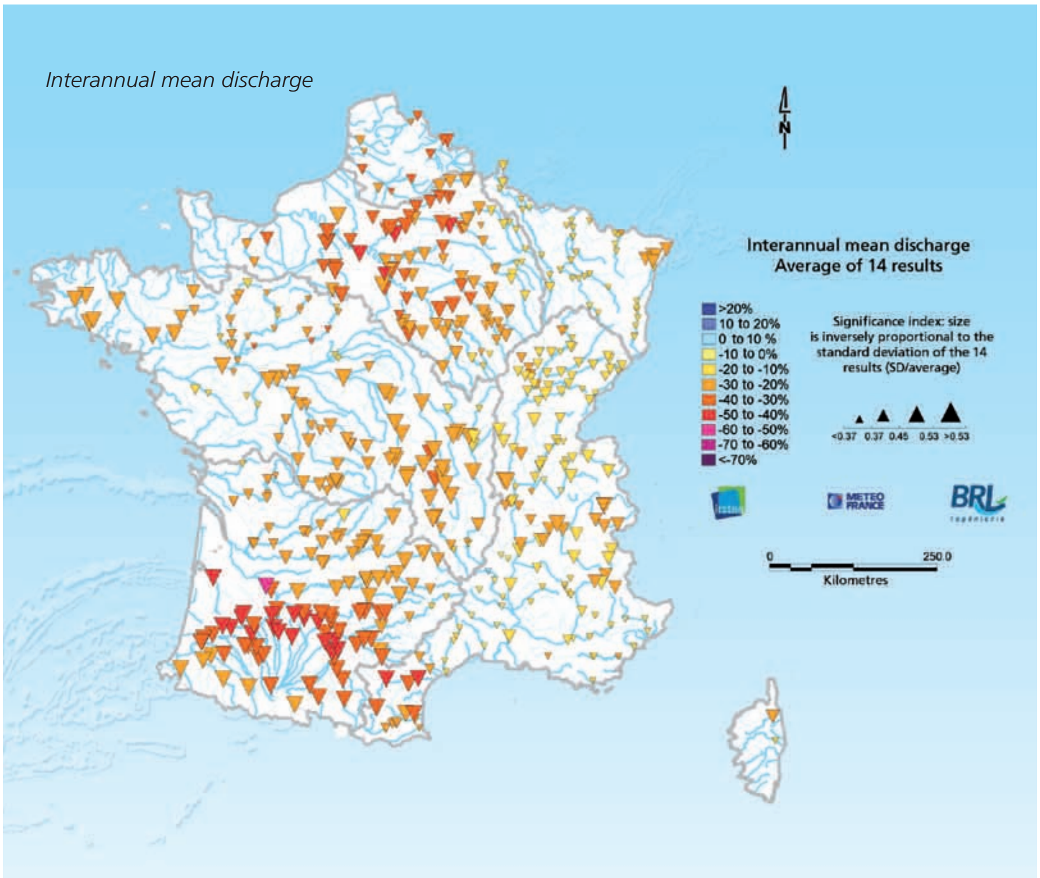



*Change in effective evapotranspiration in 2050 calculated by the SIM model, on the basis of 14 regionalised climate projections according to scenario A1B, in millimetres per year (Boé* et al.*, 2009). Cross-hatching indicates regions where there is significant uncertainty among the projections concerning the sign of change (plus or minus).*

## Projected impact on runoff and extreme situations

Climate change will have a strong impact on runoff and river discharges. The results of the Explore 2070 project, using seven climate projections (scenario A1B, for the period 2046-2065) and two hydrological models (GR4J and SIM), signal a probable drop in the interannual mean discharge throughout continental France, of approximately 10 to 40% in a majority of river basins (Chauveau *et al.*, 2013; see Figure 18). The foothills of the Pyrenees will be particularly affected with drops ranging from 10 to 60%. The main cause is a drop in the cumulative annual precipitation coupled with an increase in evaporative demand.

**Figure 18**

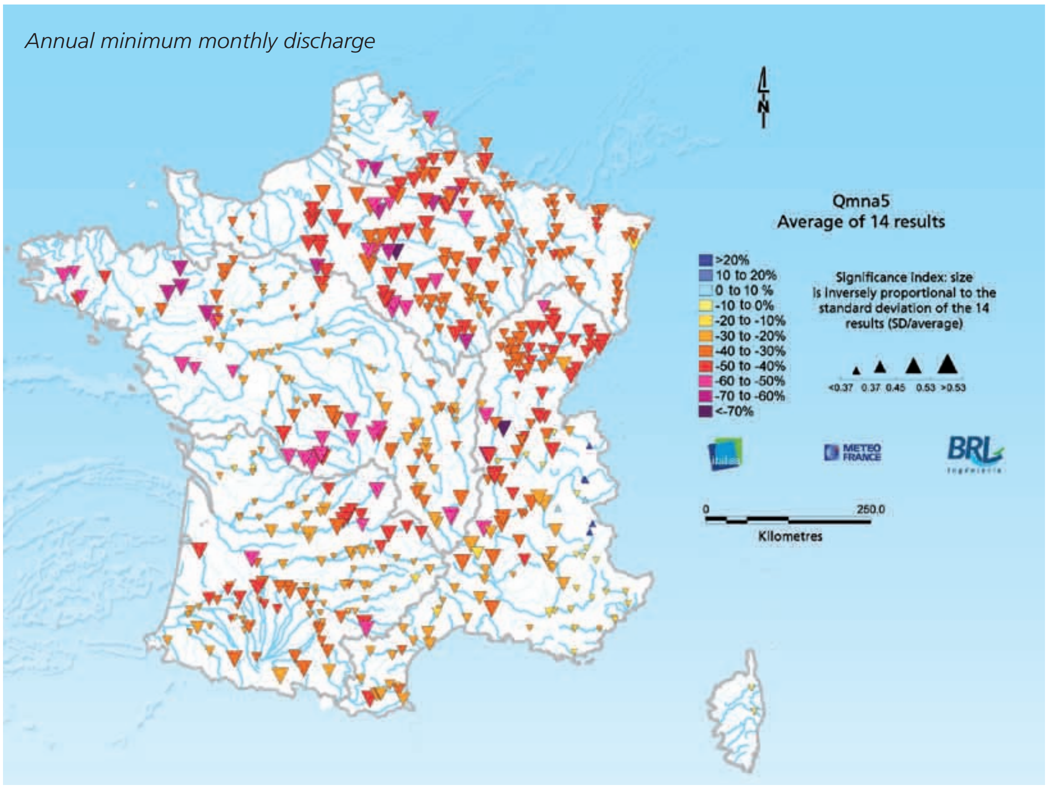



*Possible changes in the interannual mean discharge (%) in the period 2046-2065, compared to the 1961-1990 value (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013; Chauveau* et al.*, 2013). The results are the averaged outputs of two hydrological models (GR4J and SIM) that were supplied with the disaggregated outputs of seven climate models (a total of 14 simulations according to scenario A1B).*

Concerning low-flow discharges, a majority of the simulations agree that there will be a general drop even greater than that for the interannual mean discharge. The annual minimum monthly discharge with a five-year return period (QMNA5, see Box 1) could decrease by 5 to 65%, depending on the region (see Figure 19).

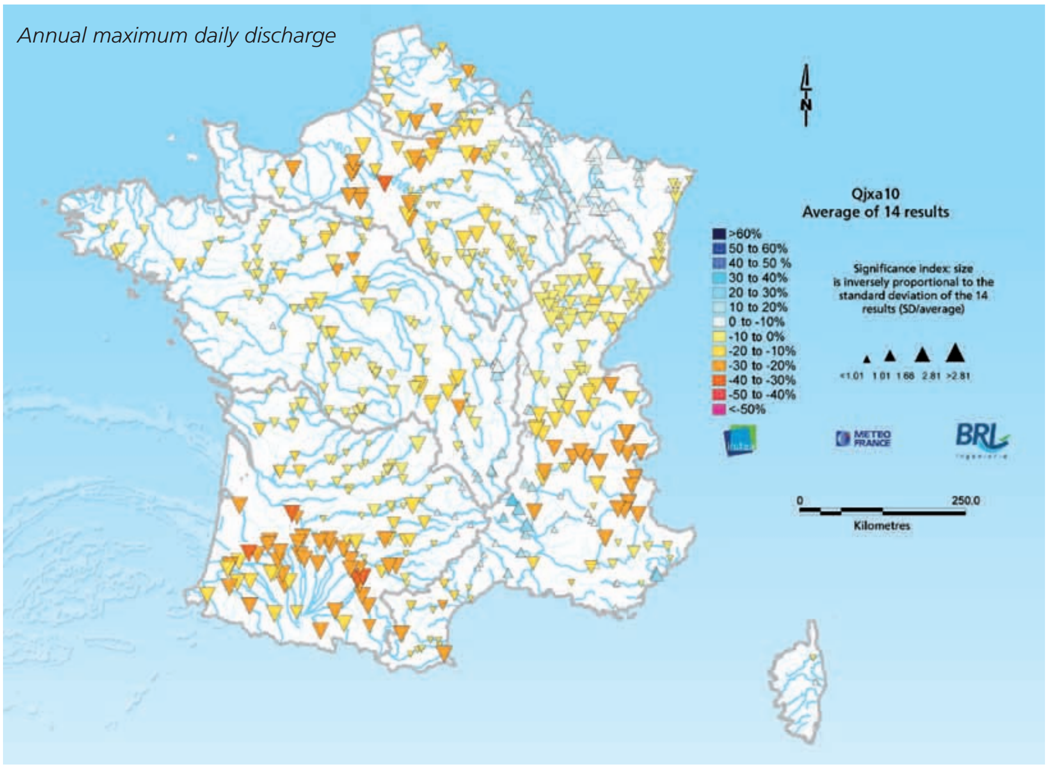
The discharges for the months of August and September in river basins with a pluvial oceanic regime could drop by 30 to 70% over large parts of the country. This reduction in discharges could be particularly severe in the Seine-Normandie basin, on the left bank of the Garonne River and in the northern half of the Rhône-Méditerranée basin. Concerning flood risks, the annual maximum daily discharge with a ten-year return period (QJXA10) could increase in the Cévennes and in the north-eastern section of the country (see Figure 20).

**Figure 19**




*Possible changes in the annual minimum monthly discharge with a five-year return period (QMNA5 in %) in the period 2046-2065, compared to the 1961-1990 value (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013; Chauveau* et al.*, 2013). The results are the averaged outputs of two hydrological models (GR4J and SIM) that were supplied with the disaggregated outputs of seven climate models (a total of 14 simulations according to scenario A1B).*

**Figure 20**




*Possible changes in the annual maximum daily discharge with a ten-year return period (QJXA10 in %) in the period 2046-2065, compared to the 1961-1990 value (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013; Chauveau* et al.*, 2013). The results are the averaged outputs of two hydrological models (GR4J and SIM) that were supplied with the disaggregated outputs of seven climate models (a total of 14 simulations according to scenario A1B).*

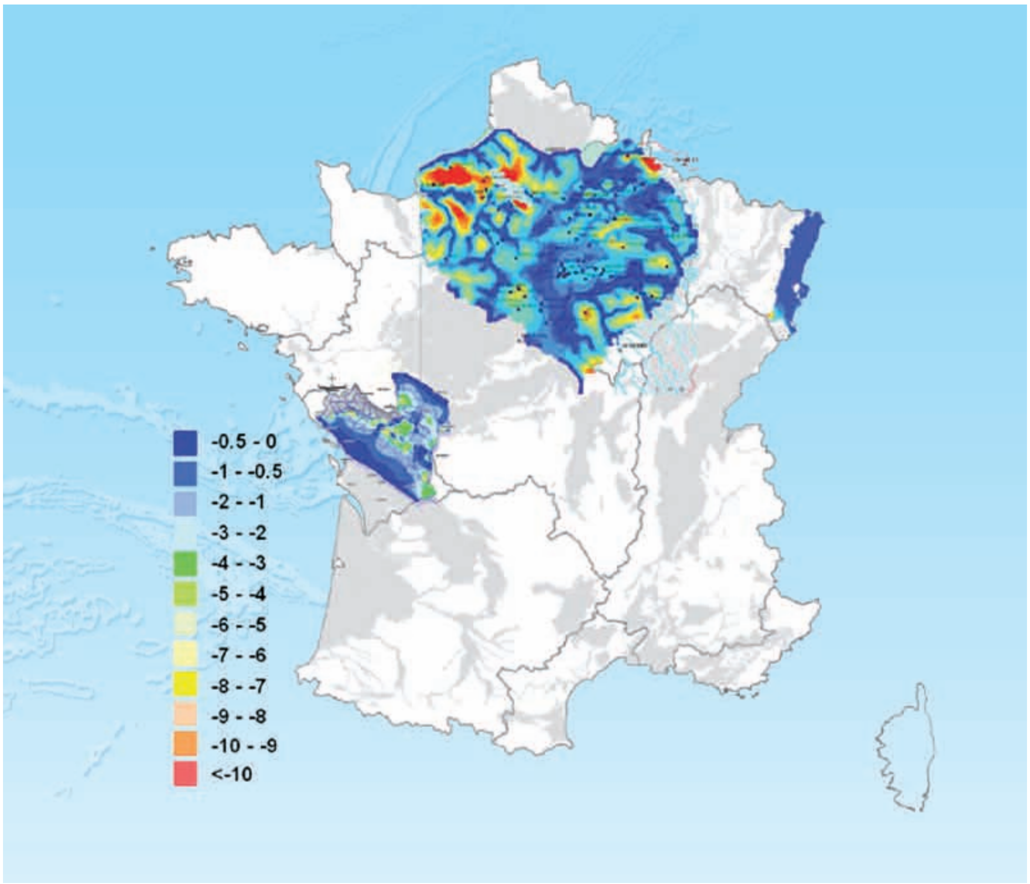
## Projected impact on groundwater

A number of studies project a major change in the recharge and the piezometric levels of large groundwater bodies. In France, a more or less general decrease in groundwater recharge of 10 to 25% is expected (Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013; Boé *et al.*, 2009). The south-western section of the country could be the most severely impacted with reductions of 30 to 50% (Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013; Boé *et al.*, 2009).

Concerning piezometric levels, the simulations all signal a drop in monthly mean levels due to the decrease in recharge. Spatially speaking, the results vary widely depending on where the piezometers are located, with slighter variations in valleys compared to plateaus situated farther from a river. Among the more optimistic projections, very slight drops of approximately 0.5 to 1.5 m are foreseen, e.g. throughout most of the Seine and Rhine River basins, and even local increases in some regions, e.g. Poitou, confined groundwater in the Aquitaine region (Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013; Habets *et al.*, 2013; see Figure 21). The more pessimistic projections suggest major reductions of up to ten metres on plateaus, e.g. the Caux and Beauce areas, and significant but more limited drops of 1 to 4 m in basement aquifers.

These severe drops may be explained primarily by a reduction in rainfall and a considerable increase in evapotranspiration, the latter due to the increase in temperatures insufficiently compensated by an increase in the humidity of the air.

**Figure 21**




*Change in piezometric levels (in m) in three river basins for the period 2046-2065, if there is no change in the pumped volumes. ARPEGE projection, scenario A1B, Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013.*

## Projected impact on water temperatures

The trend in water temperatures will be similar. Modelling work for the Explore 2070 project estimated on the basis of 31 monitoring points throughout the country that the average annual increase in water temperatures would be 1.6°C (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013). This increase could, however, vary from a minimum of 1.1°C to a maximum of 2.2°C. These average increases mask major differences between monitoring points, with median increases in water temperatures between 0.6 and 2.2°C, and between 2 and 2.5°C for air temperatures.

## Interactions between climate change and anthropogenic pressures

The data presented above highlights the severity of the changes expected in the decades to come. The impact of these changes on the water cycle could be heightened or attenuated by human activities. For example, channelling or impoundment of rivers could worsen the floods that will probably be more frequent in the decades to come. Changes in land use, notably agricultural practices, could increase the risks of erosion and excess suspended matter at the heads of river basins, given the probable increases in extreme events (heavy rains). Urban sprawl could limit infiltration surfaces, thereby worsening peak flood levels and reducing groundwater recharge. Increased irrigation, the development of crops requiring large amounts of water during low-flow periods (fuel crops, corn, poplar trees, etc.) or population growth in certain regions of France could all contribute to increased abstractions, with as a result reductions in average discharges in rivers and in groundwater piezometric levels, and greater risks of severe low-flow discharges during the summer.

Finally, degraded water quality in conjunction with an increase in the temperature could cause modifications in the fate and the distribution of chemical substances between the various environmental compartments, which would in turn modify the conditions for aquatic organisms in terms of exposure, bioavailability and consequently the toxicity of the substances (Stahl *et al.*, 2013 ; see Box 2).

Box 2

### Impact of climate change on water quality

A great diversity of pollutants exist in water and aquatic environments. They come from many sources (industry, agriculture, towns) are are present as mixtures at low concentrations, but can provoke malfunctions in aquatic ecosystems (Schwarzenbach *et al.*, 2006; see Table 1). In the absence of drastic measures to reduce GHG emissions, it must be presumed that climate change will affect water quality in the decades to come. The effects may manifest themselves in different ways (EEA, 2011).

The increased severity and frequency of dry periods will result in major modifications to the hydrological regimes of rivers, which will lead in turn to reduced capacity to dilute contaminants. These effects may, however, be attenuated by increased residence times for contaminants in water, which would contribute to their degradation. In regions where precipitation will increase, the quantity of pollutants released to the environment via urban wastewater following rainfalls will be increased, as will be the mobilisation of "historic" contaminants stored in river sediments during flooding (EEA, 2011). The greater frequency of extreme rainfall events should also augment the transfer of phytopharmaceutical products and veterinary pharmaceuticals to surface waters (Bloomfield *et al.*, 2006; Boxall *et al.*, 2009).

A number of environmental factors such as UV radiation, whose penetration capacity in water depends largely on the pH value and the transparency of the water, two parameters that can be affected by climate change, could even modify the toxicity of certain contaminants by increasing their reactivity through a phenomenon called photo-activation.

Finally, the probable rise of pests, disease and weeds would contribute to worsening the problem due to the more extensive and frequent use of pesticides and veterinary products. However, this increased use could be counter-balanced by augmented volatilisation of certain plant-protection products and accelerated degradation of pesticide residues in soil and surface water due to higher temperatures (Bloomfield *et al.*, 2006). Over the long term, changes in land use and cover caused by anthropogenic and climate factors will probably have a greater impact on pesticide flows and their transfer to aquatic environments than the direct effects of climate change on the processes controlling the transfer and fate of these pollutants.

**Tableau 1** *A few examples of ubiquitous aquatic micropollutants (drawn from Schwarzenbach* et al.*, 2006).*

| Origin / use | Class | Substance | Related problems |
|---|---|---|---|
| Industrial chemicals | Solvents | Carbon tetrachloride | Contamination of drinking water |
| | Feedstock | Methyl tert-butyl ether | |
| | Petrochemical products | BTEX (benzene, toluene, xylene) | |
| Industrial products | Additives | Phtalates | |
| | Lubricants | PCB | Bioamplification in food chains, long-distance cross-border atmospheric pollution |
| | Flame retardants | Polybrominated diphenyl ethers | |
| Consumer products | Detergents | Nonylphenol ethoxylates | Endocrine disruption by the degraded product (nonylphenol) |
| | Pharmaceutical products | Antibiotics | Bacterial resistance to antibiotics |
| | Hormones | Ethinyl-estradiol | Feminisation of fish |
| | Personal hygiene products | UV filters | Multiple effects (only partially known) |
| Biocides | Pesticides | DDT | Toxic effects and persistent metabolites |
| | | Atrazine | Effects on primary producers |
| | Biocides for non-agricultural use | Tributyltin | Endocrine disruption |
| | | Triclosan | Effects on species not initially targeted, persistent degraded products |
| Geogenic and natural substances | Trace metals | Pb, Cd, Hg | Risks for human health Impacted quality of drinking water |
| | Inorganic substances | As, Se, U, fluoride | |
| | Taste and odour compounds | 2-methylisoborneol, geosmin | |
| | Cyanotoxins | Microcystin | |
| | Human hormones | Estradiol | Feminisation of fish |
| Disinfection / oxidation | Disinfection by-products | Trihalomethane, haloacetic acids, bromates | Impacted quality of drinking water, human-health problems |
| By-products | Metabolites, by-products of chemical substances mentioned above | Metabolites of perfluorinated compounds (PFAS) | Bioaccumulation in spite of low hydrophobicity |
| | | Metabolites of herbicide chloroacetanilides | Impacted quality of drinking water |

# Conclusion and outlook

As indicated by the historical data, the global climate has always fluctuated over time under the direct and indirect influence of various phenomena (orbital forcing, change in global albedo, disturbances in atmospheric currents, feedback loops). However, human activities, notably the release of greenhouse gasses (GHG), have clearly caused changes in the climate since the end of the 1800s, resulting in increases in air temperatures and the average sea level, as well as a reduction in snow-covered surfaces and ice caps.

In continental France, analysis of long data series has produced estimates of average increases of approximately 1°C in air temperature and 1.6°C in water temperature over the last century. Loss of snow cover at medium altitudes is a further factor confirming that climate change is effectively under way. Other parameters, such as precipitation, evapotranspiration and surfacewater/groundwater hydrology, are also affected but the trends are not as clear given the difficulties in distinguishing between the effects of climate change and those of direct human activities, and because in some cases data series are not long enough.

To assess, over the coming decades, the possible changes in the climate and in the various components of the water cycle (precipitation, evapotranspiration, surface water, groundwater), climate models coupled with hydrological models have been formulated and tested with the various GHG emissions scenarios.

For continental France over the coming decades, all climate projections (whatever the greenhouse-gas (GHG) emissions scenario) foresee warming between 1.5 and 3°C. Longer term, the projections diverge widely depending on the scenario and are much less reliable. They indicate warming from 2°C to more than 4.5°C by 2100.

Concerning water resources, the simulations for precipitation, evapotranspiration and discharges are more uncertain and differ depending on the model. However, evapotranspiration is expected to increase in eastern France. Monthly mean discharges in rivers should decrease and low-flow levels should worsen over large parts of the country, particularly in the southern half. Finally, groundwater recharging may drop along with piezometric levels. Human activities will most likely reinforce the effects of climate change on water resources, notably due to increases in abstractions for agriculture.

Consequently, even though there are numerous uncertainties concerning these projections, the potential impact of climate change on water resources in France should be considerable with a clear trend toward a reduction in those resources. Aquatic environments and fish in particular will be heavily impacted in the above scenarios. This latter point will be the topic of the following chapters.

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2

# Changes in fish communities in a context of climate change

# Introduction

Lakes, rivers and marshes cover only 0.01% of the surface of the planet. But in spite of their small surface area, they are home to a vast diversity of species (Mc Allister, 1997). Approximately 9% of all animal species identified to date (approximately 1.4 million) live in continental aquatic environments (Balian *et al.*, 2008). Some 40% of the 30 000 fish species worldwide and over 100 000 invertebrate species live in fresh water[7]. However, that richness notwithstanding, freshwater environments have shown relative and absolute extinction rates much higher than those for marine and terrestrial environments (Dudgeon *et al.*, 2006; Heino *et al.*, 2009). In continental France, of the 69 species[8] assessed, four species of freshwater fish have disappeared and four others are critically endangered (IUCN France red list; MNHN; SFI; Onema, 2010). Worldwide, over a dozen species would appear to have become extinct (see *http://creo.amnh.org*). This decline may be explained primarily by overfishing, water pollution, modifications to hydrological regimes, the destruction, fragmentation and uniformity of habitats and the increased numbers of invasive species (Dudgeon *et al.*, 2006).

Climate change will most likely worsen this phenomenon by increasing water temperatures, reducing precipitation and contributing indirectly to the emergence of greater conflict concerning the use of water resources (Xenopoulos *et al.*, 2005). Empirical observations over the 1900s showed that climate change has already affected many species and communities of species in different parts of the world (Hughes, 2000; McCarty, 2001; Walther *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003).

It has therefore become essential to understand the precise effects of climate change on fish communities in order to implement adaptation measures that are consistent with the measures designed to mitigate the other anthropogenic pressures weighing on the environment (Heino *et al.*, 2009).

For a number of decades, numerous projects to determine the current effects of climate change on the environment have been undertaken. Various approaches have been proposed, including experiments under (semi-)controlled conditions and analysis of past and present fish-monitoring data (see Box 3). The results of this work have enhanced understanding of the current impact of climate change on different spatial and temporal scales.

The purpose of this chapter is to present the most recent results on observed changes in freshwater fish, ranging from individual fish to the entire community, in response to climate change.

*7. Data presented during the Eawag annual information day in June 2010 (http://www.eawag.ch/index_EN).*
*8. The total number of freshwater fish species inventoried in continental France is 95. The characterisation report produced by IUCN dealt with 69 species among the 95 (source: IUCN France; MNHN; SFI; Onema, 2010).*

## What data is required to study the long-term evolution of aquatic communities?

Decades-long data series on the targeted species and, ideally, the environmental conditions (temperatures, physical-chemical characteristics, hydrology, etc.) are required to study the long-term evolution of aquatic communities. In France, data have been gathered at the monitoring points of the hydrobiological fish network (RHP) since 1995 and those established at nuclear power plants (CNPE) since 1977. Note that many of the RHP monitoring points were transferred to the new WFD monitoring networks in 2007.

### The hydrobiological fish network (RHP)

Launched nationwide in 1995, the RHP network was initially made up of approximately 650 monitoring sites where annual electrofishing campaigns were carried out. This project was part of two water-quality monitoring programmes, namely the national basin network (RNB) and the additional basin network (RCB). In 2007, RNB and RCB were replaced by the surveillance-monitoring network (RCS) and the operational-monitoring network (RCO) respectively.

Within these two new networks, the number of sites where fish monitoring takes place is 1 506 out of the total of 1 569 monitoring points in the RCS (see Figure 22). Work is carried out at each monitoring point once every two years and the resulting data serve to assess the status of fish communities and to detect trends on the river-basin level. However, the shift in the objectives set for the new RCS network (checks on good status using bioassessment tools) led to changes in the sampling strategy (methods, tools used, etc.) that has not simplified the analysis of the data series.

### Monitoring at nuclear power plants

EDF, the French electricity company, has a total of 19 nuclear power plants in France, including 14 on major rivers (Loire-Vienne, Rhône, Seine, Garonne, Rhine-Meuse-Moselle), four on sea coasts and one on an estuary (Gironde). Since its commissioning, each nuclear power plant has been subjected to environmental (including hydrobiological) monitoring by a scientific team. A public report is drafted annually for each plant and delivered to the State services. The purpose of the physical-chemical and biological programme is to monitor the concentration in water of the chemical substances released by the plant to the environment, to observe the natural evolution of the surrounding environment and to detect any abnormal trends caused by the plant. These monitoring programmes are an outstanding source of data for the assessment of fish communities.

Figure 22


*Position of surface-water qualitative monitoring points (RCS) in the river-basin districts.*

# General trends in observed impacts of climate change

In going through its life cycle, each species has a number of more or less strict requirements in terms of water quality (e.g. oxygen content) and habitat (e.g. flow velocity in rivers). These parameters are conditioned by two key factors:

- temperature, which influences the productivity of the ecosystem;
- hydrology, which influences sediment transport and consequently the habitat.

The interaction between these two factors has an influence on the level of dissolved oxygen.

Given that these two factors shift from the source of a river to the estuary, it is possible to establish guilds[9] of species that have their successive (or cumulative) habitats along the longitudinal gradient. Huet (1949) proposed a classification system for fish species based on the width and slope of a river, factors that are correlated with the river morphology, hydrology and water temperature.

Generally speaking (see Figure 23), it may be said that:

- the cold-water rheophilic[10] and stenothermal[11] species are found in the upstream sections of rivers (trout zone). These species include brown trout (*Salmo trutta*), bullheads (*Cottus* spp.), brook lamprey (*Lampetra planeri*) and minnows (*Phoxinus* spp.);
- the rheophilic cyprinids, e.g. barbel (*Barbus barbus*), daces (*Leuciscus* spp.), schneider (*Alburnoides bipunctatus*), gudgeons (*Gobio* spp.), chub (*Squalius cephalus*) and nase (*Chondrostoma nasus*), are found in the intermediate sections of rivers (grayling and barbel zones);
- finally, the limnophilic[12] and thermophilic[13] species are generally found in downstream sections with slight slopes (bream zone), e.g. bitterling (*Rhodeus amarus*), white bream (*Blicca bjoerkna*), rudd (*Scardinius erythrophthalmus*), bleak (*Alburnus alburnus*), roach (*Rutilus rutilus*), pikeperch (*Sander lucioperca*), perch (*Perca fluviatilis*), common carp (*Cyprinus carpio*).

Given that the life cycles of fish and their distribution are determined primarily by the temperature and hydrological regime, global warming is potentially a major cause of change in fish populations and communities. Whether gradual or sudden, effects are produced on many levels, for example by modifying certain processes such as growth and reproduction, or by modifying the phenology[14] of populations and consequently the relations within food webs. Climate change can also induce changes in the ranges of species and consequently in the structure of communities (see Figure 24). In the following pages, examples illustrating the diversity and impact of these effects will be presented.

*9. Group of taxonomically similar species (fish in this case) that have comparable requirements in terms of one or more ecological factors (temperature, hydrology, etc.).*
*10. Species that spend their entire lives in running waters.*
*11. Species capable of tolerating only very slight variations in temperature above or below mean values.*
*12. Species that live in calm sections of rivers or in stagnant waters (e.g. marshes).*
*13. Species that prefer warm waters.*

**Figure 23**

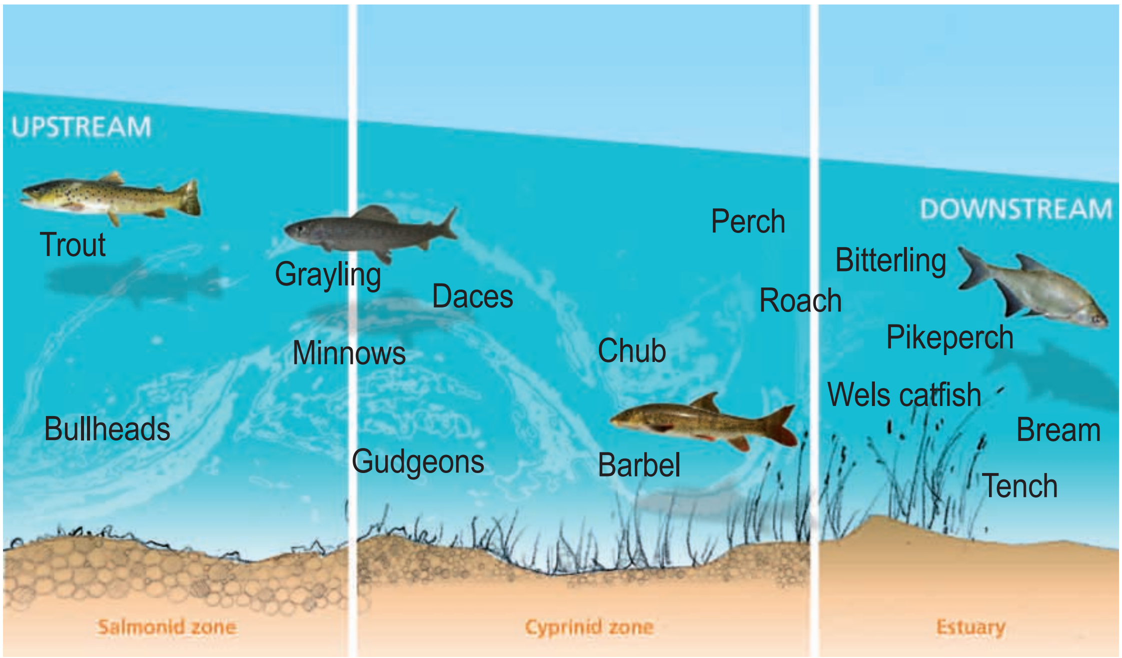


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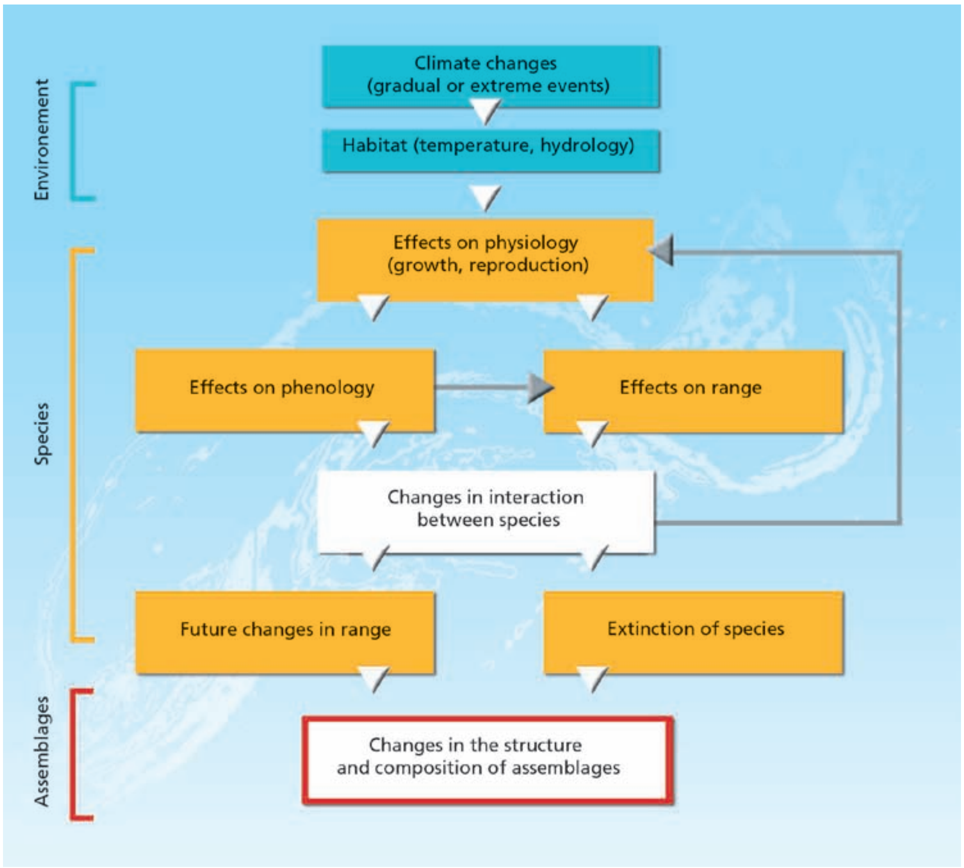
*Diagram showing the changes in fish communities along the longitudinal (upstream-downstream) gradient.*

**Figure 24**




*Potential consequences of climate change on assemblages of fish species (diagrams modified, originally from Hughes, 2000 and Buisson, 2009).*

*14. Phenology is the study of the timing of periodic events (generally annual) among life forms, determined by seasonal variations in the climate. In botany, periodic events are, among others, flowering, sprouting of leaves, fruition. In the animal kingdom, examples are the arrival of migratory birds, the return of salmon to spawning grounds, etc.*

## Potential and observed impacts of climate change on the physiology of organisms

All vital functions, such as metabolism, ingestion and digestion rates, swimming and reproduction, depend on the environmental conditions and notably the water temperature (Piffady, 2010; Souchon and Tissot, 2012; see Figure 25). For example, sexual maturation and gamete formation are generally triggered by a change in temperature at which the future reproducers begin to mature. The trigger may be a rise or fall in temperature, a threshold or phenomena linked to the day-night cycle. The same is true for each step in the reproductive process including migration, spawning, egg development (see for example Migaud *et al.*, 2002).

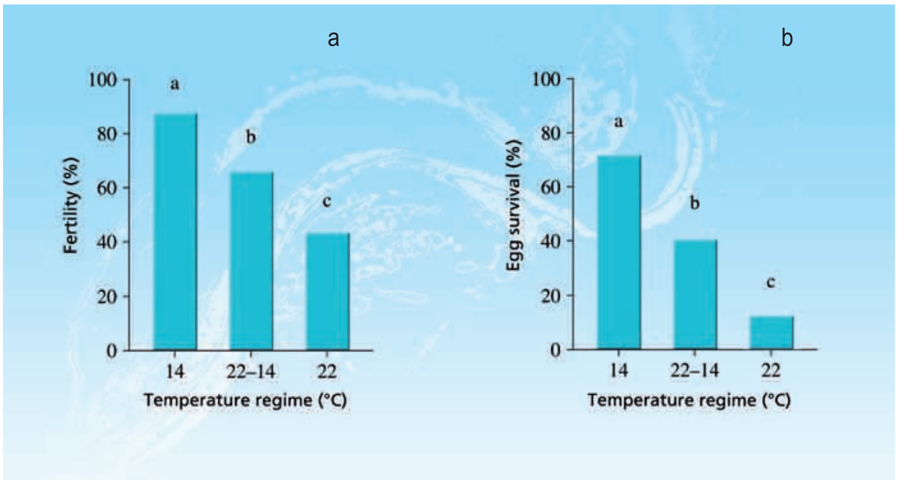
**Figure 25**


*(a) Optimum temperature range (blue) and resistance zone (orange) of juvenile fish, (b) of adults, (c) optimum temperature range for reproduction (Souchon and Tissot, 2012).*

**ABB**
Common bream
(*Abramis brama*)
**ALA**
Bleak
(*Alburnus alburnus*)
**ALB**
Schneider
(*Alburnoides bipunctatus*)
**BAR**
Barbel
(*Barbus barbus*)
**BLB**
White bream
(*Blicca bjoerkna*)
**CHN**
Nase
(*Chondrostoma nasus*)
**ESL**
Pike
(*Esox lucius*)
**GOG**
Gudgeon
(*Gobio gobio*)
**GYC**
Eurasian ruffe
(*Gymnocephalus cernuus*)
**LEG**
Pumpkinseed
(*Lepomis gibbosus*)
**LEL**
Dace
(*Leuciscus leuciscus*)
**PAT**
South-west European nase
(*Parachondrostoma toxostoma*)
**PEF**
Perch
(*Perca fluviatilis*)
**RHA**
Bitterling
(*Rhodeus amarus*)
**RUR**
Roach
(*Rutilus rutilus*)
**SAL**
Pikeperch
(*Sander lucioperca*)
**SIG**
Wels catfish
(*Silurus glanis*)
**SQC**
Chub
(*Squalius cephalus*)
**TES**
Blageon
(*Telestes souffia*)

Experiments under controlled conditions have attempted to assess the impact of the temperature regime on the physiology of certain fish, notably cyrophilic[15] and stenothermal species. For example, it has been shown that an increase in average temperature from 14 to 22°C during vitellogenesis[16] in Atlantic salmon (*Salmo salar*) significantly reduced the fertility and survival rate of eggs (King *et al.*, 2007, see Figure 26).

**Figure 26**




*(a) Mean fertility rate and (b) mean survival rate of eggs under different temperature regimes. Regime 1) constant 14°C, regime 2) first 22°C for six weeks, then 14°C for six weeks, regime 3) constant 22°C. Different letters (a, b, c) above the bars indicate significant differences in the results (diagrams modified, originally from King* et al.*, 2007).*

Comparable results have been noted for rainbow trout (*Oncorhynchus mykiss*), coho salmon (*Oncorhynchus kisutch*), European bullhead (*Cottus gobio*) and for roach (*Rutilus rutilus*) (Flett *et al.*, 1996; Pankhurst *et al.*, 1996; Brodersen *et al.*, 2011; Dorts *et al.*, 2012), which highlights the great sensitivity of certain species to modifications in the temperature regime (threshold temperatures, amplitude, duration, repetition over time) and the importance of environmental factors such as the availability of food (Brodersen *et al.*, 2011). It should also be noted that modifications in the temperature regime can affect the capacity of species to withstand exposure to toxic substances (see Box 6, page 55).

These results, obtained under controlled conditions, have also been observed *in natura*. For example, just downstream of the Tihange nuclear power plant in Belgium, the increase in water temperature would seem to accelerate the maturation and development of ovaries in roach (Mattheeuws *et al.*, 1981). Similar results have been noted in the European bullhead. Higher temperatures in certain parts of the Bez river basin in France would seem to increase the growth of juveniles, accelerate maturation and reproductive efforts, and reduce life spans (Abdoli *et al.*, 2005, 2007). A consequence of the acceleration during maturation, a stage during which growth slows, might be a reduction in the final size of the fish (Abdoli *et al.*, 2005, 2007). This phenomenon has been observed on a much larger scale in both marine and freshwater environments for other fish species and is thought to be linked to climate change (Daufresne *et al.*, 2009; Jeppesen *et al.*, 2010; Sheridan *et al.*, 2011; Cheung *et al.*, 2012). Over the past 20 years, the average size of entire communities of fish would seem to have decreased. One of the mechanisms proposed to explain this phenomenon is a classic application of Bergmann's rule, which stipulates that warm-blooded animals tend to be smaller in warmer environments. However, given that fish are ectothermic, another underlying mechanism has been suggested to explain this phenomenon. According to Edeline *et al.* (2013), accumulated energy, i.e. the difference between the energy ingested and that expended to maintain life, increases faster in small animals than in larger animals when temperatures rise. This mechanism would make them more competitive in using resources than large animals, thus resulting over the long term in a reduction in sizes and a reorganisation of ecosystems (see Figure 27).

*15. Species that prefer cold environments.*
*16. The process by which the vitellus develops. It contains the endogenous and exogenous reserves of the egg.*

No conclusions may yet be drawn, but the increase in water temperatures caused by climate change would already seem to have affected the growth and perhaps the reproduction of certain organisms. The experiments and analyses presented below provide a rough idea of the magnitude of the changes that could occur in response to a more significant increase in temperatures.

Figure 27

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*Climate change could prove favourable for smaller species and lead to a reduction in the size of animals from larger species.*

## Effects on phenology

Seasonal variations in the climate determine the timing of an array of periodic events in fish, such as reproduction and migration. Phenology, the study of when seasonal activities occur, reveals the temporal responses of fish to environmental changes.

Over the past decades, phenological changes have been observed in many parts of the world and in a wide variety of taxonomic groups, including butterflies, amphibians, birds, mammals and many ligneous and herbaceous plants (Parmesan and Yohe, 2003; Root *et al.*, 2003).

There are fewer studies on fish due to the lesser number of data series spanning long time frames (see Box 3). However, the work by Wedekind *et al.* (2010) revealed that over a 62-year period, the spawning period of the grayling (*Thymallus thymallus*) occurred three weeks earlier in response to the increase in water temperature. Schneider *et al.* (2010) noted a similar phenomenon in the Walleye (*Sander vitreus*) over a period of 69 years. Gillet *et al.* (2006) observed that gonade development in the roach would seem to have accelerated due to the increase in average temperatures in Lake Geneva (over a 7-year monitoring period). Similar results were found at the Tihange nuclear power plant in Belgium where the increase in water temperature downstream would seem to accelerate the reproduction cycle (spawning three weeks earlier) in roach (Mattheeuws *et al.*, 1981).

Concerning diadromous salmonids and even though a link with climate change has not been established, a shortening of the biological cycle of Atlantic salmon has been observed in rivers in the Bretagne and Basse-Normandie regions (30-year monitoring period) and in the U.K. (60-year monitoring period, leading to a more rapid renewal rate of populations (Baglinière *et al.*, 2004; Aprahamian *et al.*, 2008). A 30-year monitoring programme of diadromous salmonids migrating up the Bresle River (Somme and Seine-Maritime departments) has shown that migration of sea trout now occurs primarily in the summer to the detriment of the fall migratory wave. Migration of salmon now occurs almost 45 days later than was previously the case, in mid September

(Euzenat, Fournel, Fagard and Delmotte, data not published). Similar results have been registered for the Atlantic salmon (see Figure 28) in the Nivelle River (Basque country), the Scorff (Bretagne region) and the Oir, a tributary of the Sélune River (Basse-Normandie region) (Bal, 2011).

**Figure 28**

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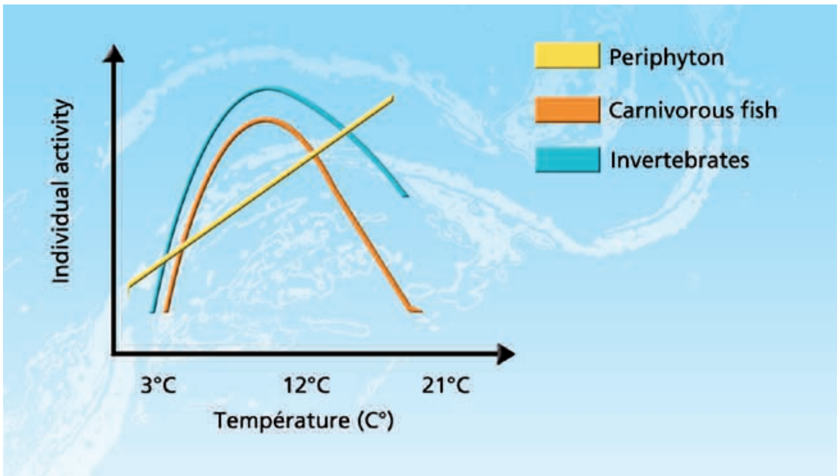
*The reproductive period of the grayling may occur earlier in the year due to higher water temperatures.*

Changes in phenology due to climate forcing may result in a loss of trophic synchronisation between species and consequently a restructuring of food webs (Beebee, 1995; Martin, 2007; Saino *et al.*, 2009; Helland *et al.*, 2009; Shutter *et al.*, 2012). For example, the increase in spring temperatures since the beginning of the 1960s provoked a temporal shift between the algal bloom of diatoms in a temperate North-American lake and the Daphnia populations that consume them (Winder and Schindler, 2004). Various studies have also shown the importance of:

- temperature in the predator-prey relations between the Dolly-Varden trout (*Salvelinus malma*), *Glossosoma* caddisfly larvae and the periphyton (Kishi *et al.*, 2005; see Figure 29);
- the period of abundant snow (frozen lake) in the interaction between brown trout and Arctic charr (*Salvelinus alpinus*) (Helland *et al.*, 2009).

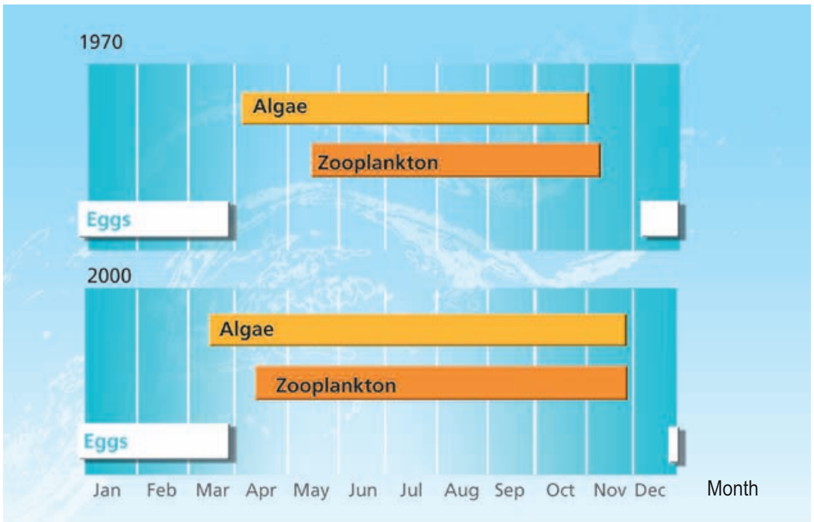
**Figure 29**




*Interaction between temperature and predation, according to a lab experiment by Kishi* et al. *(2005). In the optimum thermal zone for the fish (12°C), the top-down control over the invertebrates encourages periphyton productivity. At low temperature (3°C), no effects are observed. At 21°C, periphyton productivity is controlled primarily by invertebrate activity, which is still fairly high compared to the carnivorous fish.*

Finally, in Lake Geneva, the earlier development of phyto- and zooplankton in response to the increase in water temperature is thought to have increased the numbers and accelerated the development of whitefish larvae (*Coregonus lavaretus*), a species consuming plankton (*Gerdeaux*, 2004; see Figure 30).

Figure 30




*Improved synchronisation between whitefish (*Coregonus lavaretus*) populations and the productivity of phyto- and zooplankton in Lake Geneva (www.cipel.org).*

In light of the above data and in spite of the relatively limited duration of the data series, it would seem that the phenology of some fish species has already been modified in step with the climate change currently under way, with as a result in certain lakes a modification in the relations between predators and preys.

## Changes in species distribution

Species inhabit zones where the environmental conditions are favourable to their biological cycle. When climate change occurs, they can:

- either adapt their physiological functions and in effect their life-history traits (individual adaptation or selection on the population level);
- or migrate, thus modifying their distribution in order to survive the climate change, on the condition that the dispersal capabilities of the species and the available resources are sufficient to enable such movements (Walther *et al.*, 2002).

A very large number of studies has shown that changes in distribution toward higher latitudes and/or altitudes have taken place over the past decades in response to rapid warming of the climate (Parmesan and Yohe, 2003; Chen *et al.*, 2011). A large number of taxonomic groups and particularly fish have made such changes in their ranges. A meta-analysis (review of 77 articles published between 1980 and 2011) attempted to assess the amplitude and direction of the changes observed over the past years (Comte *et al.*, 2013). Though most of the studies focussed primarily on a small number of families (*Salmonidae*, *Cyprinidae*, *Centrarchidae* and *Percidae*), the overall results are consistent and apply to both contraction and extension of ranges. For each of the families studied and depending on the species and its geographic location, either an increase or decrease in favourable habitat ranges was observed. However, it would seem that the species located upstream (trout zone, barbel zone) are those that more often suffer a reduction in their habitat range. Conversely, the limnophilic and thermophilic species (bream zone) would tend to benefit from an extension of their habitat range.

Figure 31

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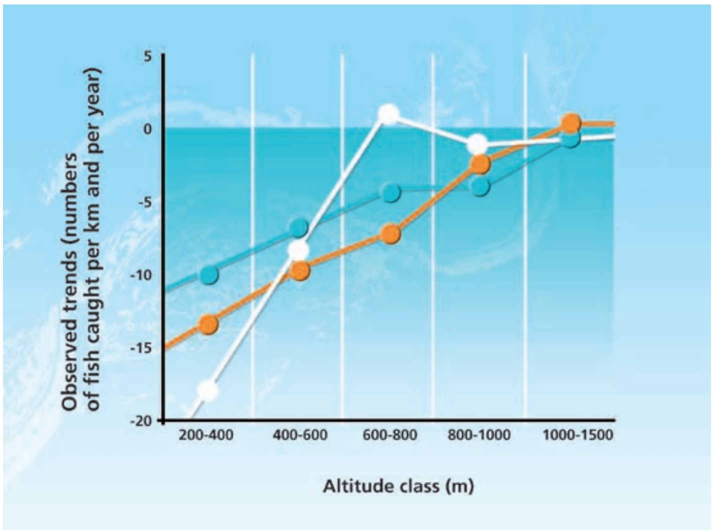
*Trout have been confronted with a considerable reduction in favourable habitats since the 1980s.*

These results have been confirmed for France as a whole. Comte and Grenouillet (2013) compared the modelled spatial distribution in the French hydrographic network between an "old" period (1980-1992) and a more "recent" period (2003-2008). Their results revealed that most species moved to higher altitudes (13.7 m per decade on average) and further upstream (600 m per decade on average). In a manner consistent with the changes in annual isotherms, fish species have moved along altitudinal gradients and extended their upper limit, while significant reductions in the lower limits of habitat ranges along the upstream-downstream gradient have also been observed, notably for species inhabiting the intermediate and upstream sections of rivers (see Figure 31). However, the speed at which most species move along the altitudinal and upstream-downstream gradients is insufficient to compensate for climate change (temperature change). Species are thought to have accumulated considerable delays (altitude = 46.8 m per decade, movement upstream = 15 km per decade) in responding to climate change.

A Swiss study has confirmed these trend data for brown trout (Hari *et al.*, 2006; see Figure 32). Over the past three decades, the reduction in size of thermally favourable habitats and the increased frequency of proliferative kidney disease (PKD) (see Box 4) have led to a massive loss in the numbers of fish from an average of 907 per kilometre before 1987-1988 to an average of 484 per kilometre afterwards.

Figure 32




*Trends in trout angling catches in Swiss rivers (per km and per year) as a function of the altitude (an indication of population sizes in each altitude class). The white circles correspond to trends observed over the period 1978 to 1987, the blue and orange circles (two separate data series) correspond to trends observed over the period 1988 to 2001. The first observation is that the decline in numbers decreases as the altitude increases. Secondly, prior to 1988, numbers were stable above 600 metres, but since then the dividing line is closer to 1 000 metres, which suggests that the drop in numbers is no longer observable exclusively in the lower sections of rivers (diagrams modified, originally from Hari* et al.*, 2006).*

## Changes in the distribution of other aquatic organisms

Fish are not the only aquatic organisms whose geographic distribution is likely to be modified by climate change. The geographic range of some cyanobacteria capable of producing toxins, e.g. *Cylindrospermopsis raciborskii*, has recently undergone modifications, due notably to the influence of climate change (Gugger *et al.*, 2005a; Gugger *et al.*, 2005b), with serious consequences in health and ecological terms (food webs, ecological functioning). Similarly, certain tropical diatom species, e.g. *Hydrosera triquetra* and *Diadesmis confervacea*, have over the past few years become permanent inhabitants in most rivers in southern France, probably in response to the observed rise in temperatures (Coste, 2006).

Macroinvertebrates are also affected. For example, Floury (2013) showed that warming and, to a lesser degree, the reduction in the discharge of the Loire River were involved in the disappearance or the progressive decline of rheophilic and cryophilic macroinvertebrates, e.g. *Chloroperlidae* spp. Conversely, it would appear that limnophilic and thermophilic taxa benefited, including certain invasive species, e.g. *Corbicula* spp. Taxa that are sensitive to pollution (*Brachycentridae, Philopotamidae*) have also made a comeback over the past few years due to the improvement in water quality.

Finally, it is not impossible that global warming has had an influence on spatial trends in the proliferative kidney disease (PKD) noted in trout, grayling and salmon (Hari, 2006). Warming is thought to have extended the seasonal activity of the pathogenic agent which can propagate only when water temperatures exceed 9°C. In addition, the disease manifests itself only when temperatures exceed 15°C (Gay *et al.*, 2001; Chilmonczyk *et al.*, 2002; Wahli *et al.*, 2002). The increase in water temperatures could boost the propagation of the disease, even if to date the primary cause would seem to be linked to practices in commercial fishing (release of fish from infected fish farms). The same is true for fish pathogens such as *Ichthyophonus* spp. and *Argulus coregoni*, whose propagation and virulence could be modified by climate change, e.g. an increase in pathogen growth rates, physiological or immune-system changes in hosts, etc. (Marcogliese, 2008; Kocan *et al.*, 2009).

The studies presented above indicate that changes in distributions have already been observed in some rivers, on both local and larger scales. These changes may result in smaller ranges or even the local extinction of species. This is because the climatically favourable habitat of a species may become too small or too isolated from the initial geographic zone due to natural (divisions caused by river basins, relief, the continent itself) and/or anthropogenic fragmentation (dams, weirs, hydromorphological alterations) that exceeds the capacity of the fish to disperse in step with the current rapid rate of climate change (Devictor *et al.*, 2008; Isaak *et al.*, 2013; Comte and Grenouillet, 2013). Note that certain studies suggest that in addition to climate change seen as a gradual change in water temperatures, it is also important to take into account the impact of extreme events (see Box 5). On the other hand, some species may benefit from climate change and also be in a position to take advantage of breaks in biogeographic boundaries caused by human activities, e.g. canals between river basins, global trade, voluntary introduction of species, thus gaining access to numerous new habitats and potentially becoming invasive (Walther *et al.*, 2002; Rahel and Olden, 2008). Similar to changes in phenology, these changes in the distribution of species modify community structures. For example, a study by Daufresne and Boët (2007) revealed an increase in species richness and a decrease in equitability[17] in fish communities in response to an increase in water temperatures in certain French rivers (Loire, Rhône, Seine). The drop in equitability is thought to be due primarily to the low number of species benefiting from climate change. Other studies have also

*17. Equitability is an indicator for the relative presence of species within a community. The more the numbers of each species tend to be equal, i.e. equitable or even, the higher the level of equitability. On the other hand, if a majority of the individuals in a community belong to the same species, equitability is low.*

highlighted an increase in the species richness of fish communities in French rivers (Poulet *et al.*, 2011; Alonso *et al.*, 2013). Three potential causes for the local increase in species richness have been mentioned:

- the introduction of non-native species;
- the reduction in organic pollution, which has encouraged recolonisation by certain species;
- climate change, which has encouraged colonisation further upstream by thermophilic species.

However, a number of researchers think that this increase could be temporary because the speed at which a species appears is generally faster (a single individual is sufficient) than that at which a species disappears (Wilson, 1990).

Encadré 5

## What is the effect of extreme events on aquatic biodiversity?

The consequences of climate change are generally perceived as gradual changes in certain environmental variables (temperature, precipitation, etc.). However, the issue of extreme events has come increasingly to the fore as a decisive element in biodiversity, highlighting the need to take these phenomena into account in the study of climate change and its impacts.

In France for example, the heat wave of 2003 would seem to have been a major event for biodiversity that resulted in high mortality levels in fish populations in certain rivers, notably among the species inhabiting the trout and grayling zones. In parallel, changes in the migratory rhythms of four diadromous species (Atlantic salmon - *Salmo salar*, Allis shad - *Alosa alosa*, eels - *Anguilla anguilla* and sea lampreys - *Petromyzon marinus*) and an increase in their mortality rates were observed in the Garonne and Dordogne Rivers and in the Loire basin (Conseil économique et social des Pays de la Loire, 2004; Travade and Carry, 2008).

In the Saône River, mollusc communities were also impacted (Mouthon and Daufresne, 2006). Certain bivalves (*Pisidium* genus) almost disappeared from samples taken in 2003 and did not show high levels of resilience in 2004. Only eight of the 24 species present in the Saône River, upstream of Lyon, would seem to have withstood the heat wave somewhat better.

These observations suggest that some species have limited resistance and resilience in the face of temporary increases in temperatures (Mouthon and Daufresne, 2006). Heightened frequencies of extreme events in the future could have more negative consequences than gradual changes in climatic conditions. However, only long-term monitoring will provide the data required to assess precisely the resilience of populations confronted with sudden changes in the climate (Matthews *et al.*, 2013).

Figure 33

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*The increase in the frequency of extreme events due to climate change, e.g. dry periods, will have serious consequences for aquatic biodiversity.*

Climate change is not the only factor involved in the modifications noted in the distribution and structure of communities. Other factors such as alterations in hydrological regimes and improvements or decreases in water quality also play a crucial role (see Box 6). The arrival of new species may also be explained by the development of waterways as well as voluntary (stocking) or accidental introductions. The drop in the numbers of certain species, notably diadromous fish, is due to various factors such as overfishing, development work in rivers (obstacles to migration), problems with water quality, etc. Grenouillet and Comte (2014) discovered that the estimated changes in distribution (colonisation or disappearance) for 32 freshwater species in continental France caused by non-climate factors were far greater than the changes caused by the climate. It would thus appear that the role of climate change in modifications to fish distribution (at least for a certain number of species) is often overestimated and that better assessment of other factors, both natural and anthropogenic, is required. In addition, the study revealed a certain latency to the effects of climate change concerning both colonisations and local extinctions, i.e. some populations persisted in areas subject to theoretically unfavourable climates and other areas (variable in size depending on the species) subject to theoretically favourable climates remained uninhabited. In the final analysis, climate change is simply one factor in global change. It is therefore very important to stress the fact that anthropogenic pressures and climate change act together and tend to increase the vulnerability of environments and species, an example being the greater increases in water temperatures due to reductions in river discharges.

**Figure 34**

a © D. Bossot - Onema
b © Y. Falatas - Onema

*Climate change must not mask the many other pressures weighing on aquatic environments and that inhibit the adaptation of organisms to changes in the climate.*

## Impacts on aquatic organisms caused by the interaction between water quality and climate change

The health of aquatic organisms can be indirectly affected by a number of environmental parameters influenced by climate change, e.g. temperature, water pH and salinity, penetration of UV rays in the water column, etc. The effects of interactions between climate change and chemical stresses caused by certain potentially toxic aquatic pollutants are an example of the consequences that could turn out to be particularly harmful for certain species. There are a number of aspects to these effects.

### ■ Heightened sensitivity to modifications in temperature regimes

The capacity of species or populations to tolerate thermal stress may be reduced if there is simultaneous exposure to toxic chemical substances. The modifications caused by climate change in certain environmental parameters, such as water temperature, interact with other stress factors weighing on the environment, thus affecting the physiological functions in charge of maintaining homeostasis, i.e. the capacity of an organism to maintain its equilibrium in spite of external pressures (Noyes *et al.*, 2009). Ectothermic organisms such as fish, whose body heat is derived from the environment, are particularly sensitive to the interactions between temperature and contaminants. The tolerance of four species of freshwater fish to upper temperature limits is limited in fish exposed to sub-lethal concentrations of two insecticides (endosulfan and chlorpyrifos) (Patra *et al.*, 2007). Similarly, the acclimation potential of brook trout (*Salvelinus fontinalis*) and Atlantic salmon (*Salmo salar*) to temperature rise is reduced by sub-lethal concentrations of DDT and exposure of a small cyprinid (*Pimephales promelas*) to low concentrations of cyfluthrine reduces its thermal-tolerance range by almost 30% (Noyes *et al.*, 2009). These effects would seem to be bidirectional because water temperature also influences the sensitivity of fish to toxic substances. In a context of climate change, exposure to toxic substances will represent a particularly difficult problem for aquatic species already living close to the limits of their "thermal tolerance". Stenothermal species, which can withstand only very small variations in temperature, will have greater difficulties in adapting to temperature rise and are likely to be confronted with high mortality rates resulting in local extinctions, notably where the environment is already disrupted (Kimberly and Salice, 2012).

### ■ Increased toxicity for certain fish species

Numerous studies have revealed a direct relation between water temperature and the toxicity of a wide range of contaminants for several fish species (Noyes *et al.*, 2009). For example, for channel catfish (*Ictalurus punctatus*), the toxicity of atrazine, a widely used herbicide that was banned ten years ago, increases with a rise in water temperature and a drop in the level of dissolved oxygen. Similarly, the mortality of juvenile rainbow trout (*Oncorhynchus mykiss*) exposed to endosulfan, an insecticide, increases when the water temperature rises from 13°C to 16°C. Conversely, the toxicity of other insecticides such as DDT and pyrethrenoide-based products increases at lower water temperatures. Even though the underlying mechanisms are not yet fully understood, it would seem that the relation between temperature and toxicity is in part due to a temperature-controlled modification of the metabolism of the organisms, which influences the biotransformation of the bioaccumulated contaminants. That is the case for certain persistent organic pollutants such as PCBs (polychlorinated biphenyls) where the biotransformation by rainbow trout into toxic active metabolites (i.e. hydroxylated PCBs) increases when the water temperature rises from 8 to 16°C (Noyes *et al.*, 2009; Hooper *et al.*, 2013).

### ■ Alteration of bioaccumulation processes

Climate change is also likely to cause certain modifications in the structure and type of trophic interactions, in migratory patterns and in the feeding behaviour of certain species, which could alter bioaccumulation and bioamplification processes for persistent organic pollutants (POP) in aquatic food webs (Noyes *et al.*, 2009). The experimental data acquired on fish indicate generally higher levels of contaminant bioaccumulation and of elimination rates when water temperatures rise (Noyes *et al.*, 2009; Sokolova and Lanning, 2008). These increased levels of contamination in organisms result notably from a modification in the ventilation rate in response to a reduction in oxygen solubility at higher temperatures.

Recent studies (e.g. Gouin *et al.*, 2013) attempted to estimate, on the global level, the impact of climate change on exposure and accumulation levels in aquatic food webs using the IPCC climate projections. Given constant levels of hydrophobic organic contaminants (HOC), the results of simulations carried out using "multimedia" models indicate that the projected levels of environmental exposure are at most two times as high as current levels. The direct effects of climate change on potential HOC bioaccumulation in aquatic food webs are extremely variable and highly dependent on the partition equilibrium properties of these substances between the various environmental compartments and on biotransformation constants. The study authors note, however, a number of residual uncertainties (i.e. potential effects on pollutant emissions, physical-chemical properties of substances and degradation constants) affecting the study results (Gouin *et al.*, 2013).

### ■ Indirect effects caused by ecosystem degradation

The number and size of "dead zones", i.e. aquatic environments with low levels of dissolved oxygen, have increased significantly over the past decades. This phenomenon is caused by excessive levels of nutrients (N and P) in water due to the use of fertilisers and made worse by the combustion of fossil fuels, the loss of wetlands and urbanisation (Diaz and Rosenberg, 2008). The frequency, duration and scale of hypoxic or anoxic zones are likely to increase because of climate change, notably due to greater run-off of nutrients in regions subjected to more frequent extreme rainfall and to greater stratification of water columns. Recent studies would seem to indicate that fish subjected to repeated and/or prolonged hypoxia may suffer alterations in reproductive functions controlled by the endocrine system, to the point of producing detrimental effects on populations (Thomas *et al.*, 2007). This phenomenon is likely to occur in addition to the effects produced by the many pollutants in aquatic environments that can cause endocrine disruptions, including natural hormones, synthetic hormonal compounds, certain medicines for human and veterinary use, and a vast array of chemical substances (brominated flame retardants, plasticisers, detergents, herbicides, pesticides, etc.).

# Case studies in continental France

## The Rhône basin

The Rhône River has undergone development work to produce hydroelectric power and enable navigation. The work modified the original hydromorphological conditions and created new environments (canals, impoundments, short-circuited sections with regulated discharges). In addition to these more or less recent hydromorphological changes that structure the physical habitats of species, since the end of the 1970s the chemical quality of water has been modified (reduction of organic pollution and certain toxic substances) and non-native species have appeared and developed. These phenomena modify the biological structure and functioning of the Rhône ecosystem. Over the past three decades, the temperature regime of the Rhône has also undergone warming averaging 1.5°C in the upper reaches and 2.0°C in the lower reaches below the confluence with the Isère River (Daufresne *et al.*, 2004; Daufresne and Boët, 2007; Poirel *et al.*, 2008; see Table 2).

**Tableau 2** *Average temperature per decade, monitored at 15 points along the Rhône and its tributaries (from the upstream sections on the left to the downstream sections on the right), and the differences between successive decades (according to Poirel* et al.*, 2008).*

| Average / decade | SCX | LEM | ARV | POU | CRE | BUG | AIN | JON | SAO | SAL | SPE | RGL | ISE | SOY | CRU | TRI | DUR | ARA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1977-1986 | - | 11.3 | - | 10.4 | 11.0 | 11.4 | 10.6 | 12.5 | 13.0 | 12.8 | - | - | 10.1 | 12.0 | 12.1 | 12.1 | 13.1 | 13.2 |
| 1987-1996 | - | 11.9 | - | 11.3 | 11.9 | 12.1 | 11.6 | 13.3 | 13.4 | 13.7 | 14.7 | 14.7 | 10.7 | 13.2 | 13.5 | 13.4 | 13.5 | 14.7 |
| 1997-2007 | 7.4 | 12.3 | 8.4 | 11.4 | 12.2 | 12.4 | 12.1 | 13.9 | 14.0 | 14.0 | 15.1 | 15.4 | 10.8 | 14.1 | 14.1 | 14.0 | 13.5 | 15.2 |
| **Difference between successive decades** | **SCX** | **LEM** | **ARV** | **POU** | **CRE** | **BUG** | **AIN** | **JON** | **SAO** | **SAL** | **SPE** | **RGL** | **ISE** | **SOY** | **CRU** | **TRI** | **DUR** | **ARA** |
| (87/96) - (77/86) | - | 0.60 | - | 0.90 | 0.89 | 0.78 | 1.00 | 0.76 | 0.42 | 0.93 | - | - | 0.58 | 1.16 | 1.38 | 1.32 | 0.39 | 1.49 |
| (97/06) - (87-96) | - | 0.38 | - | 0.03 | 0.31 | 0.30 | 0.47 | 0.63 | 0.58 | 0.34 | 0.44 | 0.70 | 0.08 | 0.92 | 0.59 | 0.51 | 0.02 | 0.58 |

Pougny (POU), Creys-Malville (CRE), Bugey (BUG), Jons (JON), Loire sur Rhône (LSR), Saint Alban (SAL), Seuil de Peyraud (SPE), Roche de Glun (RGL), Soyons (SOY), Cruas (CRU), Tricastin (TRI), Aramon (ARA), Pont de Chazey (AIN), Couzon (SAO), Beaumont Monteux (ISE), Porte du Scex (SCX), Arve au Bout du Monde (ARV), the Rhône at Halle de l'Ile (LEM), Durance (DUR).

This rise in the average temperature and, more precisely, the earlier dates at which the various thresholds are reached, the reduced duration of the cold period and the lengthening of the warmest period are thought to explain in part the variations observed in macroinvertebrate and fish communities.

Since 1979, fish communities have come to be dominated by species preferring relatively warm waters (e.g. chub), whereas cold-water species (e.g. dace) have declined (Daufresne *et al.*, 2004; Daufresne and Boët, 2007). This phenomenon has also been noted for macroinvertebrates, with the *Athricops* and *Potamopyrgus* genera replacing *Chloroperla* and *Protoneumura* (Dolédec *et al.*, 1996; Daufresne *et al.*, 2007), except in the lower Rhône, where communities are already dominated by limnophilic and thermophilic taxa.

In the Rhône river basin as a whole, the effects of climate change can already be widely observed even though trends remain difficult to assess due to the existence of multiple confounding factors (human activities).

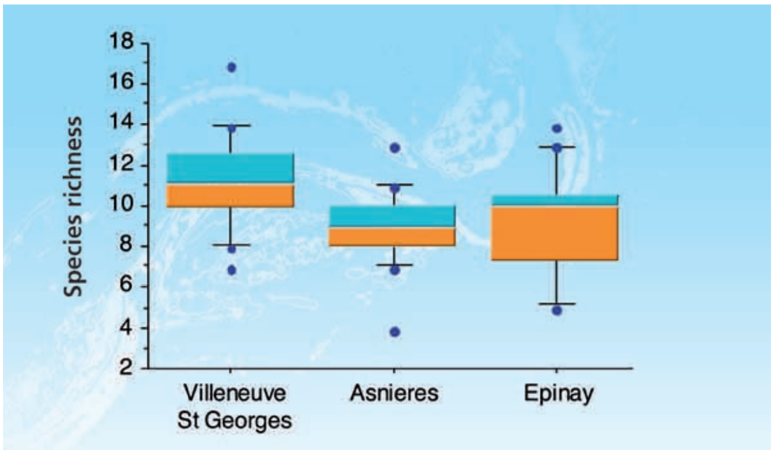
## The Seine basin

Similar to the Rhône basin, the basin of the Seine River has undergone extensive anthropic development. Whereas the original fauna comprised some 30 species during the last glacial periods (between 24 and 33, depending on the hypotheses), human activities since the Middle Ages resulted at the end of the 1900s in the detection of 23 new species due to direct (voluntary introductions) or indirect (modifications made to aquatic environments) efforts (Belliard *et al.*, 1995, 2009). Over the same period, seven migratory species out of the ten original disappeared from the river basin, on the one hand because of the creation of obstacles in the main rivers and, on the other, the deterioration in water quality and the disappearance of perifluvial wetlands (Belliard *et al.*, 1995, 2009).

Since the 1970s, major efforts have been made to restore the quality of the river, thus enabling the return of certain migratory species (European smelt - *Osmerus eperlanus*, sea trout, shad, sea lampreys - *Petromyzon marinus*) and increases in the abundance of species particularly sensitive to the quality of the environment (barbel, dace). That being said, species richness continues to vary widely along the longitudinal gradient, with generally more diversified fish communities upstream of Paris (see Figure 35).

Within the Seine basin, fish communities have been considerably influenced by a vast array of factors producing effects on different spatial and temporal scales. This context makes it very difficult to determine the impact of climate change alone on fish populations. In addition, less information is available on changes in water temperature than for the Rhône. Preliminary studies covering the period 1998 to 2004 do not indicate a rise in water temperature in the Grande Bosse side channel between Montereau and Nogent sur Seine (Tales, 2008), however the data series is so short that it is difficult to draw any robust conclusions. The same authors also

**Figure 35**




*Changes in species richness of fish communities along the longitudinal axis of the Seine River between 1990 and 2005 (diagrams modified, originally from Belliard* et al.*, 2009). The bottom and top of the boxes represent the 25th and 75th percentiles (i.e. the box contains 50% of the observed values), and the ends of the whiskers represent the 10th and 90th percentiles (i.e. the interval between the whiskers contains 80% of the observed values). The median is represented by the border between the blue and orange sections.*

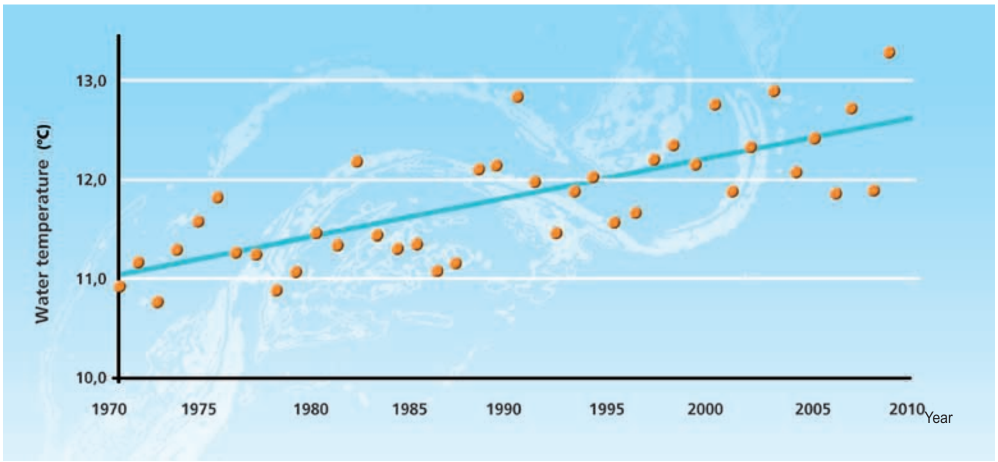
could not establish any significant correlation between fish communities and hydroclimatic variability. The work by Belliard *et al.* (2009) would nonetheless suggest an increase in the numbers of perch and a decrease in the numbers of cyprinids during the heat-wave years (2003-2004). The mechanisms involved could not be identified (direct effect of temperature or predation between species).

## Lake Geneva

Lake Geneva lies at an altitude of 372 metres and covers 580 square kilometres. It receives inputs from various rivers in the Swiss cantons (Valais, Vaud, Fribourg and Geneva) and from the neighbouring French departments (Haute-Savoie, Ain). Among these numerous tributaries, the Rhône has by far the largest discharge and alone represents 75% of the inputs to Lake Geneva.

The creation of a systematic monitoring programme for lake waters in 1957, on behalf of CIPEL (International commission to protect Lake Geneva), produced data on water temperatures. The results reveal an increase in the annual average temperature of over 1°C at the bottom of the lake (309 metres) and of over 1.5°C at five metres below the surface over the past 40 years (CIPEL, 2009). The winter temperature of the lake rose from 4.5°C in 1963 to 5.1°C in 2006 and vertical thermal stratification due to the lower density of warm water now occurs one month earlier than 30 years ago (see Figure 36).

**Figure 36**




*Change in annual average temperature at a depth of five metres in Lake Geneva (according to www.cipel.org).*

These changes have had visible consequences for planktonic and fish communities, and generally speaking on ecosystem functioning. Due to the earlier occurrence of thermal stratification, maximum primary production of phytoplankton and of herbivorous zooplankton now takes place one month earlier in the spring (Anneville *et al.*, 2005). Massive consumption of the phytoplankton by the zooplankton provokes a sharp drop in algal biomass and results in the transparent-water phase[18] being brought forward from June to May. The phosphorous available in the upper water layer is more rapidly consumed by the primary production and quickly becomes a limiting factor, whereas sufficient concentrations remain in the deep, cold waters receiving less light. These conditions are favourable for the series of "autumn" algae that develop over the summer in the deep waters. These algae contribute very little or not at all to energy transfers to the higher levels of the feed web due to their lack of palatability for zooplankton, resulting in a significant restructuring of trophic transfers in the lake.

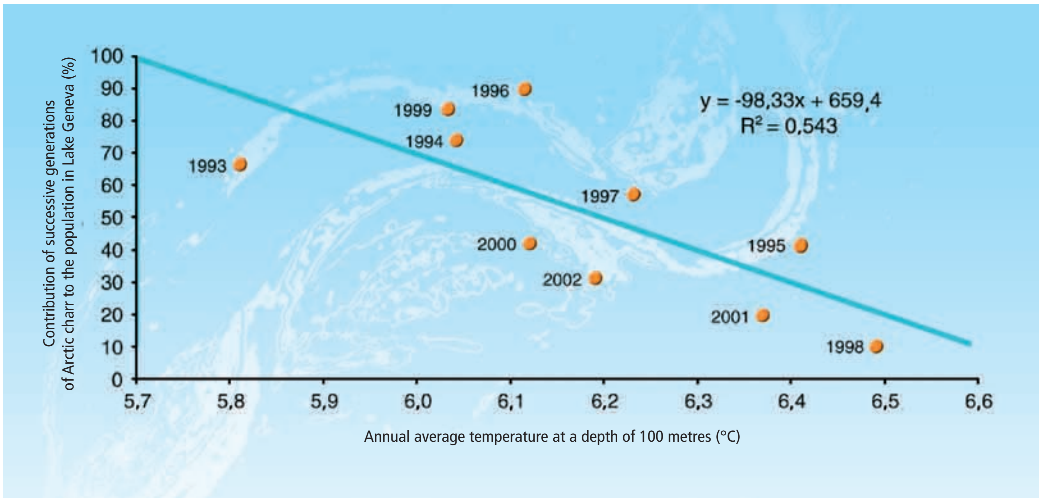
*18. The transparent-water phase occurs following the spring development of phytoplankton, when the algae are eaten by the herbivorous zooplankton. This phenomenon has increased in frequency with the development of eutrophication.*

A number of changes have also been noted concerning fish communities (Jeppesen *et al.*, 2012). The reproduction period for roach is now approximately one month earlier, whereas that of perch has remained virtually unchanged. Spawning by whitefish, a cold-water species, now occurs approximately two weeks later in December, in response to the rise in water temperature. Given that plankton cycles take place one month earlier, the whitefish larvae now inhabit waters that are warmer than 30 years ago and offer more abundant nutrients. These phenological changes have resulted in an increase in whitefish populations, a fact confirmed by catch data over the past 30 years (less than 50 tons in the 1970s and over 300 tons since 1997) (Gerdeaux *et al.*, 2004).

On the other hand, Arctic charr, a relic species from the glacial period, would appear to be particularly threatened because its oogenesis is blocked by temperatures exceeding 7°C (Danis *et al.*, 2004; see Figure 37). Over the long term, projections indicate that the Arctic charr will disappear and will be replaced initially by whitefish, subsequently by cyprinids.

Climate change thus impacts the composition of the communities inhabiting Lake Geneva and the overall functioning of the lake ecosystem. It should be noted however that major oligotrophication efforts have been made over the past decades and probably contributed to the observed effects.

**Figure 37**




*Strength of Arctic charr cohorts[19] as a function of the annual average water temperature at a depth of 100 metres in Lake Geneva. Ovulation in Arctic charr is blocked if the water temperature at a depth of 100 metres exceeds 7°C (*Gerdeaux, 2011*).*

*19. Index indicating the relative importance of a cohort in the population.*

# Conclusion and outlook

The physiology, biological rhythms and distribution of fish depend on environmental factors such as temperature, hydromorphological conditions and water quality (dissolved oxygen, pollutant concentrations, etc.). Climatic disruptions impact these factors and thus constitute a major source of change for fish species.

Though it is very difficult in the freshwater context to distinguish between the effects of climate change and those of local anthropogenic pressures, a number of studies have revealed the impact of temperature increases on fish communities. Changes in certain physiological characteristics in response to an increase in water temperature have in turn resulted in changes in reproduction, growth and seasonal rhythms. In addition, some species have moved up river, extending their range when movement is not blocked by other factors such as weirs and dams. These movements have led to changes in the composition of communities with as a consequence modifications in species richness and in the number of dominant species.

Even though the signs are still not very clear in some rivers and interpretation is difficult due to anthropogenic pressures, the consequences of climate change are observable over France as a whole. They contribute to the impact of human activities in rivers (dams, reservoirs, sealing of banks, abstractions for various uses, release of polluted water, etc.) and can in certain cases reinforce the ecological modifications.

Unfortunately, the lack of long data series and the change in the sampling strategy for the surveillance-monitoring network limit the possibilities of studying current changes in communities in the context of climate forcing.

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3

# Anticipating the impact of climate change on fish communities

# Introduction

As indicated in the previous chapters, recent climate trends (first chapter) have already progressed sufficiently to cause considerable effects on fish communities in the lakes and rivers of continental France, at multiple levels of scale from individuals to communities (second chapter). Given the major conservation and/or economic issues surrounding certain species and the role played by fish in aquatic ecosystems, the need to assess the future impact of the trends on fish populations has taken on crucial importance.

A number of models have been developed recently to asses the impact of climate change on species distribution and thus anticipate its effects. Most of these models are based on the notion of niche for each species. A niche may be defined as the multi-dimensional space representing both the position occupied by a species in a given environment and all the conditions required to sustain the species (Hutchinson, 1957). The geographic areas offering these conditions correspond to the potential range of the species (fundamental niche). However, within the fundamental niche, a number of factors limit the dispersal of the species (geographic barriers, etc.) and its survival (predation, pathogens, etc.) to a more limited, effective range, called the realised niche.

Among the existing models, species distribution models (SDM) input the data describing the effective range of species (realised niche) and add a number of measured environmental variables such as the climate, topography or soil type in order to statistically model the ecological envelopes in which the species can live (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005). These envelopes then serve as filters in selecting areas that in the future will offer favourable conditions for various species (Pearson and Dawson, 2003; Jeschke and Strayer, 2008). A basic hypothesis underlying these models is that the species have achieved stability (equilibrium) within their environment (Guisan and Zimmermann, 2000; Guisan and Thuiller, 2005). This is because the data used to build the models are generally collected over a relatively short period and a limited geographic zone. The data thus constitute a "snapshot" of the effective distribution of species and the models do not take into account colonisation dynamics and limiting factors such as environmental disturbances (e.g. pollution, land use, droughts) and past events (e.g. glacial periods), which can lead to situations where an equilibrium does not prevail. In addition, the future distribution does not take into account any new interactions between species (e.g. predation, competition) or their capabilities to disperse or to adapt to changes in the environment. When used in conjunction with environmental-change scenarios, these models produce projections for the zones where the combinations of variables are potentially favourable for a species. These zones must therefore not be interpreted as the future range of the species, but rather as potentially favourable habitats in the future (Guisan and Thuiller, 2005).

Contrary to statistical models, mechanistic (matrix or individual-based) or hybrid models attempt to reproduce a part of the processes by incorporating ecophysiological traits and/or demographic data specific to the species (Kearney and Porter, 2004; Buckley, 2008) (see Box 8). These approaches are based primarily on the physiological tolerance limits of species (Guisan and Thuiller, 2005; Kearney, 2006) and can be used to determine, for example, the climatic limits to the range of a species. The advantage of these types of model is that they do not depend on the observed distribution of a species and some explicitly take into account adaptive and evolutionary processes. In other words, they model the fundamental niche of the species. However, they require a great deal of knowledge and data on the ecology and physiology of the organisms, information that is not always available. For this reason, these models should, at this point, be seen as research topics rather than as management tools.

The purpose of this chapter is to present the approach adopted by statistical distribution models and the main results of these models, without neglecting the other modelling approaches. The results inform on the potential effects, over the coming century, of climate change on the distribution of the fish in France.

# Distribution models

## General structure

The basic ideas behind distribution models are fairly simple in that the models describe the link between:

- the environmental variables known to influence species distribution;
- the data on species distribution, drawn from atlases and inventories.

Statistical models produce a probability of occurrence for a species as as function of the environmental variables. They can subsequently be used to model the effective distribution of the species (realised niche), then to project the changes in favourable habitats (potential distribution) over space and time (see Figure 38).

Figure 38

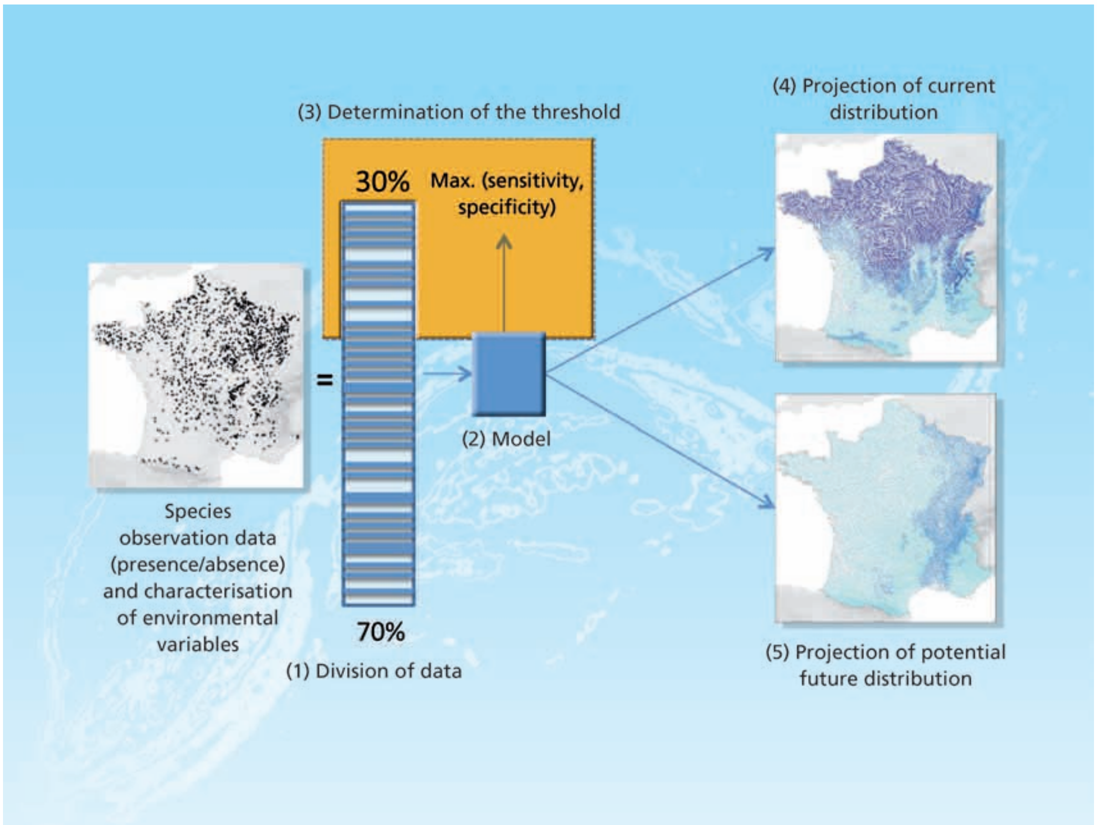



*Diagram showing the various steps in statistical modelling (diagrams modified, originally from Nenzén and Araújo, 2011).*
*(1) The observation data on the species are randomly divided into two batches for the model calibration and assessment phases (see below).*
*(2) 70% of the data are used for the calibration phase.*
*(3) The resulting model is applied to the remaining 30% of data to test model performance (sensitivity, specificity). The results serve to determine a probability threshold between presence and absence of the species. The model is used to project the probability of occurrence to the current environment (4) and the future environment (5).*

The formulation of species distribution models involves the following steps:
■ selection of the statistical methods;
■ description and selection of the data used to build the models;
■ the main steps involved, e.g. calibration, validation and projection of the favourable or unfavourable habitats (see Figure 15) in a suitable context, for example the French hydrographic network (Vogt *et al.*, 2007);
■ production of results, i.e. indices for species and communities.

These different steps are discussed in detail below.

## Selection of the statistical methods

The different approaches to statistical modelling are traditionally grouped into six major types:
■ geographic envelopes;
■ climate envelopes;
■ multivariate methods;
■ regression methods;
■ classification methods;
■ learning methods (Guisan and Zimmermann, 2000).

These approaches differ in terms of the required types of data, the underlying hypotheses, the mathematical algorithms and/or the complexity of the model.

Three types of models are commonly used (Elith *et al.*, 2006; Lawler *et al.*, 2006; Pearson *et al.*, 2006; Buisson, 2009) (see Box 7). However, none have achieved true consensus because they all have a number of advantages and disadvantages. For this reason, some researchers have suggested that all the approaches be considered simultaneously with a comparison of the output variables (Thuiller *et al.*, 2009). Others favour using a single statistical approach (Logez *et al.*, 2012).

Box 7

### Presentation of the statistical methods

The most commonly used types of statistical methods are presented below.
■ **Generalised linear models** (GLM) (McCullagh and Nelder, 1989) can model relations more complex than simple linear regressions. **Generalised additive models** (GAM) (Hastie and Tibshirani, 1990), a non-parametric extension of GLMs, produce smoothed response curves on the basis of the observation data. **Multivariate adaptive regression splines** (MARS) (Friedman, 1991) are an adaptive adjustment method using non-linear regression, based on data divided into subgroups for which local adjustment (smoothing) is carried out.
■ **Classification methods such as Linear discriminant analysis** (LDA), which builds synthetic variables using linear combinations of explanatory variables to enhance discrimination of presence/absence data and **Classification and regression tree methods** (CART) (Breiman *et al.*, 1984), based on building a decision tree in order to rank data according to the explanatory variables.
■ **Learning methods such as Artificial neural networks** (Rumelhart and McClelland, 1986) are based on weighted non-linear combinations of the explanatory variables that are optimised to improve predictions. **Random forest methods** (RF) (Breiman, 2001) build hundreds to thousands of decision trees (similar to CART). **Aggregated Boosted Trees** (ABT) (Friedman, 2001) are based on building sequences of decision trees combining a boosting algorithm and a regression-tree algorithm.

## Description and selection of the data used to build the models

### ■ Presence (and absence) data

The presence data[20] constitute the basic input for distribution models. These data are generally drawn from inventories using standardised and systematic protocols (electrofishing sampling strategies), but also local observations (sport fishing) and museum collections. Presence can thus be documented on various spatial scales depending on the source of information (monitoring point, river reach, river basin).

Data representativeness is a decisive factor. For each species, the data must be capable of describing the most complete range of favourable and unfavourable conditions possible, in order to model as accurately as possible the effective distribution of the species (Stockwell and Peterson, 2002; Barry and Elith, 2006). Distribution modelling implies that the data must cover all or almost all of the range, i.e. on the European scale for most taxa (with the exception of certain exotic species, such as catfish and topmouth gudgeon). Practically speaking, the species that have not undergone extensive study or are relatively rare are generally not included in assessments.

### ■ Environmental variables

To produce robust projections, selection of the environmental data (called the explanatory variables) is an important step because it implies selecting the parameters that best describe the realised niche of the species (Pearson and Dawson, 2003; Dormann, 2007; Broennimann *et al.*, 2007).

The environmental data may be drawn directly from data-collection campaigns in the field on the local scale or from geographic databases providing information on, for example, the climate conditions, relief or land use. Specifically concerning climate data, national data on the current and future situation are available from Météo-France as well as from international organisations (Worldclim[21]). However, the spatial resolution is limited (maximum resolution = a raster[22] with cells of 1 km x 1 km, in general). Downscaling[23] can subsequently be used to link the presence data obtained on the scale of a monitoring point or a river reach with the available climate data (see the first chapter).

Selection of the explanatory variables is subject to a certain number of constraints. For example, selection of a limited number of explanatory variables, based where possible on confirmed biological mechanisms, produces results that are easier to interpret and more robust. The variables should also limit as much as possible any redundancy in the information they provide (correlation) in order to avoid bias caused by collinearity phenomena. Conversely, when useful variables, e.g. water temperature, are not available but are nonetheless fundamental in explaining species distribution, it is possible to use another highly correlated variable as a proxy, for example the air temperature (Buisson *et al.*, 2008; Sharma *et al.*, 2007; Lassalle and Rochard, 2009a).

## Main modelling steps

The steps in statistical modelling are presented below.

The first step, called the calibration step, corresponds to a learning phase in which the model is designed to produce predictions that correspond as closely as possible to the observed presence-absence data. The output data of a calibrated model generally corresponds to presence probabilities ranging from 0 to 1.

*20. Ideally, absence data could also be used. However, it is much more difficult to prove the absence of a species than its presence due to constraints inherent in sampling techniques.*
*21. http://www.worldclim.org/.*
*22. Image data divided into a matrix of squares.*
*23. A technique used to obtain information on the local or regional scale from larger-scale climate projection models or data analyses (see the first chapter).*

The second, validation step is an assessment phase to determine the predictive performance of the model. A number of approaches exist and are generally based on confronting the projections with a set of observed data that were not used for the calibration phase. To judge the predictive performance of a model, various indices are used (Liu *et al.*, 2005; Nenzén and Araújo, 2011). Examples are the sensitivity (the percentage of correctly predicted presences) and the specificity (the percentage of correctly predicted absences). The currently most widely used coefficients are True skill statistic (TSS) (Allouche *et al.*, 2006) and Area under the receiver operating characteristic curve (AUC) (Hanley and McNeil, 1982). The capacity of a model to make correct predictions may differ for the presence and absence of a species, which means it is necessary to use the different indices during the assessment phase to quantify the level of confidence that may be vested in the model.

Note that in both cases, the presence probabilities calculated by the model (between 0 and 1) can be converted into a binary variable (presence = 1, absence = 0) for comparison purposes with the input data (presence-absence). To that end, a threshold must be set[24]. Above the threshold, the probability of occurrence for the species is assumed to be a presence, below the threshold an absence. This technique simplifies model interpretation, however it masks a part of the uncertainty affecting the model.

## Determining the favourability of current and future habitats

At the end of the calibration and validation steps, the calibrated models are used to project the current distribution of each fish species. Using the results and in view of anticipating the impact of climate change on fish communities, the probabilities of future occurrence under the new climate conditions are then calculated in order to project the potentially favourable, future habitats for each of the studied fish species.

## Results

### ■ Results on the species level

By comparing the current and future ranges (presence-absence) for each species, it is possible to calculate the gains and losses of potentially favourable habitats and the changes (expansion, displacement, shifts, contraction) in the range, and then to estimate the vulnerability and the risks of local extinction for a species in a given context. The change in the distribution of a species is generally expressed using indices, notably:

- the variation in prevalence, i.e. the change (between the current and future climates) in the number of spatial entities where the presence of the species is predicted (expressed as a percentage of favourable sites);
- the Species range change (SRC) (Thuiller *et al.*, 2009), i.e. the difference in the future between the number of "newly favourable" spatial entities and the number of "no longer favourable" spatial entities, divided by the number of currently favourable spatial entities for the species.

These indices[25] may be accompanied by an expert-knowledge-based index indicating the degree of relevance of the projections taking into account the biology of the studied species (see Box 8).

### ■ Results on the community level

The individual responses for each species present in each assemblage are then combined to assess the effects of climate change on the structure of communities. A number of indices are produced:

- the first is species richness, i.e. the total number of species present in each spatial entity (current and future richness, and the difference between the two). This index is calculated by adding together all the presence-absence maps of the studied species for both the present and the future;

*24. A threshold above which the habitat is considered favourable for the species must be set, taking into account a specific combination of environmental data. Traditionally, a threshold of 0.5 has been used, but other approaches have been suggested. They are based on the capacity of models to correctly reproduce presence and absence in order to optimise the threshold probability of occurrence value (Liu* et al.*, 2005; Nenzén and Araújo, 2011).*

*25. Note that other indices may be formulated on the basis of the results obtained, e.g. length of river reaches gained or lost by a species.*

■ it is also possible to qualify the change in the composition of communities using a renewal index estimated on the basis of loss or gain of species at a given point (Peterson *et al.*, 2002; Buisson and Grenouillet, 2009);

■ finally, a "similarity" index (e.g. the Jaccard index) compares the number of species found in both communities and the number of species found in only one or the other of the communities. It can vary between zero (no common species) and one (identical communities). Generally speaking, an increase in similarity suggests greater uniformity of communities whereas a reduction indicates differentiation (Olden and Rooney, 2006; Buisson and Grenouillet, 2009).

Box 8

### Qualitative assessment of projections based on expert knowledge

In addition to statistical indices, the predictive performance of the models can be assessed by experts (ichthyologists) on the basis of current knowledge on species ecology. For example, for the Explore 2070 project (MEDDE/Biotope, 2013), the results were assessed in light of the the intrinsic capabilities of the species to disperse. The dispersal capability was assessed using three criteria:

■ the intrinsic capability of the species to disperse under favourable conditions (Keith and Allardi, 2001; Jenkins *et al.*, 2007);

■ the capability of the species to overcome obstacles to flow, whether natural or anthropogenic;

■ the degree to which the species is manipulated by humans, either voluntary (stocking) or involuntary manipulation (e.g. escape from a fish farm).

The resulting index is expressed on a scale of three, i.e. the probability of the species being able to colonise a new habitat is low, medium or high.

For a species for which the probability of colonisation is low, it is assumed that its future favourable habitat will not differ significantly from the habitat projected using the "zero dispersal" hypothesis (see Box 11). If the projection foresees a major reduction in the favourable habitat, the species is considered highly vulnerable. Conversely, when the probability of colonisation for a species is high and the future favourable habitat increases significantly under the "unlimited dispersal" hypothesis, the species is considered less vulnerable to climate change.

## The limits of modelling

Multiple sources of uncertainty are inherent in the use of models. Uncertainty may arise from the hypotheses on the GHG emission scenarios (see the first chapter) or from the design itself of the models due to the equations used or the processing of the equations (climate models, species distribution models, downscaling models). It may also be caused by the quality of the biological and/or environmental variables or the lack of representativeness of certain processes. The sources of uncertainty are listed below.

### ■ Quality of the biological and environmental variables

The capacity of models to correctly project the ecological niche of species depends directly on the quality and relevance of the ecological input variables. However, numerous constraints and uncertainties weigh on the collection of biological and environmental data.

#### *Biological variables*

The capacity to detect the fish of a given species can vary widely from one site to another, depending on the behaviour and abundance of the species, the type of environment, the sampling method, and can also vary according to the season of the year (meteorological and hydrological conditions). For example, adult carp live in areas that are too deep for electrofishing and their reproductive success (presence of juveniles) varies widely over time. Consequently, the absence of a species in a sample does not mean that the species is necessarily absent on the site. Anthropogenic pressures can also skew modelling of realised niches for many species (see the section below).

#### *Environmental variables*

Integration of all the environmental variables informing on the ecological requirements of species is relatively difficult for reasons having to do with data availability and with statistical issues. Environmental variables fluctuate over both time and space. In general, model inputs consist of averaged data that mask extreme events that may occur more often in the future.

In addition, when certain fundamental variables are not available, proxies are used. That is notably the case for water temperature or river discharges, which are proxied by the use of air temperature and precipitation respectively (however, see Box 9). The use of proxies can lead to errors in some cases, for example when the water temperature is not linked to air temperature because the water is supplied by the water table or in the case of mountain streams supplied primarily with snow melt.

Other data, such as certain physical-chemical variables, e.g. oxygen content of water, are generally not input directly into models because standardised, large-scale measurements are technically difficult to obtain.

Finally, if the given range of environmental variables is too narrow, only partial characterisation of the niche for a species will be possible. In this case, favourable environmental conditions will not be taken into account, which will skew the calculated relation between species occurrence and the environmental variables.

All these factors result in approximations that, for certain species, reduce the capacity of models to produce robust projections on their ecological niche.

Box 9

### Inclusion of hydrological data in distribution models

A line of research currently being explored attempts to integrate hydrological variables in distribution models by connecting a hydrological model to the climate models and then inputting the resulting hydrological data in the distribution models (Jähnig *et al.*, 2013).

This development work is currently under way, but is confronted with numerous technical difficulties. Even though the links between river discharge and ecological characteristics have been studied at length (see for example Bergerot, 2013; Anderson *et al.*, 2006; Lancaster et Downes, 2010; Poff and Zimmerman, 2010), the impact of modified hydrological regimes on biological behaviour is still poorly understood due to the large number of factors (hydrological factors and their interaction with other environmental factors) affecting the response of individual organisms.

## ■ Projections exceeding the data available for models

Extrapolation is a statistical term pertaining to the projections of a model using sets of data that are not those for which the model was designed (see Figure 39).

Figure 39

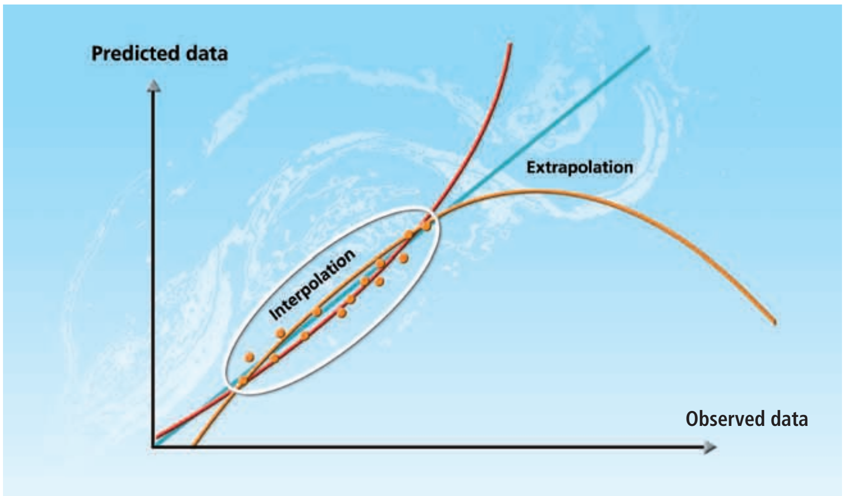



*Diagram showing the limits of interpolation in describing data and the risks of extrapolation.*

That is notably the case when models are used to predict distribution changes according to climate scenarios in which the climate variables exceed the ranges of values encountered under current conditions. The underlying hypothesis is to assume that the statistical relations established for the current data (during the calibration phase of the models) will continue to hold for values lying outside the current ranges of values. If this hypothesis turns out not to be true, the result for the projections is additional errors the degree of which it is fundamentally impossible to ascertain.

## ■ Non-inclusion of certain biological processes

To date, a large number of biological mechanisms have not been taken into account in species distribution models. That is notably the case for the dispersal capabilities of each species and the speed at which they can colonise a habitat. A Swedish exploratory study on pike revealed that the non-inclusion of dispersal capabilities led to overestimation of habitat gains for fish located downstream and underestimation of habitat losses for fish located upstream (Hein *et al.*, 2011).

Similarly, projections do not take into account biotic interactions (competition, predation, pathogens, etc.). This may have consequences for the results. Even though the importance of the biotic interactions is implicitly taken into account in the sampling data (Davis *et al.*, 1998; Sinclair *et al.*, 2010), the interactions are highly likely to change, notably due to the influence of climate change:

■ exotic species introduced voluntarily or accidentally into rivers in continental France, such as the largemouth bass (*Micropterus salmoides*), could benefit from climate change and become invasive, thus potentially entering into competition (or even predation) with native species (Leprieur and Rubin, 2011; Lauzeral, 2012);

■ in addition, climate change could encourage certain pathogens or indirectly modify host-parasite relations, thus making certain fish species more vulnerable to the diseases (Kocan *et al.*, 2009; Marcogliese, 2008) (see Box 4 in Chapter 2);

■ finally, certain species could encounter difficulties under the new climate conditions and disappear from some sites, which could work in favour of other species that were limited by the earlier presence of the first species.

Certain specific aspects such as needs in terms of food are also neglected, notably because the carrying capacity of the environment (assumed to be unlimited) is not taken into account. Similarly, distribution modelling of certain species is based exclusively on one part of their life cycle, consequently the definition of the ecological niche does not include all the environmental requirements of the species during the various stages of its life cycle, e.g. the part of the life cycle in the ocean for diadromous species.

Finally, it is also assumed that the relations between fish and the environment, established on the basis of the observed distribution, do not change over time. Modelling does not take into account adaptation phenomena (genetic selection), acclimation phenomena or the phenotypic plasticity of species confronted with climate change. However, genetic, phenological, physiological and morphological adaptations are possible and have been observed, e.g. in amphibians in the form of earlier reproduction (Beebee, 1995) and in the westslope cutthroat trout (*Oncorhynchus clarkii lewisi*) (Drinan *et al.*, 2012). These simplifications, by not taking into account the potential changes in these relations over time, may limit the capacity of models to correctly project the impact of climate change.

Other types of models are currently being developed in order to take into account some of the ecological processes mentioned above (see Box 10).

Box 10

### The impact of climate change on species distribution in hybrid models and mechanistic models

Distribution models are impaired by significant limits. In that ecological processes are not explicitly included, dispersal capabilities are generally not taken into account and difficulties arise in determining the real habitat gains and losses of the studied species. In addition, the population dynamics of the species (growth, reproduction, mortality, migratory processes) are neglected, meaning the effects of climate change on the phenology[26] of the species are absent as well, thus making it difficult to make a reasonable estimate of their speed of expansion (or disappearance) and of the effective changes in their range (Guisan and Thuiller, 2005; Franklin, 2010). In light of this situation, the shift to more mechanistic models capable of integrating the thermal requirements, population dynamics and dispersal capabilities of species has become a major issue (Thuiller *et al.*, 2008; Huntley *et al.*, 2010).

Mechanistic approaches, based on the use of individual-based models, would seem to offer promising results. Contrary to statistical models, mechanistic approaches are robust because they address generic mechanisms and are not based correlations which do not necessarily imply any causal links. In addition, they can integrate individual variability, interaction between individuals as well as between individuals and their environment (a useful feature to take directly into account the effects of climate change on population dynamics), and an explicit representation of the environment (Tyler and Rose, 1994; Wiegand *et al.*, 2004; Jongejans *et al.*, 2008). In recent years, these models have been developed notably to study the large-scale impact of climate change on diadromous fish (Rougier *et al.*, 2014) and specifically on Atlantic salmon (Piou and Prévost, 2012, 2013).

*26. Phenology is the study of the timing of periodic events (generally annual) among life forms, determined by seasonal variations in the climate.*

The formulation of hybrid models combining large-scale statistical relations and biological processes is another possible solution to improve projections (Brook *et al.*, 2009), notably for invasive species (Gallien *et al.*, 2010; Poulet *et al.*, 2012). The most commonly used hybrid models use the predictions of statistical models to delimit the parameters in mechanistic models (survival rate, dispersal rate, etc.) (Gallien *et al.*, 2010). They may include data on environmental fragmentation, an estimate of colonisation capabilities (Dullinger *et al.*, 2004; Engler and Guisan, 2009; Midgley *et al.*, 2010) and an analysis of the risks of local extinction (Anderson *et al.*, 2009).

These different approaches illustrate the complexity of the mechanisms involved and the consequences of that complexity in terms of the responses of species to climate change. They also place our capacity to predict the consequences of climate change for species and populations in a rather critical light. They require considerable knowledge on the processes related to population survival and demographics, as well as on the effects of the environment (temperature, discharge, etc.) on those processes (Helmuth *et al.*, 2005; Porter and Kearney, 2009; Buckley, 2010; Piou *et al.*, 2010). As a result, they are difficult to implement and can be used for only a limited number of species that have undergone extensive study (Lauzeral, 2012).

## ■ Non-inclusion of anthropogenic pressures

In general, only climate forcing is taken into account in distribution models for future projections (but see Lassalle *et al.*, 2009b). Yet many other anthropogenic pressures, such as water abstractions, pollution, dams and weirs, loss of ecological continuity, fishing, stocking, etc. constitute important factors in the local presence of species (see for example Pont *et al.*, 2006).

These pressures can skew the modelling results for the realised niches of many species, for example certain favourable environments are not or no longer occupied by a species due to dams, abstractions, etc. That is the case for Atlantic salmon in the Seine basin. In the wake of various anthropogenic pressures, its range has been drastically reduced since the end of the 1800s (Belliard *et al.*, 2009). Conversely, certain modifications made to the environment can encourage the presence of a species, e.g. the slowing of the current by an obstacle is favourable for limnophilic species. Finally, stocking of commercial species (brown trout, pike, etc.) occasionally occurs in environments seen as less favourable, which distorts the modelling of the realised niche. It would be difficult to integrate these parameters in the models given the lack of available data and the lack of knowledge concerning how they will evolve in the future (see Box 11).

In addition, during the formulation of distribution models, it is assumed that these pressures will not change in the future and that their interactions with the environment will not change either, which does not seem very likely. Certain anthropogenic pressures increase the vulnerability of aquatic environments, notably through greater abstractions or degradation of water quality. That is why it is necessary, when interpreting modelling results, to assess the dynamics of fish populations assuming greater anthropogenic pressures. In addition, if the results are used locally, *ex post* analysis should be carried out to check that the habitats considered favourable by the models are in fact favourable in spite of any local pressures (hydromorphological alterations, eutrophication, etc.).

## Accounting for obstacles to river flow

To date, very few studies include in models the presence of obstacles to river flow, in spite of their significant impact on the effective distribution of aquatic species and on their future evolution.

For the Explore 2070 project (MEDDE/Biotope, 2013) and in work by Buisson *et al.* (2008), this variable was taken into account by projecting future distributions **assuming that dispersal is either equal to zero or unlimited**[27]**.**

- In the first case, only those zones currently considered favourable will be favourable in the future. The favourable area for a species can therefore either remain stable or decrease in size.
- In the second case, a species is deemed capable of dispersing throughout the entire hydrographic network. No obstacles block its dispersal.

The projections produced by these two scenarios indicate the range of possible outcomes. Depending on the ecology of each species (e.g. inherent dispersal capability), hypotheses can be drawn up to zero in on the most probable projections.

Explicit inclusion of obstacles to river flow in models has been proposed by Lassalle *et al.* (2009b) for migratory species (see also Hein *et al.*, 2011, in Sweden). However, only very large obstacles (dams) were taken into account in that study.

Today, the data on obstacles in French rivers (ROE-Onema[28] database on river obstacles) should help in devising models including the obstacles to dispersal for all freshwater species in continental France. For further progress, it will be necessary to obtain more complete and precise data on all obstacles (i.e. head-drop, existence of fish passes, etc.).

*27. In Buisson* et al. *(2008), only the hypothesis of unlimited dispersal was taken into account.*
*28. See http://www.Onema.fr/REFERENTIEL-DES-OBSTACLES-A-L.*

# Main changes expected for fish in France in response to climate change

Studies based on species distribution models have increased rapidly in number over the past few years. Even though this type of study has been run far less often for fish than for terrestrial organisms, a recent bibliographical review nonetheless inventoried 66 scientific publications from 1980 to 2011 on the expected effects[29] of climate change on the distribution of freshwater fish around the world (Comte *et al.*, 2013). The study highlighted the heavy taxonomic preference in favour of salmonids, which represent 54% of the articles published. In France, there are only five native salmonid species out of the 69 species assessed (IUCN France; MNHN; SFI; Onema, 2010). What is more, less than 10% of the inventoried articles address species considered vulnerable by the IUCN (2009). The most studied groups are, in decreasing order, salmonids, cyprinids, centrarchids and percids (see Figure 40).

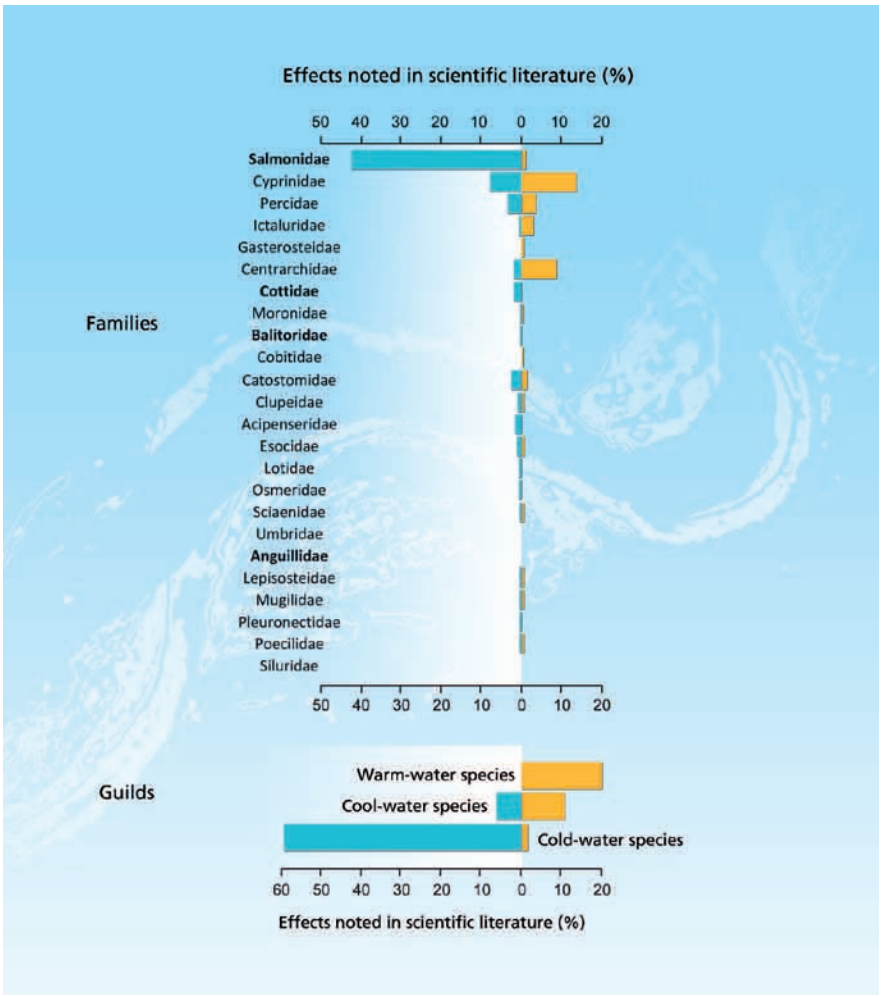
Among the species covered, some have specific characteristics that make them more difficult to model. For example, studies carried out on numerous taxonomic groups have shown that species inhabiting areas with a limited range of environmental conditions (specialist species) were more precisely modelled than species occupying wider ranges (generalist species), however, see also Jimenez-Valverde *et al.*, 2008. On the national level, projections concerning fish species that are more tolerant in terms of the thermal and altitudinal conditions are less precise than those for other species (Grenouillet *et al.*, 2011). In addition, rare species are particularly difficult to model due to the small quantities of occurrence data available (Lomba *et al.*, 2010). This lack of data in turn limits assessment possibilities concerning the response of the species to changes in its environment. However, certain modelling approaches specifically target the rare species, thus making it possible to provide at least a minimal description of their realised niches (Engler *et al.*, 2004; Hernandez *et al.*, 2006; Hayer *et al.*, 2008; Wisz *et al.*, 2008; Lomba *et al.*, 2010).

## Potential effect of climate change on the distribution of freshwater fish

In spite of significant uncertainty, certain major trends would seem to emerge on the national level. Cold-water species, characterised by narrow thermal tolerances such as brook lamprey, brown trout and bullheads, would seem to be the species most systematically impacted by climate change (Pont and Rogers, 2003; Buisson *et al.*, 2008; Buisson *et al.*, 2010; Tisseuil *et al.*, 2012a; Explore 2070 – MEDDE/Biotope, 2013) (see Figure 41, Box 12).

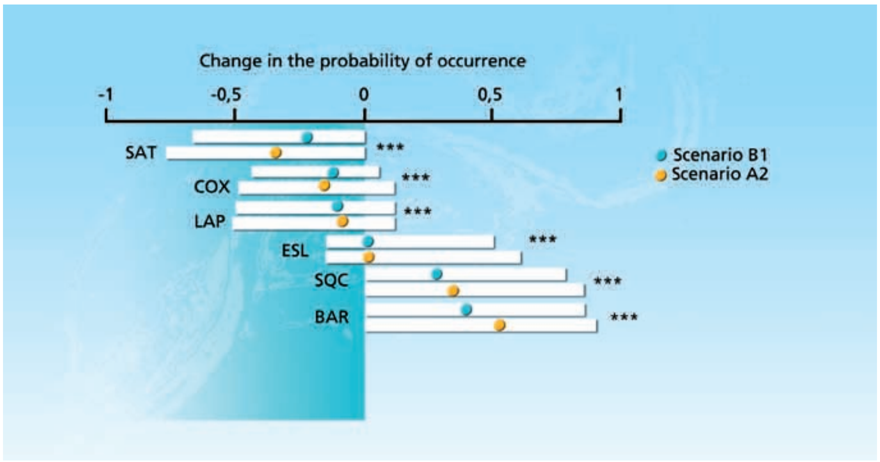
*29. A total of 77 publications were analysed, of which 66 addressed expected effects and 11 observed effects.*

**Figure 40**




*Proportion of negative expected effects (blue bars, reduction in favourable habitats) and positive expected effects (orange bars, increase in favourable habitats) for freshwater fish species grouped in taxonomic families and/or thermal guilds (diagrams modified, originally from Comte* et al.*, 2013).*

**Figure 41**




**Brown trout:** SAT
**Bullheads:** COX
**Brook lamprey:** LAP
**Pike:** ESL
**Chub:** SQC
**Barbel:** BAR

*Changes in the probabilities of occurrence according to the SRES B1 and A2 scenarios for the period 2051 to 2080, for six species of river fish (diagrams modified, originally from Buisson* et al.*, 2008). The change is the difference between the current and future average probabilities of presence for all the sites studied in France. The median values (points) and the minimum-maximum values indicate the amplitude of the changes in the probability of presence. A significant difference between the two scenarios is signalled by *** ($p < 0.01$).*

## Assessing the vulnerability of fish to climate change, the example of brown trout

For the Explore 2070 project, the potential impact of climate change on the distribution of 38 fish species was assessed using scenario A1B for the period 2060 to 2089. The assessment included both quantitative analysis based on the projections of the distribution models and qualitative analysis based on expert knowledge. The precise method employed is presented in detail in the final report that may be downloaded from http://www.developpement-durable.gouv.fr/-Explore-2070-.html.

The vulnerability analysis is presented as a data sheet indicating the effective distribution of the species, its colonisation capability, an analysis of the projections for current and future favourable habitats, and a vulnerability assessment including quantitative and qualitative indices (colonisation capability and the level of uncertainty affecting the results) (see Boxes 8 and 11).

### Current distribution and species biology

Brown trout are now found primarily in mountainous regions (Alps, Pyrenees, Massif Central, Vosges, Jura), in rivers in Brittany, in coastal rivers in Normandy and in northern France, as well as in certain rivers in limestone plains. In the above rivers, the thermal requirements of the species are met (4 to 19°C).

### Colonisation capability

Brown trout have excellent colonisation capabilities. In addition to its proficiency in overcoming obstacles, humans intervene significantly to promote sport fishing (stocking). Consequently, the capability of the species to disperse to new habitats is high.

### Projection of current distribution of favourable habitats

The model indices for sensitivity (74% of presences are correctly projected) and specificity (78% of absences are correctly projected) are high in general. The projection of the current distribution of favourable habitats for trout corresponds on the whole with the observed distribution of the species in France (see Figure 42).

### Projection of future distribution of favourable habitats

In that trout have high colonisation capabilities, the unlimited-dispersal scenario was preferred for the analysis (see the definition in Box 11). According to that scenario, the favourable habitat for brown trout is projected to be reduced by one-third in 2070 (see Figure 42). The remaining habitat would consist of refuge zones at the heads of river basins.

### Assessment of species vulnerability

For France as a whole and on the basis of the results, brown trout would appear to be highly sensitive to climate change.

They are therefore very vulnerable. The confidence index assigned by the experts to these results is 3 (on a scale of 1 to 3, where 3 is the highest level of confidence).

**Figure 42**

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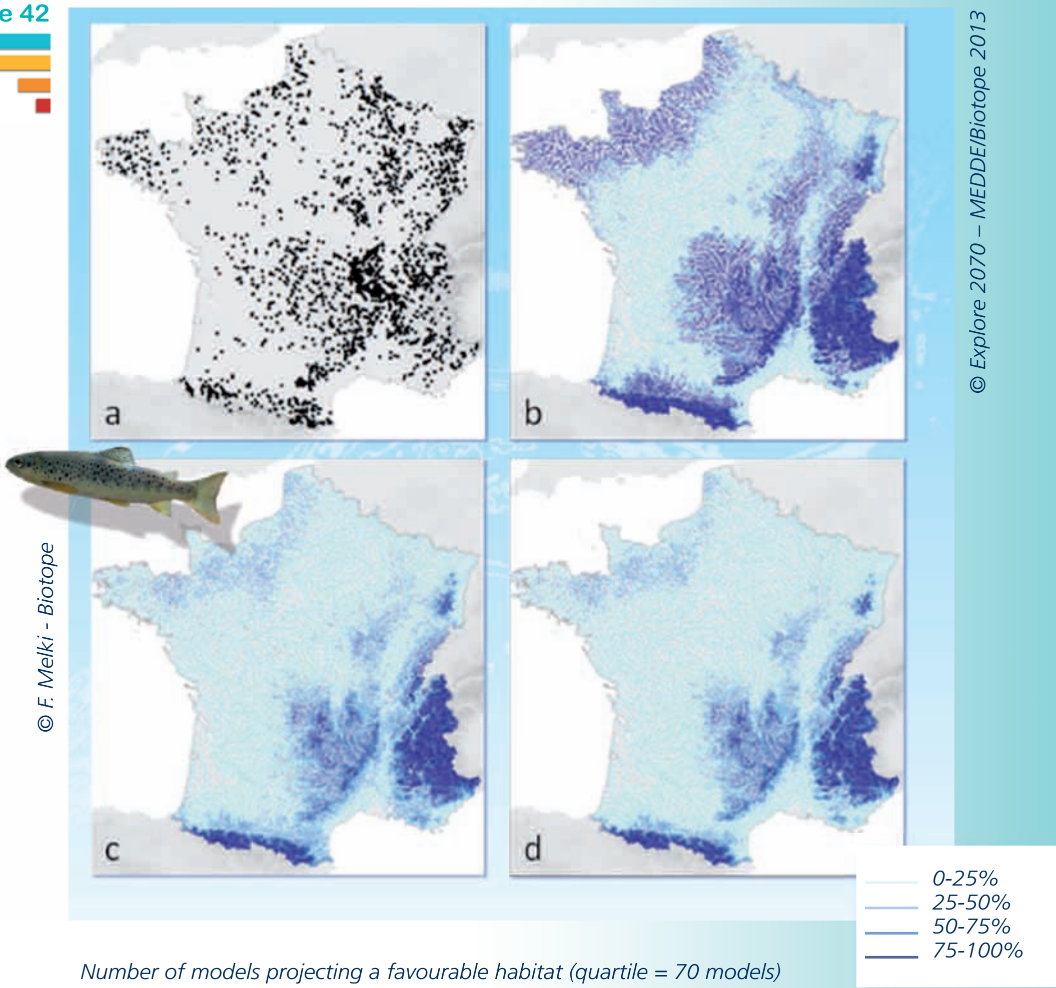



© Explore 2070 – MEDDE/Biotope 2013

*Examples of favourable-habitat projections for a species (brown trout) that reacts negatively to climate change.*
*(a) Presence observed (n=2 703 out of 4 381 sampling stations, source Onema, 2000-2008, using electrofishing).*
*(b) Habitats projected as currently favourable.*
*(c) Habitats potentially favourable in the future according to the zero-dispersal scenario.*
*(d) Habitats potentially favourable in the future according to the unlimited-dispersal scenario (scenario A1B for the period 2060 to 2089). The higher the number of models projecting a favourable habitat, the greater the probability that the river reach is in fact favourable for the species (Explore 2070 - MEDDE/Biotope, 2013).*

Other species, essentially those inhabiting the bream and barbel zones (see Chapter 2), systematically respond positively to climate change. For example, that is the case of chub and barbel (Pont and Rogers, 2003; Buisson *et al.*, 2008; Buisson *et al.*, 2010; Explore 2070 - MEDDE/Biotope, 2013) (see Box 13). However, greater uncertainty weighs on these projections than on those for cold-water species. Because these species have very large ranges, the predictive capacity of models is reduced in light of the variables taken into account. As a result, only partial knowledge is available on their realised niche (Grenouillet *et al.*, 2011; Logez *et al.*, 2012).

Concerning their distribution, the modelling results generally indicate an extension of their ranges to sections further upstream. The ranges of species living exclusively at the heads of river basins would be reduced to high-altitude refuge zones and the risks of their local extinction would be increased in certain lower-lying basins. The ranges of species in downstream zones would be modified with upper limits farther upstream, whereas changes in the downstream limits would depend more or less on the species. For some species, new river basins could become favourable. However, there is uncertainty concerning the capability of these species to colonise the new habitats and hydraulic constraints could limit their movement upstream.

It is also important to note that modelling of the realised niche for certain species, notably those located downstream, remains highly uncertain in spite of a major effort to improve processes (due to less effective sampling in large environments, less precise data due to greater heterogeneity and increased anthropogenic pressures).

Worldwide, the effects of climate change on the distribution of fish point in the same direction as the projections carried out in France. Cold-water species such as salmonids will likely be subjected to primarily negative effects whereas species located in the intermediate and downstream sections, such as cyprinids and centrarchids should benefit (Comte *et al.*, 2013).

Box 13

## Assessing the vulnerability of fish to climate change, the example of chub

For the Explore 2070 project, the potential impact of climate change on the distribution of 38 fish species was assessed using scenario A1B for the period 2060 to 2089. The assessment included both quantitative analysis based on the projections of the distribution models and qualitative analysis based on expert knowledge. The precise method employed is presented in detail in the final report that may be downloaded from http://www.developpement-durable.gouv.fr/-Explore-2070-.html.

The vulnerability analysis is presented as a data sheet indicating the observed distribution of the species, its colonisation capability, an analysis of the projections for current and future favourable habitats, and a vulnerability assessment including quantitative and qualitative indices (colonisation capability and the level of uncertainty affecting the results) (see Boxes 8 and 11).

### Current distribution and species biology

Chub are present in all French rivers with the exception of Brittany, a small number of coastal rivers and in the extreme northern section of the country. They are not present in rivers at mid and high altitudes. The species is fairly ubiquitous and tolerant.

### Colonisation capability

The species has not been extensively manipulated by humans (except as bait) and has good colonisation capabilities. It is therefore likely that it can rapidly colonise favourable habitats.

### Projection of current distribution of favourable habitats

The projection of the current distribution of favourable habitats for chub corresponds well to the observed distribution of the species in France, but would seem to be slightly underestimated. The sensitivity index is 76% (proportion of presences correctly projected) and the specificity index is 74% (proportion of absences correctly projected).

### Projection of future distribution of favourable habitats

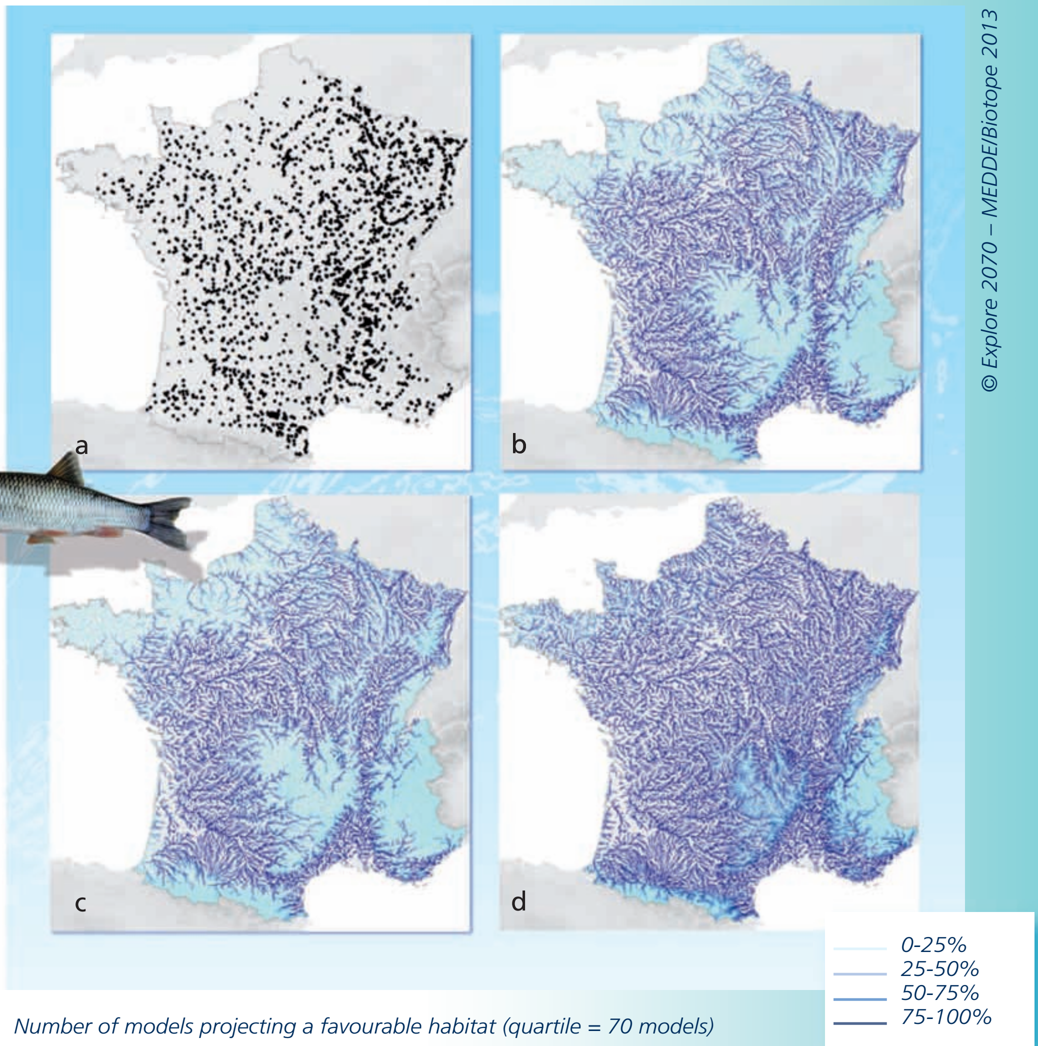
In that chub have non-negligible colonisation capabilities, the unlimited-dispersal scenario was preferred for the analysis (see the definition in Box 11).

According to the A1B climate-change scenario selected, by 2070 the species should benefit from a major increase in favourable habitats. With the exception of mountain regions and the coast in the north-western section of the country, the entire hydrographic network should become favourable (see Figure 43).

### Assessment of species vulnerability

Chub should benefit strongly from climate change and colonise virtually all the river reaches in the basins where they are already present. The vulnerability of the species is low. The confidence index assigned by the experts to these results is 3 (on a scale of 1 to 3, where 3 is the highest level of confidence).

**Figure 43**

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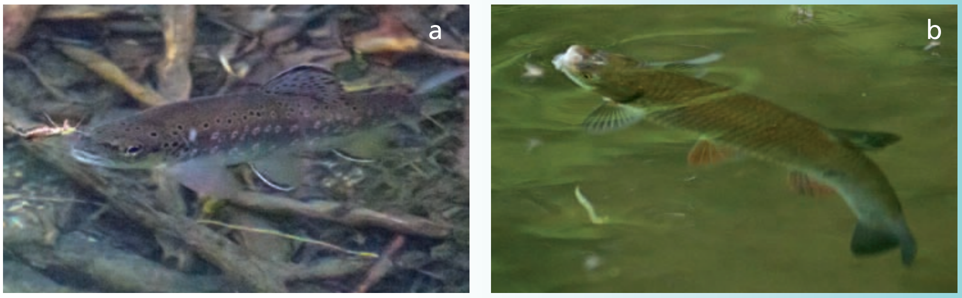
*Number of models projecting a favourable habitat (quartile = 70 models)*

*Examples of favourable-habitat projections for a species (chub) that reacts positively to climate change.*
*(a) Presence observed (n=2 219 out of 4 381 sampling stations, source Onema, 2000-2008, using electrofishing).*
*(b) Habitats projected as currently favourable.*
*(c) Habitats potentially favourable in the future according to the zero-dispersal scenario.*
*(d) Habitats potentially favourable in the future according to the unlimited-dispersal scenario (scenario A1B for the period 2060 to 2089). The higher the number of models projecting a favourable habitat, the greater the probability that the river reach is in fact favourable for the species (Explore 2070 - MEDDE/Biotope, 2013).*

**Figure 44**




a, b © N. Poulet - Onema

*According to the statistical models, future climate change should be detrimental for brown trout (a) and beneficial for chub (b).*

## Potential effects of climate change on diadromous fish in European and French river basins

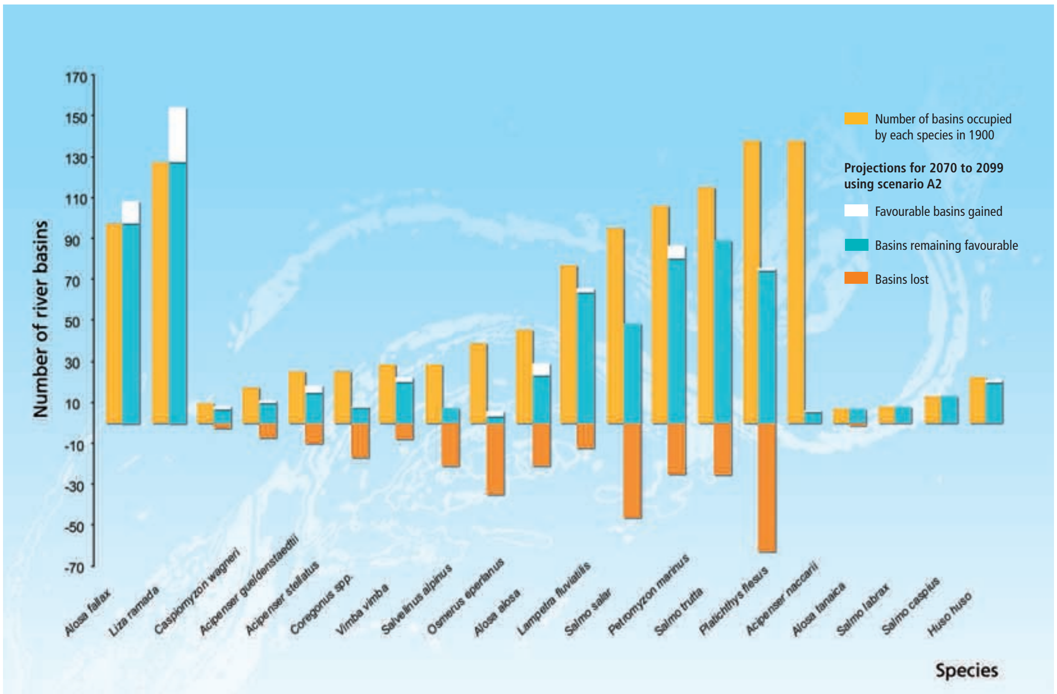
The results of the projections run for diadromous fish differ depending on the species. For the European and North African basins, Lassalle *et al.* (2009ac) showed that among the 20 species studied using an intermediate GHG emissions scenario (scenario A2, see Figure 45), three long-term (2070 to 2099) trends stood out:

■ species for which the number of favourable basins increased (10 to 30%), e.g. eels and Twaite shad - *Alosa fallax*;

■ species for which the number of favourable basins decreased (16 to 92%), e.g. Atlantic salmon and Arctic charr;

■ species for which distributions changed little or not at all, e.g. Caspian lamprey - *Caspiomyzon wagneri*.

**Figure 45**




*Predicted changes in distribution for each diadromous[30] species (presence or absence in each river basin) for Europe and Northern Africa (Lassalle* et al.*, 2009c).*

Concerning France, the results of the studies converge with those for Europe for Atlantic salmon and eels (scenarios A1B, A2 or B1, Buisson *et al.*, 2008; Explore 2070 - MEDDE/Biotope, 2013). On the other hand, simulations produced by demogenetic[31] individual-based models indicate that strong variations in discharge between summer and winter could cause greater problems for the continued existence of salmon in small French coastal rivers than the increase in temperature (Piou *et al.*, 2010; Piou and Prévost, 2013). According to these authors, degradation of the conditions required for marine growth is thought to potentially be the factor having the greatest impact on the risks of local extinction (Piou *et al.* 2010; Piou and Prévost, 2013). These results are consistent with a study by Friedland (1998).

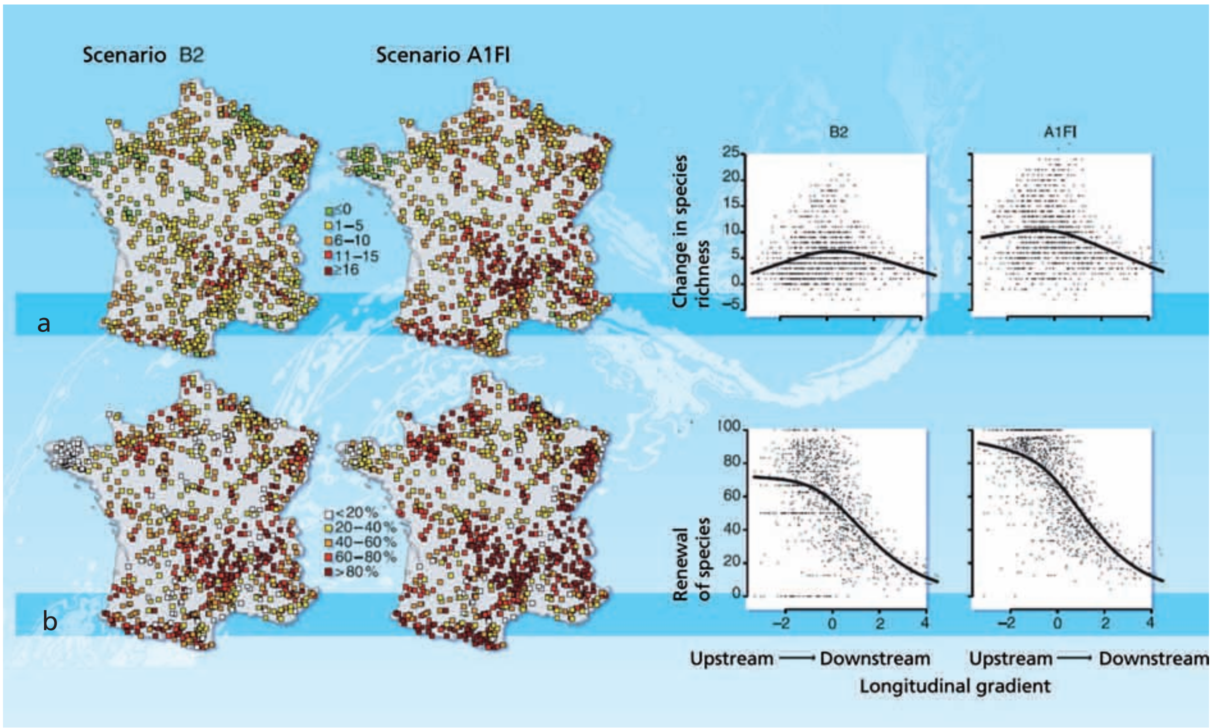
*30. A diadromous fish spends part of its life in the sea and part in fresh waters.*
*31. The key parameters determining the evolutionary potential and the continued existence of populations are 1) demographics, i.e. sufficient reproduction, and 2) conservation of a diverse gene pool, a factor in adaptive capacity. Demogenetic models look at these two parameters and their interaction with the environmental and demographic stochasticity resulting from global warming, for example.*

## Potential effects of climate change on the community scale

Study of the potential response of communities to climate change consists of compiling the responses for each species and not on a direct approach addressing the community scale. This is because each species has a number of ecological specificities that distinguish its response to climate change, in terms of both the trend (positive or negative) and the amplitude of the response. For this reason, it was deemed preferable to proceed by first modelling the impacts on individual species before compiling all the results for the species in view of assessing the impact on the community level. However, it should be noted that this approach has a disadvantage in that it cannot take into account biotic interactions nor the capacity of environments to serve as habitats for species not included in the species modelling. In addition, not all the species present in France are taken into account. For this reason, the perception of communities remains partial.

Modelling to date concludes that species richness of fish should, on the whole, increase in all French rivers (Buisson *et al.*, 2008; Buisson and Grenouillet, 2009). This increase may be explained by the fact that habitats made favourable by climate change will likely be rapidly colonised by a large number of species from the downstream sections of rivers. According to Buisson (2009), the species richness in intermediate and upstream zones should increase more than in downstream sections where it should remain more or less constant (see Figure 46). These results are in line with a number of monitoring programmes carried out over the past decades on sea fish (e.g. Hiddink and ter Hofstede, 2008) and freshwater fish (e.g. Daufresne and Boët, 2007). The changes in species occurrence will probably result in greater uniformity of communities in rivers (Buisson and Grenouillet, 2009; Tisseuil *et al.*, 2012b). Finally, variations in diversity between communities (beta-diversity) will also change, due to two distinct underlying mechanisms. In the upstream and downstream sections, variations will be caused primarily by a modification in the species richness within communities (colonisation or local extinction), whereas in intermediate sections, the main mechanism will be a renewal of species, i.e. new species arriving from adjacent communities will replace species that have gone locally extinct (see Figure 46) (Tisseuil *et al.*, 2012b).

**Figure 46**




*Projected change in (a) the species richness of fish communities and (b) taxonomic composition, according to scenarios B2 and A1FI. The changes are shown in map form (left) and along the upstream-downstream gradient (right) (Buisson and Grenouillet, 2009).*

# Conclusion and outlook

Over the past few years, numerous tools have been developed to assess the impact of climate change on living organisms. Among those tools, statistical distribution models play an important role because they are relatively simple and can project the potential habitat changes of a given species in response to different climate-change scenarios. In that certain ecological processes are not taken into account in these models, other tools, namely mechanistic models, have been developed in parallel. They are more powerful, but require much more knowledge on species biology. That is why their application to a large number of species has remained limited.

Even though the many underlying assumptions limit the possibilities of transposing the results locally, the projections produced by the distribution models reveal trends that can be used to assess the vulnerability of each species and any changes in the richness and composition of communities along the upstream-downstream gradient.

Generally speaking, all the models foresee an upstream shift in the ranges of cold-water species. The ranges of species living exclusively at the heads of river basins would be reduced to high-altitude refuge zones and the risks of their local extinction would be increased in certain lower-lying basins (piedmonts, plains). Conversely, the conditions for species located in intermediate zones or downstream, such as cyprinids and centrarchids, would improve. On the community scale, an increase in species richness and greater uniformity of communities is expected in all rivers. In other words, the communities will probably be richer, but more similar to each other, resulting in a loss of diversity. It should however be noted that rare species are not taken into account due to a lack of sufficient data.

The vulnerability of species to climate change depends on the ecological requirements of each species and some of these requirements are currently not taken into account in the models for freshwater fish in continental France (dispersal capabilities, anthropogenic pressures, adaptive and evolutionary processes, etc.). A quantitative approach in conjunction with a critical analysis of the results based on expert knowledge would now appear to be a solution to refine the potential distribution maps for each species in the context of climate forcing.

In the future, the formulation of hybrid models combining both statistical and mechanistic models should make it possible to refine the projections produced by the distribution models, on the condition that the necessary data are available.

**Figure 47**

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*Bullheads, a group of small, benthic species inhabiting cold-water rivers, will likely be affected by climate change.*

The development of these models should proceed in parallel with the many research projects already under way to understand the pressure-impact relations (changes in thermal and hydrological regimes, sediment dynamics, invasive species, etc.) that are factors in defining adaptive measures. Use of data series spanning long time periods, for both biological and environmental data, e.g. discharges, water temperature, etc., is also essential. In addition, it would appear that knowledge on species' ecology, even that of the most common species, is far too fragmentary and insufficient for mechanistic models. Filling in the gaps is a further priority.

Finally, too few studies address time periods spanning the next decades, which are nonetheless an intermediate target of great importance for management. A great amount of work must be put into all the above topics.

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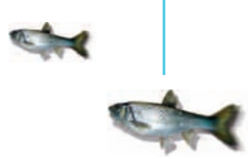


4

# Taking action to reduce the vulnerability of fish communities

# Introduction

The previous chapters highlighted a number of climate-change issues. In France, air and water temperatures rose approximately 1°C between 1900 and 2000. Surface-water and groundwater hydrology were also affected but the trends are not as clear given the difficulties in distinguishing between the effects of climate change and those of local human activities. For the coming 30 years, all climate projections (whatever the greenhouse-gas (GHG) emissions scenario) indicate warming between 1.5 and 3°C. Given an increase in evapotranspiration, monthly mean discharges and groundwater recharging rates will likely drop and the severity of low-flow periods worsen over vast sections of continental France.

These climate and hydrological changes entail numerous consequences for freshwater fish species. For example, effects on the reproduction, growth and seasonal rhythms of certain species have been observed. Some species have moved up river, extending their range when movement is not blocked by other factors such as weirs and dams. For the coming decades, all the models foresee a shift in the ranges of cold-water species to areas farther upstream. Under these conditions, species located in intermediate zones or downstream, such as cyprinids and centrarchids, would benefit while those inhabiting upstream sections would be particularly threatened. Anthropogenic pressures (dams, impoundments, sealing of banks, abstractions for an array of uses, release of polluted water, etc.) will reinforce these effects, most likely leading to an acceleration of ecological modifications in freshwater environments.

The probable consequences of climate change have resulted in greater awareness of policy-makers, which has in turn led to the preparation of adaptation plans on the world, national and local levels. This chapter presents those plans and the corresponding measures. The first part presents the various types of adaptation strategies, their conceptual framework and the steps involved in their formulation. The second begins with a review of French initiatives targeting adaptation to climate change. It then goes on to discuss in detail a number of measures designed to effectively reduce the vulnerability of fish species in France.

# Adaptation strategies

## Definitions

The fourth assessment report of the Intergovernmental panel on climate change (IPCC, 2007) defined adaptation as "Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities". Adaptation complements mitigation, the purpose of which is to limit concentrations of GHGs in the atmosphere (see Box 14).

Box 14

### Adaptation or mitigation?

Contrary to adaptation, mitigation strategies attempt to limit the increase in concentrations of GHGs in the atmosphere (IPCC, 2007).
The two are complementary in that mitigation attempts to avoid that to which we will have difficulty adapting and adaptation attempts to adjust to that which we will not be able to avoid. And in fact, if GHG emissions are not reduced, implementation of effective adaptation strategies will be much more complex and the results uncertain. With the above in mind, the United Nations framework convention on climate change (UNFCCC) highlighted the need to create synergies between the measures undertaken for mitigation and adaptation because it is the combined effort on both aspects that will determine the level of risk arising from the impacts of climate change. It should be noted, however, that some mitigation measures, e.g. the development of certain energy sources (nuclear power, hydroelectricity, agrofuels) may counteract some adaptive measures (water temperatures, ecological continuity).

In other words, the objective is to develop a series of measures to foresee and reduce the vulnerability[32] of ecosystems over different spatial and temporal scales. Vulnerability is a function of the character, magnitude and rate of climate variability to which a system is exposed, its sensitivity and its adaptive capacity.
The IPCC (2007) defined different types of adaptation:

- anticipatory (or proactive) adaptation which takes place before the impacts of climate change are observed;
- autonomous (or spontaneous) adaptation which does not constitute a conscious response to climatic stimuli, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems;

*32. Vulnerability is central to the concept of adaptation. According to the IPCC (2007), "Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes". Vulnerability is the result of three factors together, i.e. 1) system exposure to climate impacts and risks (character and magnitude of climate disturbances), 2) system sensitivity (potential harm) and 3) its adaptive capacity (to adjust and cope with the consequences of the disturbances). The vulnerability of an environment or a species increases when its sensitivity and exposure are high and its adaptive capacity is low.*

■ planned adaptation which is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change, and that action is required to return to, maintain or achieve a desired state;
■ reactive adaptation which takes place after the impacts of climate change have been observed. Recently, other forms of adaptation have emerged, e.g. ecosystem-based adaptation (see Box 15).

Box 15

**Ecosystem-based adaptation (EbA)**

Ecosystem-based adaptation brings into play sustainable management, conservation and ecosystem restoration to ensure the supply of the services required by populations to adapt to the negative effects of climate change. The objective is to maintain and increase resilience, while reducing the vulnerability of ecosystems and human communities to the negative effects of climate change. EbA is an adaptation technique that can produce beneficial effects in many fields (social, economic, cultural), contribute to preserving biodiversity and reinforce the traditional knowledge of native populations and local communities.

The value of these multiple definitions is to show the diversity of possible measures and the necessary synergies, notably between the proactive measures implemented by public policy and the efforts of water managers to adapt reactively. An understanding of the different types of adaptation is also essential in view of assessing costs and defining plans of action (Basilico *et al.*, 2010). Certain measures are said to be "reversible" because it is possible to change the strategy and/or recalibrate the measure, whereas "irreversible" measures produce effects over the long term and cannot be replaced or recalibrated (risk of maladaptation[33]).

## ■ The different steps in formulating an adaptation strategy

There is no set procedure for devising adaptation strategies or measures. However, EU organisations attempt to guide Member States in order to set up consistent and viable programmes on the EU level.

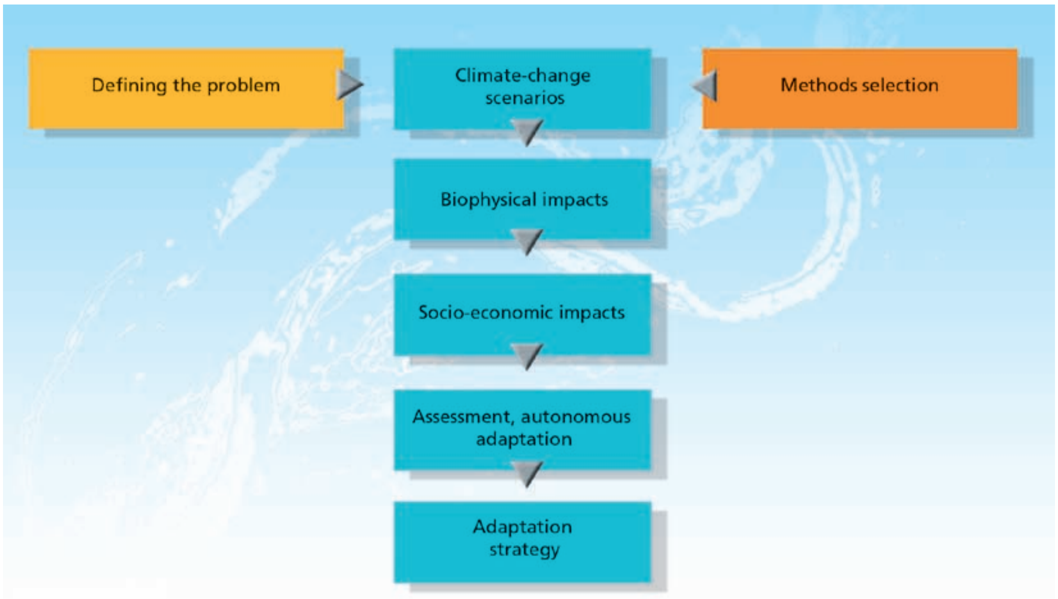
The scientific literature notes two approaches to adaptation strategies and measures, the first is "top-down" and the second is "bottom-up" (Carter *et al.*, 1994).

The top-down approach calls on climate models based on projected socio-economic scenarios to estimate the impacts on regions, environments and species, and the resulting vulnerabilities (vulnerability is seen here as the end point of the analysis) (see Figure 48).

By taking into account past experience and adaptive capacity using different indicators (economic resources, infrastructure, technological level, etc.), the bottom-up approach starts with adaptive capacity to assess the sensitivity of regions, environments and species (vulnerability is seen here a starting point of the analysis). Today, assessments have become increasingly complex and often mix the two approaches in preparing decisions (Dessai *et al.*, 2004; Kates and Wilbanks, 2003; McKenzie Hedger *et al.*, 2006). It is even possible to speak of case-by-case analysis for hydrosystems given their high sensitivity and vulnerability to climate change.

*33. Maladaptation is any change in natural or human systems that inadvertently increases vulnerability to climatic stimuli, i.e. an adaptation that does not succeed in reducing vulnerability but increases it instead (IPCC, 2007).*

Figure 48




*Top-down approach, guided by the climate-change scenarios incorporating data differentiating between economic sectors (Carter* et al.*, 1994).*

## ■ Managing uncertainty

In adapting to climate change, three types of uncertainty combine:

■ uncertainty concerning future climate changes, given that the expected impacts of a 2°C average increase in temperatures are in no way comparable to those of a 4°C increase;

■ uncertainty concerning the possible consequences of a climate scenario on the local level;

■ uncertainty concerning the adaptive capacities of our societies in the future.

These different uncertainties interact to make the overall situation even more uncertain (Mearns, 2010). The simple fact of climate change will have an effect on adaptive capacities and on the types of mitigation measures that will be taken. And the latter will in turn impact the progression of climate change. Given these uncertainties, a set of measures designed to adapt to climate change may lead to unexpected results and maladaptation. The latter may occur, for example, following a calibration error, i.e. the adaptive measures are poorly adjusted due to incorrect assessment of the character and magnitude of the future changes or due to inadequate responses to the measures. It may also occur if an adaptive measure transfers vulnerability from one system to another, hence the importance of adopting integrated approaches, or from one period of time to another, e.g. the measure may first produce positive, then negative results, or in the opposite order.

Three types of tools have been proposed by ADEME (Hernandez *et al.*, 2012) to take these uncertainties into account during decision-making:

■ adaptive management, a system to design and manage adaptation in the framework of a flexible, open and iterative process that can integrate any progress made on climate change. An example might be a long-term planning process in conjunction with a procedure to continuously revise and improve the adaptation strategy, on the basis of data supplied by long-standing observation systems and constantly updated knowledge on the climate and hydrology. In this type of system, the difficulty consists of avoiding threshold effects that may result in maladaptation;

■ no-regrets measures that produce benefits above and beyond adaptation, thus facilitating decision-making in the face of uncertainty. In other words, these measures reduce vulnerability and result in environmental and social benefits in all climate-change situations. An example might be to invest in infrastructure with a shorter service life, for instance building a series of low-cost check dams rather than one very large dam;

■ analysis of different adaptation options, in view of selecting the most effective measures after taking into account various climatic scenarios.

# A good start to water adaptation policy in continental France

Whatever the field, adaptation policies for climate change are formulated in several steps. The first step consists of doing the necessary studies and research, or setting up groups of experts from various sectors. For the specific case of freshwater fish, this step serves to assess their vulnerability and that of their environment. Following this work, preparation of summary documents and/or vulnerability indicators serve to enhance the political debate, formulate and implement regulatory policies, and to devise adaptation plans for use on the national level, prior to being adapted to lower levels. In parallel, research results are transferred to water managers, integrated in management plans and presented in data sheets for those plans. The feasibility and effectiveness of the proposed measures can thus be assessed and adapted to the local context.

## Defining issues by doing research

Over the past few years, a number of research projects funded by various organisations (Ecology ministry via notably the "Climate-change impacts and management" programme, the National research agency, Onema, the Water agencies, etc. (Basilico et al., 2009)) have attempted to assess the impact of climate change on water resources and the related ecosystems. The results have provided the elements required to formulate and implement a consistent set of adaptive measures on scales ranging from local to national. A few of these projects are presented below. Only two studies (Explore 2070 and AMICE) looked at the environments and species of freshwater ecosystems (see Box 16). For the most part, the others focussed on water management in a context of increasingly rare water resources (see Box 16).

A number of other initiatives have also been taken in recent years. Of note is the September 2009 report of the interministerial work group to assess the impacts of climate change and the costs of damage and adaptive measures in France. The work group, set up in March 2007 and managed by the Ecology ministry and ONERC, brought together various ministries (Agriculture, Health, Tourism, etc.) and a wide array of experts to assess the costs of climate change and determine the relevant adaptive measures. The work was divided into nine topics, namely agriculture-forestry, health, tourism, biodiversity, water, risks, transport infrastructure and buildings, energy and regions.

Box 16

## Research projects working on water and climate change

### Explore 2070

The purpose of the Explore 2070 project, which took place from June 2010 to October 2012, was to:

- assess the impacts of climate change on aquatic environments and water resources up to 2070 in order to foresee the main challenges and prioritise risks;
- formulate and assess adaptation strategies for the water sector by selecting the most suitable measures to meet the identified challenges while reducing the risks.

The project was managed by the Ecology ministry (Water and biodiversity directorate, Risk-prevention general directorate, Energy and climate general directorate, Sustainable-development division), with Onema, CETMEF, the Water agencies and the basin regional environmental agencies. The project brought together approximately 100 experts from research institutes and specialised engineering firms to produce a "water supply and demand" model capable of assessing the vulnerability of all river basins in France taking into account socio-economic trends and climate change in order to determine the risks of not satisfying the demands for water resulting from the four main human uses (drinking water, agriculture, industry, energy) and from environmental needs. Specifically concerning freshwater environments, the project produced vulnerability indicators for 38 freshwater fish species (see Boxes 12 and 13 in Chapter 3). All the results produced by the project may be found at the site *http://www.developpement-durable.gouv.fr/Evaluation-des-strategies-d.html.*

### AMICE

The purpose of the AMICE project, funded by the European INTERREG IV B ENO (2009-2013) programme, was to set up a comprehensive strategy to adapt to the impact of climate change on flooding and drought regimes in the Meuse basin. The project involved 17 partner organisations from Germany, Belgium, France and the Netherlands and was structured around various work groups targeting:

- improvements in knowledge on the impact of climate change on the Meuse basin, including the natural environments and all species;
- the creation of a network of dispersed structures to absorb peak discharges;
- preparation for the possible future discharges in the management systems of existing large structures;
- improvements in crisis management of floods;
- dissemination of project results and communication.

Similar to the Explore 2070 project, AMICE proposed an indicator for the vulnerability of certain fish species found in the Meuse alluvial valley.

The results of the project may be consulted at *http://www.amice-project.eu/fr/index.php.*

### R²D²2050 - Risks, water resources and sustainable management of the Durance River in 2050

The purpose of the R²D² 2050 project, part of the "Climate-change impacts and management" programme (GICC 2010-2013), was to run a prospective study on water management for a complex area highly impacted by human activities, the Durance River basin (13 000 square kilometres). The study addressed the current functioning of the hydrosystem (quantitative and biological aspects), then the river dynamics were assessed on the basis of territorial, socio-economic climate scenarios run in close collaboration with local stakeholders involved in water management.

The main determinants (input and output data of the implemented factors) were identified, described and modelled on a number of nested scales ranging from Europe as a whole to the management units in the river basin. In addition, thanks to an integrated modelling platform for the influenced regimes (taking into account management aspects), that cross-cuts the thematic work and will serve for the forward-looking resource/use studies, this project produced a dynamic and quantified image of the various management scenarios developed with the stakeholders.

*More information is available at http://onerc.developpement-durable.gouv.fr/fr/projet/r2d22050-risque-ressource-en-eau-et-gestiondurable-de-la-durance-en-2050.*

**REMedHE - Climate-change identification and impacts on integrated management of Mediterranean water resources, a comparative assessment of the Hérault and Ebre regions**

The purpose of the REMedHE project, part of the GICC 2012-2015 programme, was to understand the complex relations between climate forcing, anthropogenic pressures and discharges on an operational scale in two Mediterranean river basins, namely the Hérault River basin (2 500 km²) in southern France and the Ebre River basin (85 000 km²) in Spain. For each river basin, it was necessary to develop an integrated modelling system for water resources/uses in order to:

- represent hydrosystem functioning and changes over the past 50 years;
- propose hydrological scenarios integrating climate change and changes in water uses over the short (2025) and mid (2050) terms;
- assess the balance between resource availability and future demand;
- test adaptation/mitigation strategies by co-developing scenarios with water managers in the basins.

This approach should make it possible to compare the current and future vulnerability of water resources as a function of needs.

More information is available at *http://www.gip-ecofor.org/gicc/?q=node/535.*

**HYCCARE - Hydrology, climate change, adaptation, water resources in the Bourgogne region**

In view of preparing public decision-makers for climate-change adaptive measures, the purpose of the HYCCARE project, part of the GICC 2012-2015 programme, was to improve local characterisation of climate-change impacts and to develop synergies between researchers and local stakeholders.

The project is divided into two main parts.

- The first deals with obtaining knowledge on the impacts of climate change on water resources in a dozen river basins and on the resulting vulnerabilities. The expected results include better knowledge on the probable changes in climate risks and an estimate of basin sensitivity taking into account changes in the regeneration capacity of water resources. The high spatial-temporal resolution of the results will assist local stakeholders in perceiving the risks involved.
- The second addresses the actions of local stakeholders based on the selected approaches to adaptation and resource management. Analysis of the collective interaction concerning vulnerabilities and potential adaptation strategies will identify leverage points for generating public policy on the issues of climate change and its impacts.

More information is available at *http://www.gip-ecofor.org/gicc/?q=node/534*.

## ■ The national plan for adaptation to climate change (PNACC)

The Ecology ministry served as the driving force in launching the initial adaptation efforts in France at the end of the 1990s, which resulted in the creation in 2001 of a national observatory (ONERC) on the effects of global warming in continental France and the overseas territories, with direct links to the IPCC. The main objectives of ONERC, which became part of the Energy and climate general directorate (DGEC) in 2008, are to make information on climate change widely available, draft recommendations on preventive and adaptive measures, and contribute to dialogue on climate change with developing countries.

Following the 2004 Climate plan and the formulation of the 2006 National strategy for adaptation to climate change, France definitively adopted its National plan for adaptation to climate change (PNACC) on 20 July 2011 (see Boxes 17 and 18 for information on mitigation measures). According to ONERC, the fact that the PNACC inserts adaptation into all public policies makes it the first full-spectrum plan of its type in the EU.

It has since resulted in over 80 detailed projects comprising 230 measures spanning 20 fields including water and biodiversity. A few examples are presented below.

### Key measures in the water sector

■ Improve knowledge of the impacts of climate change on water resources and the impacts of various possible adaptation scenarios.

■ Set up effective means to monitor phenomena involving structural imbalances, shortages and droughts in a context of climate change.

■ Increase water savings and improve the efficiency of water use. Reduce abstractions 20% by 2020 (not including water stored in winter).

■ Accompany forms of economic development and land use that are compatible with locally available water resources.

■ Reinforce integration of climate-change issues in water planning and management, in particular in the work programmes of the Water agencies (2013-2018) and in the future river-basin management plans (RBMP) for 2016 to 2021.

### Key measures for biodiversity

■ Integrate biodiversity issues related to climate-change adaptation in research and experimental programmes.

■ Reinforce the existing tools used to measure the impact of climate change on biodiversity.

■ Promote integrated regional management techniques taking into account the effects of climate change on biodiversity.

■ Integrate adaptation to climate change in national strategies and plans to preserve biodiversity.

Two years following the launch of the plan, few measures have been completed, however most are under way (81% of the measures and 96% of the projects). It should be noted that some river basins have created regional versions of the PNACC in order to effectively launch initial implementation of the adaptive measures. That is the case for the Rhône-Méditerranée basin which adopted in 2013 its Basin plan for adaptation to climate change. The plan assesses vulnerability throughout the basin using indicators presented as maps for five main parameters, i.e. water availability, soil moisture levels, biodiversity, nutrient levels in water and snow cover. The basin plan proposes an adaptive strategy and a set of measures to reduce vulnerability. It may be downloaded from *www.eaurmc.fr/climat.*

Box 17

## The regional climate-air-energy plan (SRCAE)

In parallel with the formulation of the PNACC, the Grenelle 2 environmental law (12 July 2010) foresaw the creation of regional climate-air-energy plans (SRCAE) managed by the regional prefect and the president of the regional council.
The plans set regional objectives for the period 2020 to 2050 concerning reductions in GHGs, limiting energy demands, developing renewable energies, reducing air pollution (mitigation strategy) and adapting to climate change.
Practically speaking, the plans primarily address mitigation measures that will produce results in favour of biodiversity only over the very long term.

Box 18

## The territorial climate-energy plan (PCET)

The territorial climate-energy plan (PCET) is a planning document created by the national climate plan and mentioned in both Grenelle environmental laws 1 and 2. The purpose of the plan, a mandatory document for towns with over 50 000 inhabitants, is to assist local governments in incorporating energy issues in all their public policies. A further goal is to limit GHG emissions and to set up a local adaptation strategy for the effects of climate change.
A PCET generally includes:
■ a characterisation report (carbon balance, energy footprint, register of GHG emissions (diffuse, mobile, local));
■ a forward-looking study (major trends, emerging phenomena);
■ quantified objectives with deadlines, targeting results at least as demanding as the national and European objectives (factor 4 by 2050, 3x20 objectives for 2020);
■ a section targeting mitigation and another targeting adaptation;
■ indicators (generally for pressure, state and response) to monitor and assess on the desired scale (national, regional, town, etc.).

It should be noted that a PCET must be taken into account by the local development plan (SCOT) and the local zoning plan (PLU), and it must be compatible with the regional climate-air-energy plan (SRCAE) that regions must set up with the regional prefect (see Box 17). A PCET may serve as the "climate section" in the Agenda 21 plan of a local government or in a territorial sustainable-development plan. Finally, if the plan is formulated by a region, the region may integrate it directly into its SRCAE.

### ■ Integration of climate-change issues in French and European regulations on water management

Even though the IPCC warned governments as early as 1988 about the possible consequences of climate change, it took several years for the issue to feature in regulations (see Box 19).

Box 19

## Background information on adaptation worldwide

Historically speaking, it is the Intergovernmental panel on climate change (IPCC) that disseminated and popularised the concept of adaptation. The panel was created in 1988 by the World meteorological organisation (WMO) and the UN environment programme. Its mission is to report on current scientific knowledge on changes in the climate worldwide, the impacts and the means to mitigate the changes. Even though the IPCC has no regulatory powers, its influence on public policies concerning the climate and pollution control has been significant throughout the world in light of the fact that many climate plans incorporating adaptation strategies came into being starting in the 1990s.
In this context and in an effort to support the IPCC, the EU published in June 2007 a Green book on adapting to climate change in Europe. The EU pursued these efforts with the publication in April 2009 of a White book intended to assist the Member States in implementing their adaptation strategies. Finally, following consultations on the two books with the Member States over the year 2012, in June 2013 the EU adopted a comprehensive strategy for the Member States.
A summary of all the measures taken by the EU targeting adaptation to climate change is available at:
*http://climate-adapt.eea.europa.eu/web/guest*

For example, in the year 2000, the Water framework directive (WFD) did not explicitly mention climate change which was still considered a secondary pressure compared to hydromorphological alterations and chemical pollution. However, in that it set the goal of preserving and restoring water status[34], the WFD was seen as one of the main means of reducing the vulnerability of species and environments to climate change.

It is only seven years later that climate change was officially mentioned in EU documents, for example:
- directive 2007/60/CE on the assessment and management of flood risks, which highlights the need to assess flood risks taking into account climate change;
- the document sent by the EU commission to the Parliament and the Council (COM (2007) 414 final) which stresses the necessity of "addressing the consequences of climate change and in particular water scarcity and droughts".

In France, even though natural environments were acknowledged as early as 1976 (Law on the protection of nature, followed by the Law on freshwater fishing and the management of fish resources (29 June 1984)), mention of the impacts of climate change and the concept of adaptation first appeared in the Law on water and aquatic environments (LEMA, 30 December 2006). The law transposed the WFD into French law and made use of two existing basin-level water-management tools, the RBMP[35] and the SBMP[36]. The main conceptual advances concerned:
- acknowledgement of a universal right to water;
- inclusion of adaptation to climate change in management policies for water resources.

*34. The WFD is implemented via management documents, the river-basin management plans (RBMP) in France, that were created by the 1992 Water law.*
*35. RBMP, river-basin management plan.*
*36. SBMP, sub-basin management plan.*

That being said, to date, no regulations make it mandatory to integrate climate change in management policies, a factor that limits the progress toward adaptation launched by the PNACC. However, the situation should change with the integration of climate-change issues in the new RBMPs (2016-2021). In addition, a ministerial instruction from February 2013 concerning the road map for local State services in the fields of water, biodiversity and landscapes for the period 2013-2014 called on water managers to adjust abstractions to the available resources according to the guidelines laid out in the PNACC (see the "Key measures in the water sector" above).

### ■ Review of the measures to reduce the vulnerability of freshwater fish in France

In spite of abundant scientific literature on the consequences of global warming, there have been relatively few proposals to limit the impacts. In most cases, they consist of very general guidelines concerning the management of water resources and do not directly concern fish or aquatic environments (see for example the Plan bleu (Blue plan) in 2011 or the PNACC).

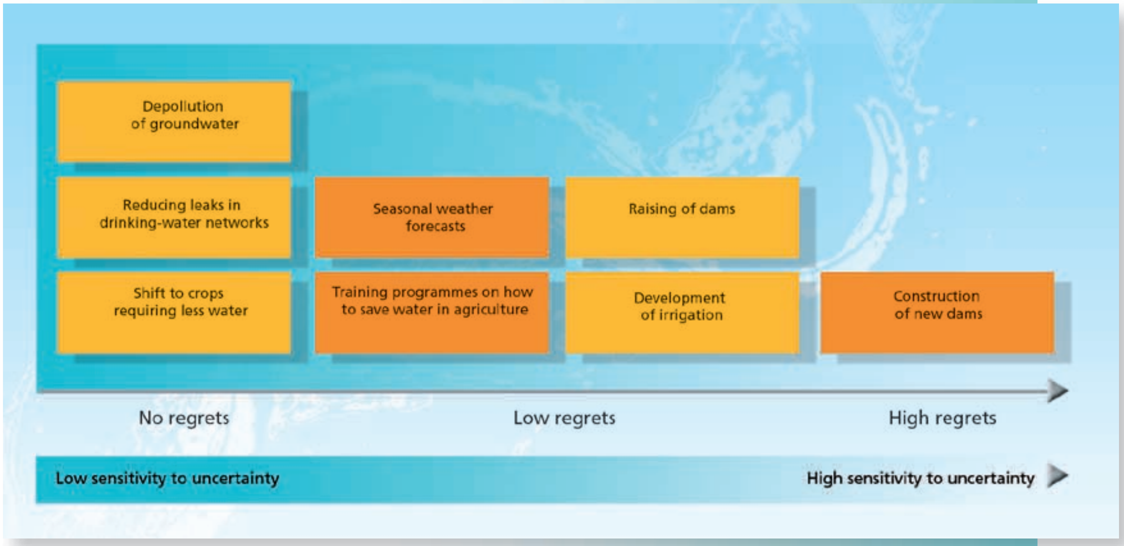
The purpose of this section is to present the initiatives and/or the measures that could effectively contribute to reducing the vulnerability of species and environments without neglecting the uncertainties inherent in climate and socio-economic projections (see Box 20). They generally fall under the category of the restoration or conservation of good ecological status now made mandatory by the WFD in that a majority involve types of measures known and implemented prior to the appearance of climate-change issues. It is therefore important to look into the specificity of climate change and of adaptation with respect to current policies and practices.

Box 20

## Managing uncertainty

In the water sector, uncertainty is a particularly important factor due to the prevalence of the long term in both the time spans involved in planning and in the service life of installations (De Perthuis *et al.*, 2010; Plan bleu, 2011). The time scales influencing decisions on hydraulic strategies and infrastructure projects are often similar to those involved in climate change (Plan bleu, 2011). For this reason, "no-regret" solutions, e.g. efforts to manage water demand, offer decided advantages in that they reduce the vulnerability to hydrological change while providing short-term benefits, whatever the future may hold in terms of climate change with its inherent uncertainties (see Figure 49).

Figure 49




*Impact of uncertainty on the effectiveness of management and adaptation measures in the water sector (Plan bleu, 2011).*

However, certain no-regret or low-regret measures that continue or expand current policies, or correspond to "marginal" adaptations (e.g. management of hydraulic efficiency or adaptation of certain structures), are particularly useful in the short term, but may turn out to be insufficient or very costly over the long term, especially when they attempt to maintain activities or uses that may be put into question by climate change, which is notably the case for irrigated crops. These measures also risk inhibiting awareness of impacts and slowing the adoption of longer-term measures and more significant changes in behaviour.

Consequently, instead of attempting to maintain what now exists or to determine the optimum solution for a given climate future (optimisation), the goal is to set up scenarios and management decisions capable of satisfactorily handling a wide range of changes occurring in the framework of several plausible hydrological futures. In other words, the objective is to encourage adaptive management, i.e. a form of management that reduces vulnerabilities and increases adaptive capacity via a step-by-step adaptation process.

## ■ Maintaining and restoring ecological continuity

The results presented in the third chapter show the degree to which the free movement of species is a key factor in their adaptation to climate change. This is because temperature rise in water inevitably leads to favourable habitats shifting upstream for many species. For certain cryophilic species, e.g. brown trout, the projected favourable habitats are thus limited to refuge zones at the heads of river basins. Efforts to maintain existing ecological continuity or to restore it where needed are therefore an important element in enabling fish to move to a new habitat. For some species, it may even be the condition *sine qua non* for their continued existence in certain river basins in continental France (e.g. brown trout, Atlantic salmon, bullheads). In addition, it allows aquatic organisms to access habitats that are larger and more diversified in terms of the environmental conditions. This manner of encouraging biodiversity is also a prudent means of splitting up the risks given the uncertainty weighing on the consequences of climate change.

A number of different techniques are available to restore ecological continuity.

The removal of obstacles (see Figure 50) or, to a lesser degree, the lowering of an obstacle, is often the most effective solution ecologically speaking, because it restores not only continuity for all species, but also the lotic habitats required for many species (e.g. salmonids and many rheophilic cyprinids) and the corresponding sediment transport. Of course, this solution encounters difficulties in terms of its feasibility, given the socio-economic aspects often linked to the obstacle (particularly dams), but remains an interesting option in terms of the challenge involved, its high degree of effectiveness and the cost.

**Figure 50**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*Photos before and after the removal in 1998 of the Saint-Etienne-du-Vigan dam on the Allier River. This project was carried out in the framework of the "Loire grandeur nature" plan targeting restoration of Atlantic salmon.*

The second type of solution is to install a fish pass, however a fish pass simply mitigates impacts and does not fully restore ecological continuity given that only fish benefit (and only some of the fish). Many different types of fish pass exist, including pool-type passes, Denil passes, rock-chute fish passes, passes for eels and bypass channels. Some enable the passage of many different species, e.g. pool-type passes and bypass channels, while others are more selective, such as Denil passes intended primarily for salmonids, and eel passes. Above and beyond regulatory requirements (see below), the decision to install a pass often depends on socio-economic considerations weighing on the obstacle (dams, hydroelectric plants, recreational activities, excessive cost of removing the obstacle, etc.).

On the national level, the maintenance and restoration of ecological continuity is the objective of the national ecological network (TVB), divided into regional ecological-continuity plans (SRCE). Restoration of ecological continuity is also an objective of the WFD. The WFD ministerial instruction 2005/12 defining "good status" indicates that "the continuity of rivers must be ensured by restoring the freedom of movement (both upstream and downstream) of aquatic organisms over spatial distances compatible with their development cycles and long-term survival in the ecosystem". These regulations were drafted to enable certain species, notably diadromous fish, to accomplish their entire life cycle (in fresh water and in the sea) (see Box 21).

The selection of obstacles for work depends on the potential for restoring movement upstream and providing access to a maximum number of spawning grounds and to growth zones for the species in question. Operations of this type have been carried out on the Gave de Pau River and in the Vienne department (removal of the Maison-Rouge dam), enabling the return of several diadromous species, including the Atlantic salmon.

Box 21

### History and current regulations governing river classifications

In 1827, article 34 in the law on river fishing stipulated that "It is forbidden to place in navigable or raftable waterways, canals and streams any obstacle, device or installation of any type for fishing purposes that completely blocks the passage of fish". This article applied "not only to dams built exclusively for fishing purposes, but also to dams built for a factory, but that also served for fishing". At that time, fish constituted an essential source of food for the population.

To enable access of all to the resource, the authorities decided to facilitate the free movement of fish by making it mandatory to install fish passes on any new structures in the rivers listed in a decree. The first decrees listing rivers for fish passes were issued in the years 1904, 1905 and in the 1920s. However, following the oil shocks in 1973 and 1979, it was decided to reinvest in the development of hydroelectric power and reduce the regulatory requirements. To protect certain rivers from an array of new dams, a river-classification system was introduced, including the notion of "reserved rivers". In reserved rivers, no new hydroelectric plants were to be authorised or conceded.

In 1984, in light of the ineffectiveness of certain passage systems for fish and the insufficient requirements contained in the 1865 law (no mandatory results), the new fishing law imposed:

- minimum results and constant maintenance of passage systems (fish passes and bypasses for downstream migration);
- modification of existing structures within five years following the publication of the official document listing the concerned species.

Article 6 of the LEMA law (2006), subsequently published as article L. 214-17 in the Environmental code (2011), reinforced the fishing law by modifying the classification system of French rivers. Two categories were created.

■ Rivers in List 1 (point 1 in section I of article L. 214-17 in the Environmental code) are protected from further degradation and should be preserved indefinitely. List 1 corresponds to an updated form of the "reserved rivers". It includes rivers judged to have very good ecological status, biological reservoirs and rivers seen as important for diadromous fish. The construction of any new obstacles to ecological continuity, for any reason, is forbidden in these rivers.

■ Rivers in List 2 (point 2 in section I of article L. 214-17 in the Environmental code), which corresponds to the concept of "classified rivers" found in article L. 432-6 of the Environmental code, should rapidly receive work on any existing structures to comply with the objectives of ecological continuity. This implies an obligation to ensure sediment transport and the movement of migratory fish, whether diadromous or not, through the creation of passes, management of gates, etc.

In efforts to adapt to climate change, action plans targeting restoration of ecological continuity differ significantly from those currently implemented via the system of river classification (see Box 21). Whereas the measures implemented in the latter case tend to favour diadromous species (continuity from the estuary to the spawning grounds), the measures required in a context of climate change consist of providing holobiotic species (aquatic species spending their entire life cycle in fresh waters) with the means to reach the habitats that, in thermal and hydrological terms, are the most favourable and are generally located further upstream. Many of the holobiotic species live in zones that diadromous species do not or rarely inhabit. Given that the species most vulnerable to temperature rise in water are located primarily in the intermediate and upstream sections (see Chapters 2 and 3), the selection procedure should also consider these sections when deciding which obstacles require work (but see Box 22). A number of initiatives have already been launched in a number of areas. An example is the Morvan regional nature park where certain rivers had become less favourable for fish populations (trout, bullheads, minnows, etc.) inhabiting the upstream sections (LIFE programme on "Heads of river basins and the corresponding native species", Baran and Milley, 2007).

Box 22

## Restoration of ecological continuity and biological invasions

The risks of invasion by exotic species, such as black bullheads (*Ameiurus melas rafinesque*), pumpkinseed (*Lepomis gibbosus*), topmouth gudgeon (*Pseudorabora parva*) and Ponto-Caspian gobies (Manné *et al.*, 2013), are frequently mentioned when work to restore ecological continuity is undertaken. This is because the combination of climate change, in the form of increased water temperatures, and the restoration of continuity in rivers could encourage their penetration. However, this scenario is not valid for all exotic species because other conditions (hydrology, productivity) besides water temperatures could limit their migration. That is the case for Wels catfish and pumpkinseed, among others.

That being said, the risks of invasion are fairly high due to the existence of impoundments, ponds and other forms of channelling. A number of measures may be taken to limit the risks. Habitat restoration could over time encourage the diversity of environments and of (native) species, thus slowing invasions (Tilman, 1999; Fargione *et al.*, 2003; Xu *et al.*, 2004). Study on the river sections where continuity should be restored must nonetheless take into account conservation issues because some exotic species develop quite well in "good-status" environments. The most striking case is that of crayfish because non-native species can be the healthy carriers of aphanomycosis, the deadly crayfish plague that can cause local extinctions of native species, whatever the quality of the environment and whether climate-change conditions exist or not. In this case, the removal or modification of obstacles separating native species from invasive species should be avoided.

Migration by these species to more favourable areas was blocked by man-made ponds. The elimination of the ponds resulted, in just a few months, in most of these species (European bullhead, brook lamprey, minnows) colonising the zones that were more favourable for their life cycles, with the exception of trout. In the Rhône valley, the home of the Rhône apron (*Zingel asper*), an endemic species, an initial plan to equip structures was carried out to encourage recolonisation of the river by the species (LIFE APRON project - 1999-2001 and 2004-2010).

### ■ Managing abstractions and maintaining hydrological regimes

Fish communities depend to a large degree on hydrological regimes for their survival (see Figure 51).

**Figure 51**

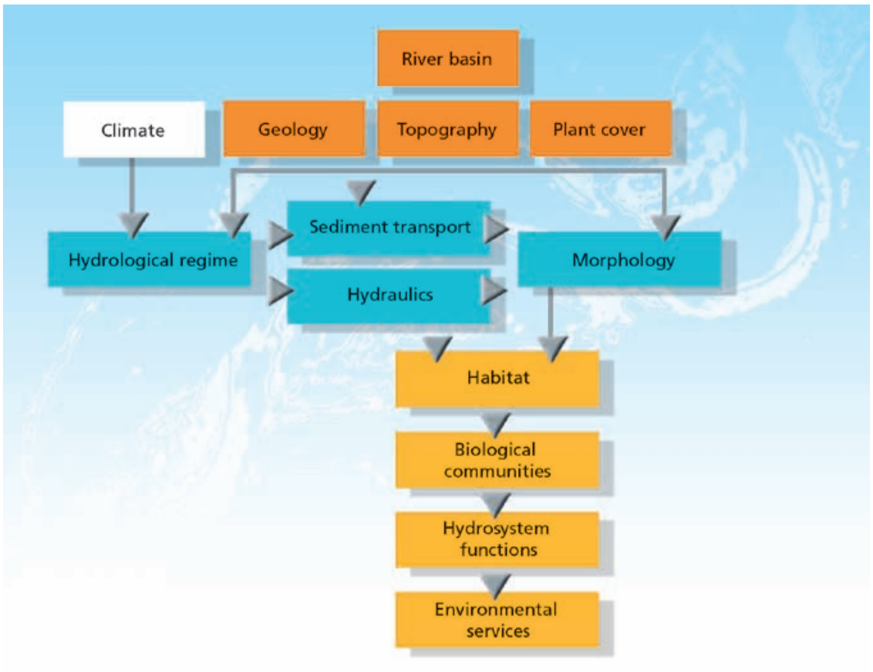



*Diagram showing the physical functioning of hydrosystems and its importance for biological communities (diagram modified, originally from Baran and Leroyer-Gravet, 2007).*

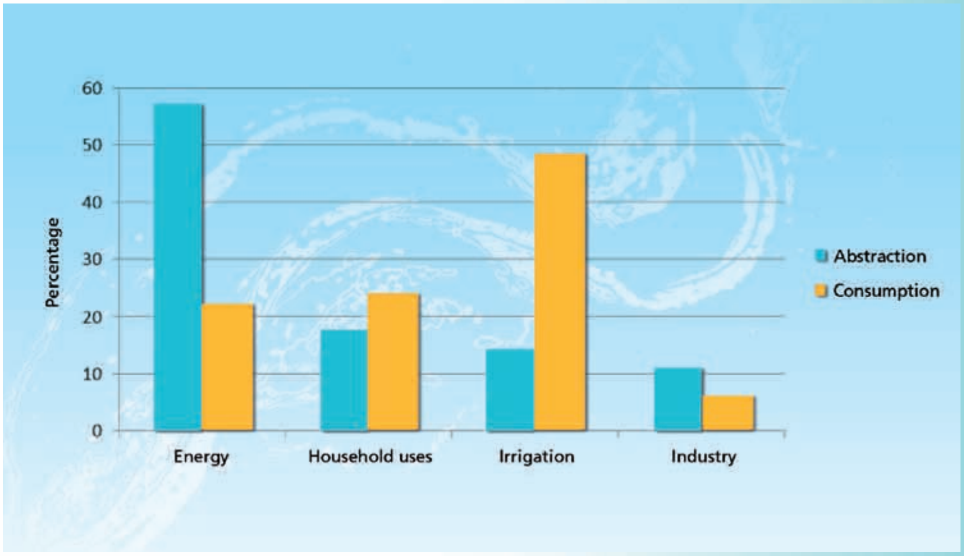
For example, the discharge in a river can directly affect the riverbed and the composition of the substratum (including the plant cover) and encourage (or discourage) the reproduction of certain species, e.g. barbel, bleak, roach, rudd and nase in the Rhône River (Cattanéo *et al.*, 2001), or provide shelter for certain species (see for example the case of reduced cyprinid predation, Schlosser and Ebel, 1989). Above and beyond the discharge itself, other parameters influence the life cycles of fish species such as the frequency, magnitude and seasonal variations in discharge because not all species can make use of the same hydrological conditions (Poff and Ward, 1989).

In the future, modifications in hydrological regimes caused by climate change should heavily impact fish, but in different manners, e.g. worsening of low-flow levels, increases in extreme values). Adaptations (behavioural, physiological, etc.) of certain species, enabling them to survive under the new conditions, may be expected. Population increases in the species adapted to the new conditions and, conversely, local extinctions in the species unable to adapt, may also be expected. These changes plead in favour of maintaining or reinforcing recolonisation capabilities and of refuge zones that may be made available through the renewed diversification of habitats. These effects will most likely be reinforced by the expected changes in abstractions (see Box 23). Measures intended to reconcile human activities and the preservation of aquatic ecosystems must be launched in the near term to limit the vulnerability of fish and, more generally, of aquatic environments.

## Trends in abstractions in the decades to come

In 2009, 33.4 billion cubic metres of water were abstracted in continental France to meet the needs for drinking water, industry, irrigation and electrical generation (Dubois, 2012). The volumes abstracted were not divided evenly among the uses with electrical generation (not including hydroelectricity) representing almost two-thirds, far more than the volumes for drinking water (17%), industry (10%) and irrigation (9%) (see Figure 52). It should be noted that at least 90% of the abstractions for electrical generation are returned to the natural environment near the abstraction point. Conversely, virtually all the water abstracted for irrigation is consumed, which makes irrigation the leading consumer.

Figure 52




*Comparison between water abstraction and consumption by type of activity in France in 2001.*
*Notes. Data applicable for continental France. Volumes are estimated on the basis of user declarations to the Water agencies for all uses. For irrigation, the "flat-rate" volumes set by the Water agencies were reassessed between 2000 and 2004 using the agricultural census from the year 2000 and the data on volumes available from water meters. Prior to 2000, the data are insufficient for a reassessment. After 2004, the "flat-rate" volumes trended down, making a reassessment unnecessary. Abstraction and consumption of water by use (not including hydroelectricity) in 2001 (Bommelaer and Devaux, 2012).*

Over the last ten years, abstractions for the four above uses have trended down, notably for industrial uses (new technologies require less water). However, in the decades to come, abstraction volumes will depend heavily on climatic conditions, production practices (notably agricultural, e.g. the replacement of irrigated corn with other crops requiring less water) and territorial planning (e.g. urban concentration versus urban sprawl). For example, abstractions for drinking water should drop by approximately 32% by 2070, but those for irrigation should increase sharply if no adaptation measures are taken (between 40 and 66% depending on territorial development, urban concentration versus urban sprawl) (MEDDE/Bipe, 2013).

The first laws attempting to regulate the quantitative management of water resources were voted in 1984 (Fishing law). The latter foresaw the setting of discharge values for structures (dams, weirs) located in riverbeds. Article L 214-18 in the Environmental code requires that structures in rivers maintain a minimum discharge ensuring at all times the life, movement and reproduction of the species living in the river at the time the structure is created. The ministerial instruction DGALN/DEB/SDEN/EN4 (21 October 2009), derived from the LEMA law (30 December 2006), reinforced this obligation by requiring an increase in minimum discharges to 10% of the interannual mean discharge for all structures by 2014[37]. In addition, it is now possible to set different minimum discharge values for different periods of the year, on the condition that the annual mean value not be less than 10% of the interannual mean discharge and that the lowest discharge value remain greater than 5% of the interannual mean discharge.

These regulatory changes increasing the minimum discharge are an important factor that now make it possible to limit certain impacts of abstractions on fish communities. In the future, additional studies must be carried out to determine on the reach scale or for individual river basins the minimum biological discharges required depending on the local context (species, hydromorphology, etc.), but also depending on the interannual mean discharges in a context of climate forcing (see Box 24). In other words, the necessary discharge must be defined as a function of the ecological requirements of the environment and the local species, and not be set arbitrarily. This progress will make it possible to improve management tools and the current regulations, and to escape from a sectoral approach that is not particularly useful given the issues involved in managing water resources.

Box 24

## How should biological minimum discharges be calculated?

A number of techniques, more or less elaborate and valid, exist to take into account biological equilibria in defining low-flow levels and/or hydrological regimes, including holistic, hydraulic and habitat-based methods (Tharme, 2003). The method most commonly used in France is the microhabitats method that can be used to assess, as a function of the discharge, changes in the "physical" habitat of a section of river for a few targeted fish species. In other words, the method links physical characteristics (of the habitat) to a biological response (quality of the habitat). This method is implemented at a monitoring point that is representative of a river reach and consists of linking physical data describing the habitat to a biological response that can be used to determine the quality of the habitat. In France, three different protocols are based on this method.

- The first is the long-standing method imported by EDF and Irstea in 1994 (Sabaton, 2003), that is based on actual hydraulic measurements (depth, velocity, sediment grain size) taken under different discharge-release conditions (in rivers where the discharge can be controlled). This method is used by the LAMMI program (Tissot *et al.*, 2011).
- The second is the EVHA protocol (1998), developed by Irstea. It differs from the first in that the hydraulic measurements are taken for a single discharge and it includes a topographical description of the monitoring point. A hydraulic model is then used to calculate water depths and velocities for different discharges.
- The third is the Estimhab protocol developed by Irstea (Lamouroux, 2002). It is one of the statistical habitat models that can be used to assess the ecological impact of the hydraulic management in a river. These models use simplified input variables (river width, water depth, most common grain sizes, measured at two different discharges) to describe changes in the habitat for a given species as a function of the discharge.

*37. This law does not apply to structures in rivers where the interannual mean discharge is greater than 80 cubic metres per second or to hydroelectric plants producing electricity during peak consumption periods. In these two cases, the minimum discharge is set at 5% of the interannual mean discharge.*

These methods have numerous limitations. For example, their complexity means that operators must receive prior training before attempting to use them and before being able to understand their subtleties when interpreting the results. In addition, none of them take into account all of the factors influencing the assessment of a biological discharge. Finally, these methods cannot be expected to produce a precise value for a biological minimum discharge, their purpose is rather to study the gain or loss of habitat at different discharges. It is therefore advised to combine methods in order to produce an assessment as precise as possible of the minimum discharge.

Pumped abstractions, not including storage/bypass structures (see Box 25), for drinking water, irrigation and industry are, for the time being, not covered by this regulation. Until recently, abstractions during the summer period were generally limited by "drought decrees". However, the regulation has since been changed and now reserves this type of decree for truly exceptional situations. Abstractions in areas confronted with shortages are currently adjusted on the basis of two indicators[38]:

- target low-flow discharges (DOE), calculated using monthly mean values capable of ensuring both good water status and all uses (eight years on average out of ten). DOE values are generally close to the QMNA5 value (see the definition in Chapter 1);
- target low-flow piezometric values (POE) if they exist.

Similar to that for minimum discharges, these regulations continue to evolve in favour of environmental preservation. In the future, the modification of these indicators to take into account the biological minimum discharge will represent major progress. In addition to adjusting abstractions more precisely to local conditions to achieve better balance between uses and the needs of natural environments, the indicators will provide a more objective basis for decision-making during crises. Some regions have already started to adapt DOE values to take into account species biology, notably in the Rhône-Méditerranée basin.

Finally, the measures recommended in the PNACC[39], targeting a 20% reduction of the water abstracted by 2020, are also critically important and must be reinforced in the future given the context of increasingly rare water resources. The current creation of collective management organisations may help in raising awareness that water resources must be shared and collectively managed by all users.

Box 25

## Upland reservoirs, a not so good idea?

To meet the needs of agriculture for water during the summer, while avoiding to pump directly from rivers, a commonly proposed solution is upland reservoirs used as "substitute reservoirs".
In theory, an upland reservoir is a small, man-made lake dug in impermeable soil and that is supplied with rainwater. However, the term "upland" is sometimes used for other types of supply as well (Chalabert, 2013). For example, reservoirs are often fed by (a bypass leading from) streams, whether permanent or seasonal, or by a spring. In permeable soils, primarily in the Vendée and Poitou-Charentes regions, reservoirs are not located in riverbeds, but are isolated from the natural environment and are supplied with water pumped from a river or with groundwater (Secrétariat technique du bassin Loire-Bretagne, 2011; FNE, 2011).

*38. There is another discharge level called the reinforced crisis discharge (DCR) under which it is no longer possible to meet abstractions for drinking water, the safety of sensitive installations and the needs of natural environments.*
*39. Currently being drafted into the RBMPs.*

Figure 53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Continuation of Box 25

*Substitute reservoirs positioned outside of riverbeds are often seen as solutions for agricultural needs that limit the impacts during the summer season. But in fact, not enough experience has been acquired to effectively assess their consequences on the local hydrology and aquatic environments.*

A substitute reservoir draws its name from its usage, i.e. a means to impound water collected when it is abundant in order to avoid abstracting water from a river during the low-flow period. An upland reservoir can therefore be used as a substitute reservoir.

These different types of water storage obviously impact the environment, however the character and magnitude of the impacts depend notably on where the reservoir is located with respect to the riverbed. When the reservoir is located in the riverbed itself, there can be modifications in the temperature regime downstream, degradation of the physical-chemical quality of water, alteration of sediment transport, loss of lotic habitats, loss of the self-cleansing function, a break in ecological continuity, etc. All these effects are generally well understood.

Reservoirs located outside of riverbeds and supplied with runoff or pumped water during the winter would seem to have fewer negative impacts on aquatic environments. However, though the impacts on the hydrology of river basins confronted with several reservoirs have not been extensively studied, some research indicates that the overall impact is far from negligible, particularly during the first month of filling. For example, filling of reservoirs during the winter can lead to reductions of up to 50% of winter discharges (Galea *et al.*, 2005; Philippe *et al.*, 2012). This impact is variable from one river basin to another. The lower the specific discharge in a basin, the greater the impact (Philippe *et al.*, 2012).

Contrary to what one might think, the issues involved in quantitative management do not exclusively concern low-flow periods. The changes in the discharge regimes (alternating high and low flows) caused by the winter storage influence sediment transport and consequently the aquatic habitats and living communities. The water transiting during high-flow periods should not be seen solely as a disposable excess, but as an essential parameter in the life of the river. Any new substitute reservoirs must take the potential impacts into account.

What is more, care must be taken not to increase the dependence on irrigation of farms in areas where climate change risks augmenting the cumulative impact of these small reservoirs on discharges or even limiting their filling. A projection based on three climate-change scenarios (increase in temperature and, in terms of precipitation, three possibilities, i.e. general decrease, general decrease but with an increase in winter and a general increase in the river basin) showed that, whatever the scenario, the existence of upland reservoirs worsened the decrease in monthly discharges and in high flows during the filling period. Reservoir filling rates were also projected to drop, falling below 90% every second year by 2050 (Philippe *et al.*, 2012).

It is thus essential, before creating substitute reservoirs, to make sure that their existence is compatible with the preservation of ecosystems and/or other uses such as drinking water, under both the current climate conditions and those expected under climate change.

## ■ Maintain and restore water quality

As mentioned in the previous chapters, the interactions between climate change and the chemical stress caused by certain potentially toxic aquatic pollutants (Wenning *et al.*, 2010) are likely to provoke malfunctions in aquatic ecosystems (Schwarzenbach *et al.*, 2006).

Over 100 000 chemical substances have already been registered in the EU, of which 30 000 are used, imported or produced in quantities exceeding one ton per year. Many end up in aquatic environments where they may produce a toxic effect at very low concentrations, on the order of 1 microgram per litre, and alter the quality of ecosystems both directly and indirectly. In addition, organic pollution, though declining over the past 30 years, is still highly present in certain sectors, notably agricultural, in the form of eutrophication. The chemical status of 21% of rivers and 40% of groundwater bodies is poor according to the WFD criteria. Awareness of these ecological impacts and the corresponding risks for human health has grown significantly since the 1970s and resulted in increasingly stringent regulations.

■ Similar to the emblematic directive 91/414/EC on pesticides, many regulations, following up on directive 76/769/EC on "marketing and use of certain dangerous substances and preparations" (abrogated and replaced by the REACH regulation EC 1907/2006 on the registration, evaluation, authorisation and restriction of chemicals), have limited the use of toxic substances to specific sectors of activity, conditions of use or to specific products.

■ The French government has invested considerable sums over the past 20 years to upgrade the sanitation systems of towns in order to improve the quality of aquatic environments and ensure compliance with the 1991 European directive on urban wastewater treatment. Treatment levels are set depending on the size of the wastewater treatment unit and on the sensitivity of the receiving environment to the released effluents. These obligations are currently contained in the General code for local governments and in the ministerial decision (22 June 2007) concerning the collection, transport and treatment of wastewater by local governments (now being revised).

■ Industrial and agricultural activities presenting a high risk of pollution must be authorised (directive 2008/1 EC). The directive establishes minimum requirements that must be included in authorisations, notably concerning the release of pollutants. The objective is to avoid or reduce polluting emissions to air, water and soil, as well as any waste produced in industrial facilities or on farms.

■ In 2000, the Water framework directive (WFD) adopted the general approach of directive 76/464/EC, but added monitoring of environments, notably with environmental quality standards (EQS) explicitly defined for water and biota (see daughter directive 2008/105 EC amended by 2013/39/EC). The WFD, which concerns all aquatic environments including coastal and transitional waters, requires preservation of non-degraded aquatic environments (reference state) and the restoration of moderately or heavily degraded environments to good status by 2015, given that good status includes both the ecological and chemical status of a water body.

A number of action plans have been launched in recent years to comply with these regulatory requirements. A first national action plan for sanitation was launched in 2007 to ensure conformity of wastewater-treatment plants and networks with the Urban wastewater-treatment directive. The purpose of the new action plan for 2012-2018 is to ensure conformity of local governments with the new EU requirements concerning the quality of environments and water uses (WFD, Bathing-waters directive, Shellfish-waters directive, Marine strategy framework directive), with particular attention paid to improving wastewater treatment in small towns (less than 2000 population equivalents) and to collection of rainwater. A further objective of the plan is to integrate sanitation in the overall process of sustainable development, taking into account climate change.

Concerning micropollutants, a national action plan was launched for the period 2010 to 2013. It comprises three main sections:

- reduce emissions at their source by taking direct action on the most harmful substances, on the sectors polluting the most and on the most severely degraded environments. This is a comprehensive approach attacking the entire life cycle of micropollutants and highlighting preventive rather than curative methods, notably concerning the marketing of products;
- improve knowledge on the status of water bodies in the framework of the RBMPs by drawing up an inventory of the emissions and releases of the substances affecting the chemical status as per the WFD or, among other measures, defining clear rules on how to interpret monitoring results, for use by all stakeholders;
- improve scientific and technical knowledge in order to identify where progress can be made and set priorities for public action by monitoring and validating results observed in study areas in the field, for example.

For sanitation, a number of technical solutions are currently being studied. For example, planted discharge zones located between wastewater treatment plants (WWTP) and the receiving environment can, in some cases, reduce the impact of the effluents notably by reducing the volumes and flows of pollutants and by providing better protection of river banks. However, the experience acquired to date is insufficient to quantify the performance of these systems concerning a reduced impact of the effluents. That is why Onema, in a partnership with Irstea, has funded a major research programme on planted discharge zones (see Figure 54). In addition to efforts to reduce emissions of pollutants at the source, improvements in the effectiveness of WWTPs for micropollutants constitute a major factor in the work to preserve aquatic environments. The Armistiq project (2010-2013), funded by Onema and managed by Irstea in conjunction with Suez Environnement and the University of Bordeaux, created technical and economic assessment techniques for both standard treatments and more recent processes not yet widely used in France (http://armistiq.irstea.fr). What is more, improvements in knowledge and practices concerning the management of urban rainwater runoff have steadily gained in importance in view of both limiting the impacts on the environment and preventing floods.

**Figure 54**

© C. Lacour - Onema

*The Marguerittes planted discharge zone (Gard department) was the topic of a research programme managed by Irstea and funded by Onema.*

There are also technical solutions to reduce the impact of agricultural effluents, e.g. by maintaining or expanding grass buffer strips along cultivated fields, etc. Finally, one of the most integrative solutions to maintain or restore a level of water quality compatible with biodiversity and drinking-water needs is probably the restoration of river hydromorphology. It has been shown that the diversification of river facies, meandering and the presence of riparian vegetation have a positive impact on the self-cleaning capacity of rivers, notably concerning nutrients such as phosphorous and nitrogen (Nicolas *et al.*, 2012). The same is true for wetlands.

Over the long term, implementation of these various regulations, plans and technical solutions should make it possible to protect the environments involved in the water cycle. As a result, pollution risks should decrease in the future.

### ■ Control anthropogenic warming of water

Temperature rise of water is unavoidable under the announced conditions of climate change. Any and all measures likely to limit warming would thus be beneficial in order to limit the vulnerability of fish.

Riparian vegetation, particularly when composed of trees (see Figure 55), plays an important role in regulating the temperature regime of small rivers by limiting the increase in surface temperatures (see for example Johnson, 2004; Durlet, 2009; Larson, 1996; Rapport Clim-arbres, 2012). For example, a study in Switzerland on the Boiron de Morges stream found that the presence of a forest along an entire reach resulted in a temperature drop of over 3.3°C compared to a reach without any riparian vegetation (Rapport Clim-arbres, 2012). Macrophytes also play a non-negligible role by inducing a drop in temperature of 1°C (Rapport Clim-arbres, 2012).

**Figure 55**

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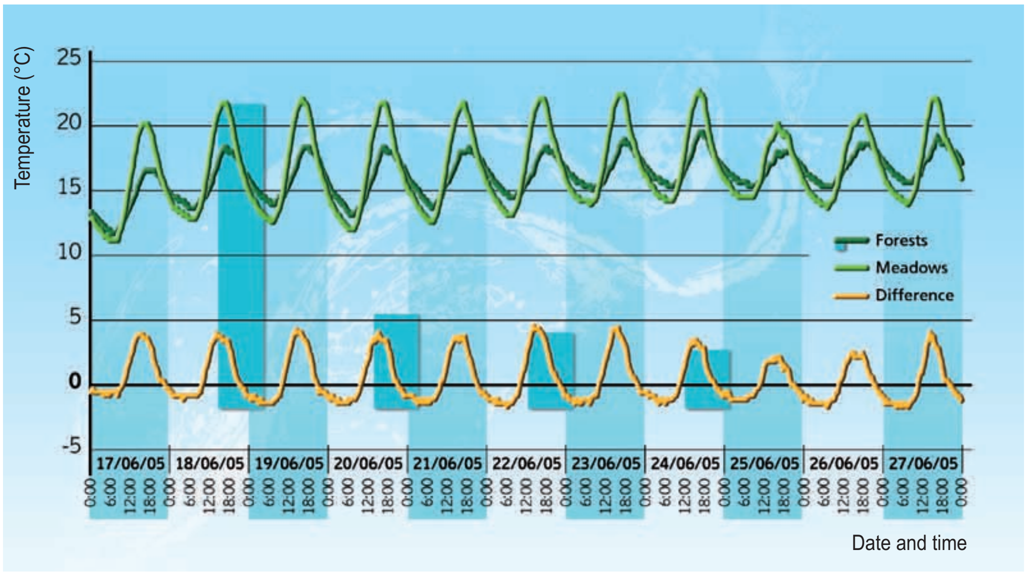
*By providing shade, riparian vegetation plays an important role in the temperature regime of rivers.*

Similar results have been observed along the Vaucorniau stream (Nièvre department), where differences in water temperature between wooded areas and meadows ranged from 0 to 5°C (Durlet, 2009) (see Figure 56). The preservation, upkeep and restoration of riparian vegetation could therefore be a decisive factor in limiting temperature rise in water, in certain rivers. Currently, the WFD has not set any precise objectives concerning the physical quality of rivers and their banks. However, all the professionals in the water sector highlight the roles played by these environments and a majority of SBMPs and management plans now include action plans to restore riparian vegetation and work on the banks, e.g. maintain a natural wooded area between farm land and river banks, limit grazing of livestock by blocking access or placing metal protective devices around bushes to enable wooded riparian vegetation to develop, plant or use cuttings to develop tree species found in the area, etc.

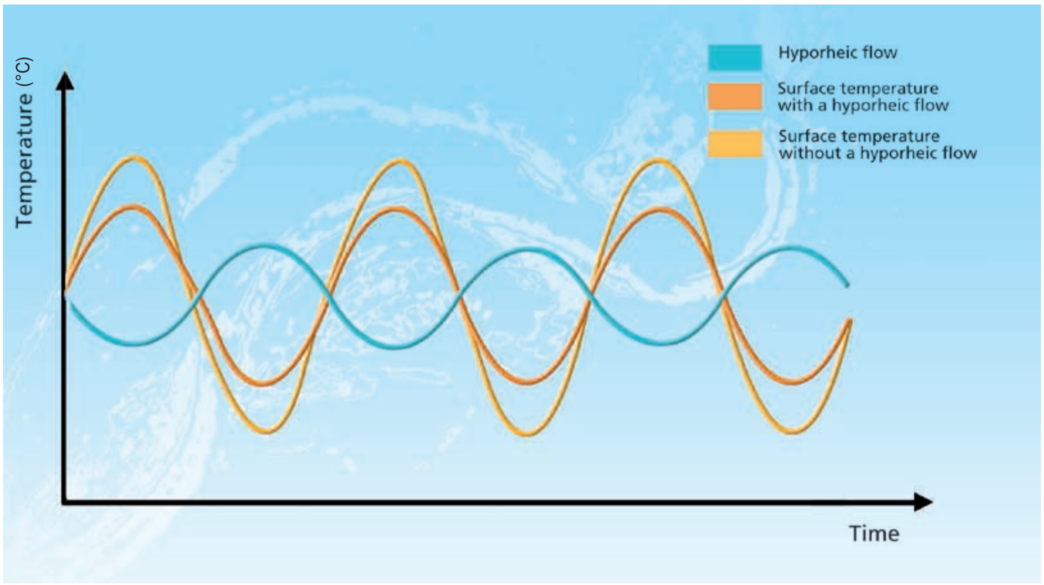
Figure 56




*Comparison of water temperatures between wooded areas and meadows along the Vaucorniau stream. Measurements were taken every 30 minutes. The absence of shade in the sections along meadows resulted in a significant increase in maximum temperatures and in thermal amplitudes in the stream (Durlet, 2009).*

Preservation of all the natural hydromorphological functions of rivers would also contribute to limiting temperature rise in water and/or to maintaining an optimum level of dissolved oxygen. Recent studies have shown that hyporheic flows play in important role in regulating the temperature regime of rivers (see Figure 57). Similarly, work to recreate meanders in a river located in the Remoray lake nature reserve (Doubs department) resulted in a rise of the water table and a reduction in the maximum summer temperatures of approximately 1 to 3°C (Rhône-Méditerranée water agency, 2006). The work consisting of injecting gravel and recreating meanders would seem to be effective in limiting temperature rise in water, similar to other measures attempting to limit clogging of rivers and to improve sediment transport.

Figure 57

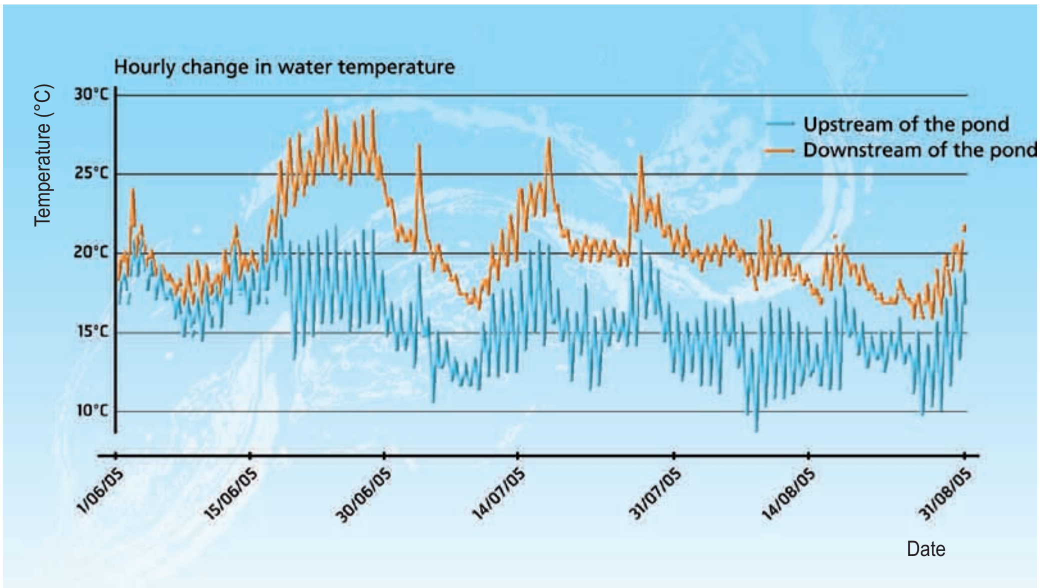



*Theoretical impact of hyporheic flows on the water temperature in rivers. The yellow line shows the surface temperature without a hyporheic flow, the orange line the surface temperature with a hyporheic flow and the blue line the temperature of the hyporheic water (Grant* et al.*, 2006).*

Regulations impose certain management techniques on existing structures, e.g. regular opening of gates to improve sediment transport and ensure ecological continuity (see the previous section). In addition, regulations also require that structure owners undertake regular maintenance work on reservoirs (removal of jamming material, debris and deposits) to maintain a natural flow of water. These different measures should, over time, improve river hydromorphology and consequently reduce temperature rise in water. It should be noted that the injection of gravel can enhance these positive effects. Finally, modifications in farming practices designed to limit soil erosion would also contribute to reducing clogging of riverbeds by fine sediment (clay, silt, fine sand).

The disconnection and even the elimination of successive ponds along a river are also a means to limit temperature rise in water. It has been shown in a number of studies that a series of ponds along a river results in significant temperature rise in water because the surface area of a pond in contact with the atmosphere is much larger than that of a river (Durlet, 2009). Measurements taken downstream of the ponds on the Cousin River in the Morvan regional park revealed significant temperature rise in the water (4.5°C) exceeding the levels that trout and bullheads can tolerate (see Figure 58) (Baran, 2005).

**Figure 58**




*Hourly change in water temperature upstream and downstream of the Champeau pond. Data from 2005. The pond covers 30 hectares, is 850 metres long, lies at an altitude of 550 m and is 3 m deep at its maximum. During the summer, the residence time of water is approximately 24 hours (Durlet, 2009).*

Similar results have been observed on the Arroux River in the Saône et Loire department (Karamalengos, 2009) and at a large number of sites in the Brenne and Sologne regions. Currently, a number of pond and river contracts highlight these detrimental effects and propose measures to forbid or limit the creation of ponds directly in riverbeds. These measures must be reinforced in the future context of widespread temperature rise in water.

Control over abstractions in rivers is another means to limit temperature rise in water. Hydrological conditions have a significant impact on temperature rise in water. A reduction in the discharge increases the ratio of the surface area in contact with the atmosphere to the total volume of water transiting a given section of the river, thus contributing to temperature rise. The various phenomena involved are even more complex for diadromous fish because climate change also produces effects in the oceans. For example, the models project that the interaction between the drop in ocean survival rates and the increase in the hydrological amplitudes in rivers could increase the probabilities of local extinctions. This phenomenon would, however, be mitigated by the increase in water temperatures in rivers, at least initially, i.e. over the next three decades (Piou and Prévost, 2013). For these reasons, in addition to the reductions directly caused by climate change, it will be necessary to control abstractions in rivers (see the previous section).

Finally, it will also be necessary to reinforce regulations to avoid temperature rise in water caused by 1) the cooling systems of nuclear power plants, 2) industrial releases, 3) urban discharges and 4) waters contained in reservoirs during the summer season (see Box 26). Enhanced control over these sources must be pursued, notably concerning the maximum temperature, the maximum discharge, the periods at which releases are authorised, etc. Currently, thermal discharges are governed by the European fish directive (1978) which limits temperature rise to 3°C for waters inhabited by cyprinids and to 1.5°C for salmonids, with a number of possible exemptions in French law. It should be noted that the absolute limit is 28°C. This directive will soon be replaced by the WFD.

Box 26

### Can hypolimnetic releases from dams reduce downstream temperatures?

In certain cases, dams equipped with hypolimnetic (deep-water) outlets[40] result in lower temperatures downstream due to stratification-destratification phenomena in the upstream reservoir. This has been observed on the Dordogne, Maronne and Cère Rivers. The water transiting the turbines, drawn from the bottom of the upstream reservoir, has a lower temperature than the water entering the reservoir. For example, if the reservoirs along the Dordogne River did not exist, it has been calculated that the water temperature in the reaches downstream of the dams would be 4°C higher than is currently the case (Lascaux and Cazeneuve, 2008). However, in some rivers, e.g. the Yonne below the Pannecière dam, the changes in the temperature regime (excessively low spring temperatures) inhibit the reproduction of the species naturally present in the river. In addition, even though the lower temperatures correspond to the needs of trout, its reproduction is disturbed by the hydrological modifications caused by the dam (Lascaux *et al.*, 2001). In light of the impacts created by man-made reservoirs (obstacles to migration, destruction of lotic sections, changes in water quality, obstacles blocking sediment transport, etc.), it must be concluded that they cannot serve as a means to reduce temperatures.

The information presented above shows that there are a number of measures available to limit temperature rise in water and most are already recommended by current regulations. The next steps will be to reinforce these measures and to raise awareness that they are essential factors in the efforts to reduce the vulnerability of aquatic species to climate forcing. The expanded monitoring network for water temperature (RNT) established by Onema in 2008 must be maintained and if possible expanded further. It is a crucial element in the work to monitor temperatures in French rivers and to assess the effectiveness of the measures implemented.

*40. The water is drawn from the bottom of the reservoir. During the summer, this water is colder than the surface water. In the winter, the opposite is true.*

# Conclusion and outlook

Adaptation to climate change is a complex phenomenon that is already well under way in France. The National plan for adaptation to climate change (PNACC) provided new impetus in 2011 by pulling together an array of separate initiatives and by coordinating a number of incentive and regulatory measures (SRCAE, PCET, SDAGE, SRCE, etc.). In the water field, however, no new binding measures have been undertaken. That being said, the information presented in this chapter makes clear that the WFD measures already implemented constitute a highly effective tool in reducing the vulnerability of fish populations in a context of climate change.

The increases in minimum discharges, the use of suitable target low-flow discharges and efforts to reduce water consumption as stipulated by the PNACC are all important steps forward in the quantitative management of water resources.

The restoration of ecological continuity, if implemented country wide for all holobiotic and diadromous species, will enable them to reach more favourable areas in the future in as much as the available habitat conditions (hydrology, physical-chemical parameters, etc.) are still conducive to their presence.

These measures must imperatively be accompanied by improvements (or at least no further degradation) in aquatic environments. To that end, it is essential that rivers offer diverse hydrological and morphological conditions, the factors required to ensure water quality and suitable thermal conditions, dispersal of aquatic organisms and their survival in a changing environment.

Clearly, contrary to efforts to constitute "sanctuaries", it will be necessary in the future to accept that certain native species are no longer suited to the new climate conditions, that they must leave their traditional ranges and that the ecosystems in a given area will change in their composition and in how they function (Dutartre and Suffran, 2011).

However, in spite of the uncertainties surrounding climatic and hydrological projections, climate change should be seen as a further argument to implement measures to attenuate pressures and thus enhance the resilience and adaptive capacity of environments and organisms.

Funding of research programmes will provide knowledge on essential aspects such as the thermal and/or hydromorphological "preferences" of fish, their movements in rivers and their capacity to adapt or to acclimate. The relative impact of anthropogenic pressures compared to climate forcing and the links between water quality, water temperature and fish populations are further issues that require the attention of researchers. Looking farther into the future, it will be necessary to test through simulation the responses of populations and communities to new management strategies attempting to encourage adaptation of aquatic species to climate change. The new strategies may decide to select certain traits promising greater adaptive capacity in order to accelerate adaptation or they may opt to encourage biodiversity in order to enhance resilience in an approach designed to spread the risks.

Finally, distribution models must be improved in view of their use on smaller scales (e.g. for river basins) and it will also be necessary to develop models focussing more closely on population and evolutionary processes (demogenetic models) in order to overcome the limits imposed by distribution models.

The continued operation and development of the observatories and measurement networks will be key factors in the future in both monitoring change and in assessing the effectiveness of the measures implemented. In the final analysis, it is important, on the one hand, to pursue and immediately amplify all types of work to restore and preserve correct functioning of aquatic environments. Their good health will make them more resilient to modifications resulting from climate change and thus reduce the vulnerability of species. On the other hand, it is important to continue the accumulation of data and research results in order to better understand, over the mid term, the phenomena involved and to improve the responses to those phenomena. The two approaches are essential because they complement each other.

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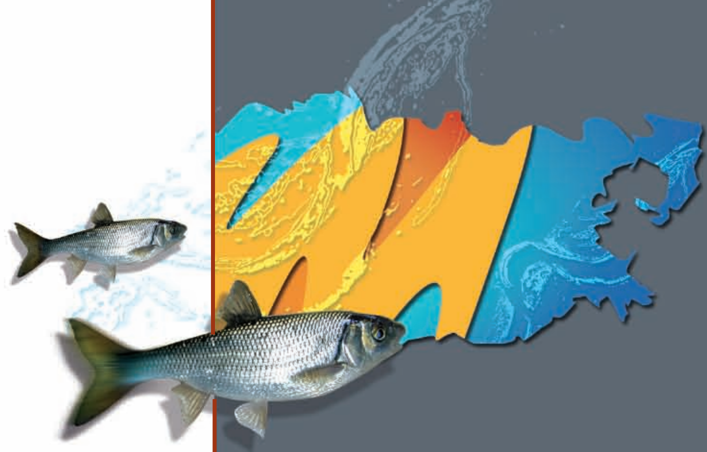


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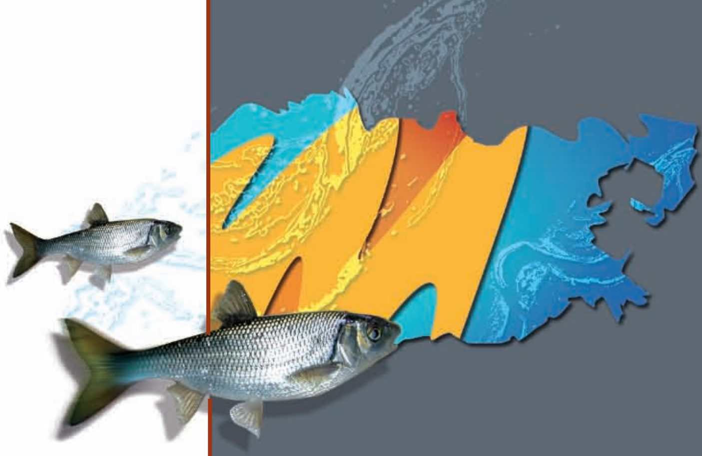

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AFAQ
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Les milieux aquatiques recèlent une véritable richesse écologique, constituent un patrimoine culturel unique et une ressource économique importante pour la société. A l'heure du changement climatique, ces milieux, déjà fortement sollicités par l'homme, font également l'objet d'inquiétudes croissantes. Quelles seront les conséquences du changement climatique sur l'hydrologie de ces milieux ? Comment les écosystèmes aquatiques et les organismes qui leur sont inféodés réagiront-ils à ces nouvelles conditions ? Quelles mesures peut-on mettre en place pour limiter leur vulnérabilité ? Les poissons, organismes emblématiques des cours d'eau et ressource pour nombre d'activités humaines, figurent parmi les espèces potentiellement concernées par le changement climatique.

Ce *Comprendre pour agir* donne un aperçu des connaissances actuelles sur le changement climatique et ses conséquences sur l'hydrologie des cours d'eau français métropolitains et sur la biodiversité piscicole. A travers cet état de l'art, sont présentés différents outils de projection et leur domaine d'application, permettant d'apporter des réponses quantitatives sur l'ampleur des changements attendus. Enfin un chapitre est dédié aux mesures d'adaptation dont la mise en œuvre compatible avec la réglementation actuelle pourrait dès aujourd'hui, et à plus long terme, limiter la vulnérabilité des poissons et des écosystèmes d'eau douce.

Un tel ouvrage apporte donc à la fois des connaissances générales sur l'évolution des hydrosystèmes et des communautés piscicoles sous forçage climatique mais également des éléments de compréhension pour appréhender et utiliser les modèles dans la limite des incertitudes inhérentes à ces outils.

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