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CLIMATE CHANGE & ITS IMPACT ON THE WATER REGIME IN FRANCE

A DOCUMENT REDACTED ON BEHALF OF THE UICN UPON REQUEST OF THE MIES

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FOREWORD

The present document includes two parts. The first one is a synthesis that follows the plan recommended by the UICN in its document called «Protocol for country baseline studies – Water, wetlands and climate change – Mediterranean component». This first part was designed so as to provide an easy and useful support to a round table on the above-mentioned subjects, within the scope of the Athens meeting; it does instead of the requested summary. The technical elements essential for the understanding and justification of the first part are presented as a report including three sections: "Status of water resources in France", "Impacts of climate change on the water regime" and "Recently adopted measures". This second part is presented as a classic report of longer durability, which will be reusable as such.

A – THE FRENCH CONTEXT

A.1 –CURRENT SITUATION OF WATER RESOURCES AND WETLANDS IN FRANCE

Rainfall reaches about 440 billion m^3 per year, of which 100 billion m^3 per year on an average are available for human use (60 billion m^3 during dry years, i.e. one in every decade), after taking into account evapotranspiration, problems of accessibility and losses during flood periods. However, these average figures mask the fact that these resources are irregularly distributed in time and space. The development of irrigated lands (*see Technical Report 1.3*) in the southern half of the country requires huge quantities of water that entail marked deficits at the local scale during dry years. The end of the 80's and the beginning of the 90's were characterised by long-lasting droughts.
France benefits by several vast sedimentary watersheds of interest for the use of underground water (the Paris Basin, the Aquitaine Basin) and of water tables accompanying the main rivers. Such ground water is a major resource for the supplying of drinking water.
The water is usually taken from surface water; underground water only accounts for 15% on an average. Nevertheless, 56% of the water that feeds public supply networks come from ground water.
Big floods (*see Technical Report 1.4*) may cover vast plains for several weeks under the influence of the Atlantic climate, while violent and torrential floods characterise Mediterranean rivers.
Lastly, France has a network of diversified lakes and wetlands, highly valuable for ecology. Wetlands cover about 2 million hectares. A report drawn up in 1994 by the Government evidenced a high degradation of this network of wetlands, and it has been assessed that more than half those existing 30 years ago have disappeared or are highly degraded.

A.2 – OUTLOOK ON THE HYDROLOGICAL IMPACTS OF CLIMATE CHANGE IN FRANCE

Simulations of general circulation models (GCMs) designed according to the hypothesis of doubling the CO_2 atmospheric concentration (by the year 2050 according to various scenarios of GHG increase) agree about highly marked anomalies of the atmospheric variables near the surface, in relation to the current climate. Although the available scenarios regarding France are still dispersed, they all simulate significant disturbances of rainfall and air temperatures to be expected during the second half of the 21st century: increased winter rainfall and decreased summer rainfall, and a more marked rise in air temperature in summer than in winter.
The use of regional hydro-meteorological models set up for the main French watersheds has allowed a first evaluation of hydrological impacts in response to the monthly anomalies simulated by GCM under the hypothesis of doubling the CO_2 atmospheric concentration. These studies (*see Technical Report*) show that the rise in winter rainfall increases the soil water content and therefore surface runoff and drainage. In mountain areas, in spite of increased precipitation, the rise in air temperature occurs simultaneously with a decrease in snowfall, which induces a reduction in winter accumulations (especially in medium mountain areas).

The decrease in summer rainfall, together with the rise in air temperature, increases the water deficit of the soil, which entails a much earlier soil desaturation and harsher low water periods in autumn.

• **Hydrological impact on a first typical watershed: the Rhone basin**

A detailed study (GICC-Rhône) has been led on the French part of the watershed that includes a high variability of climate and water regimes: a continental pattern in the Saône watershed, a mountain climate and snow water regime in the Doubs, Isère and Haute-Durance watersheds, a Mediterranean climate for the Durance, and a Cevenol climate in the South-East of the basin. The differential impact of climate change can then be examined in relation to the various hydrological contexts of the present climate.

Regarding Alpine rivers, different climate scenarios show that anomalies in the snow layer are likely to have a considerable impact on their regime. For instance, the Durance river would be subject to a reduction by about 50% of the water-equivalent and the melting would occur about one month sooner. This early snow melting would entail a flood peak in May - which is quite a month ahead of schedule - followed by much lower levels of water in July and August.

The same models predict very different impacts according to the areas of the basin, with for instance an increase in the annual discharge of the Saône and a decrease in the southern watersheds. These contrasting responses according to climate areas would be largely compensated in the case of the Rhone watershed, which would induce a slight reduction in the annual water volume at the Rhone outlet.

• **Hydrological impact on a second typical watershed: the Adour-Garonne basin**

Hydrological models forecast a stronger impact of climate anomalies in the Pyrenees than in the Alps, because of the lower height of the Pyrenees and of a more moderated increase in winter precipitation. The snow element would consequently be highly disturbed in the Adour-Garonne basin, which could entail earlier low water periods. However, the big aquifers of this basin would benefit by a better winter recharge because of an increased rainfall, which could possibly counterbalance summer water deficits within a proportion that remains to be studied.

• **Hydrological impact on small Mediterranean coastal watersheds and occurrence of extreme climate phenomena**

This question of the impact of climate change is more difficult for small watersheds than for large basins because of the difference of spatio-temporal scale between the GCM scenarios (around 100 km and monthly atmospheric anomalies) and small watersheds (several km and response time of several hours). Even so, we can assume that climate change will entail more severe floods in autumn and winter and more marked drought periods.

The issue of the increase in the frequency of high floods cannot be dealt with through the numerical approach used up to now for large basins. This would require interpreting GCM modelling in terms of occurrence of extreme phenomena, which is still beyond the limits of GCMs. A statistic analysis of these extreme events over the current period does not allow either to determine an evolution in their occurrence.

Nevertheless, independently of climate change, it is possible to forecast flash floods with high resolution meteorological models (raster of several km) for a limited area and within short time periods (daily scale) by using frequent atmospheric humidity field analyses. The coupling of these rainfall models with hydrological models of sudden floods is being tested by the scientific community (projects supported by the PATOM and PNRH national programmes).

A.3 – SECTORS MOST VULNERABLE AND SENSITIVE TO CLIMATE CHANGE

• **Earlier low water periods** in some watersheds (described in the above section)

Early low water periods could in particular worsen the problems of water use already existing in the Adour-Garonne basin, because of the extension of irrigated crops during last years.

• **Increased evapotranspiration and change in agricultural schedules**

• **Wetlands**

Two mechanisms linked to climate change could induce an invasion of sea water in the coastal ponds and the Camargue delta, i.e.: a rise in the sea level and a subsidence of the coastal area due to a lack of water supply upstream.

• **Forest ecosystems**

A climate warming of about 3° could entail a contraction of natural vegetation areas due to aridity and a slight rise in levels of vegetation with a decreased productivity. Fire-connected risks would increase because of longer drought periods.

• **Mediterranean floods**

Independently of the issue of a higher frequency of extreme climate phenomena, increased winter rainfall is likely to entail a higher number of flood events.

B - INSTITUTIONS

B.1 - INSTITUTIONS/NETWORKS CONCERNED

Created in 1992, the **Interdepartmental Commission on Greenhouse Effect** (MIES) is in charge of co-ordinating the French actions to combat GHG emissions, at the national scale as well as within the international and European authorities. Its reform held in 1998 (through modification of its regulating decree) has reinforced its means and joined it to the Prime Minister (while being put at the disposal of the Ministry of Ecology and Sustainable Development).

At the French level, a first national action programme was defined in 1993, then revised in 1995 and 1997. Its major aim was to meet the objective of the United Nations Framework Convention on Climate Change (UNFCCC) - the so-called Rio convention – i.e., stabilising emissions at their 1990 level by the year 2000. From now on, the new National Programme to Combat Climate Change (PNLCC) that covers the first decade of the 21st century and was validated on 19th January 2000 by the Interdepartmental Commission on Greenhouse Effect is consistent with the objectives undertaken by Europe and France within the scope of the Kyoto protocol (stabilising GHG emissions to their 1990 level by the year 2010).

To fulfil its missions the MIES relies on several networks:

- a network of corresponding members in the main departments of the Ministries concerned;
- a network of specialists of East-West or North-South co-operation issues. They allow to implement the French participation in the mechanisms established by the Kyoto protocol in this field;
- networks of scientific and economic experts whose services can be called upon in France, through the Co-ordinating Committee for Scientific Expertise set up within the MIES, in co-operation with the MEDD research department;
- networks of foreign or international research centres on the socio-economic aspects of policies for the prevention of climate change.

The PNLCC does not deal with issues regarding climate change effects and adaptation. The present state of research on such impacts can be found in the third national communication to the United Nations Framework Convention on Climate Change. Studies on these impacts are largely developed in France, mainly under the aegis of the GICC (Management and Impacts of Climate Change) research programme of the MEDD[1].

The ONERC (**National Observatory of Climate Warming Effects**) has been established by the Law of 19th February 2001, in metropolitan France as well as in the French overseas Departments and Territories. It aims at collecting information, studies and research works regarding the risks connected with global warming and extreme climate phenomena, in collaboration with the research centres and institutes concerned and the intergovernmental expert group on climate evolution. This observatory which is currently being set up may present proposals regarding adaptation.

Research institutes involved

A great number of French institutes have led research or collected information regarding climate change: CNRS, Météo-France, Cemagref, Cirad, Ifen, Ifremer, Ined, Inra, Inserm, IRD, GIP Medias-France.

B.2 – CO-ORDINATION

As explained above, the interdepartmental feature of the MIES enables this structure to co-ordinate all the issues connected with the climate change induced by the greenhouse effect and its impacts.

[1] Ministry of Ecology and Sustainable Development

Environmental applied research is co-ordinated by the MEDD (Ministry of Ecology and Sustainable Development).
Academic research is led in universities, as anywhere else. In addition, the CNRS (Science and Engineering Research Council) which belongs to the Ministry of Research is organised in several institutes, especially the INSUE (National Institute of Universe and Environment Sciences). There are also specific research structures such as the IRD (Institute of Research for Development), INRA (National Institute for Agronomic Research), CEMAGREF (public agricultural and environmental research institute) and CIRAD (International Co-operation Centre of Agronomic Research for Development) and, in the meteorological field, the CNRM (National Centre for Meteorological Research) which belongs to Météo-France.
The decision-making actors are, according to the subject, the Ministry of Ecology and Sustainable Development, the Ministry of Agriculture and their decentralised structures, and, in case of crises such as floods, the Home Office. These structures act after consultation with the elected councillors and representatives of the civil society, at the regional and local scale.

C - INTEGRATION OF POLICIES AND PRACTICES

Under the leadership of the MIES, France has adopted a National Programme to Fight against Climate Change (PNLCC), which mainly deals with schemes to reduce the production of greenhouse gases and, as yet, only slightly tackles adaptive measures.
The three core Laws on Water of 1964 (creation of Basin Committees and Water Agencies), 1992 (implementation of new planning instruments) and 1995 (reinforcement of the arrangements to fight against natural hazards) are the general framework of intervention from the public authorities. They have enabled the country to be better armed to fight against the effects of droughts, floods and pollution. The Government considers proposing soon new bills on water and natural hazards, that should strengthen these plans.

D – ADAPTIVE STRATEGIES

D.1 – INTRODUCTION

France has not yet defined any national programme of adaptation to climate change. However, there already exist laws about town and country planning and environmental protection, as well as plans derived from these laws for the prevention of natural risks and schemes for an integrated management of natural areas, environments and resources. It is worth highlighting that many systems are ill adapted to the current climate conditions and to climate variability, and consequently a good starting point could be to select measures allowing to reinforce the resistance of these systems to the present conditions. These measures would contribute to better protecting the country from the possible impacts of climate change on the water regime, even though its effects are still ill-known.

As regards water regime, studies evidence the following concerns for the 50 years to come:

- early low water phenomena: one month ahead for the Rhone basin, study under way for the Garonne basin;
- increased evapotranspiration and change in farming schedules;
- multiplication of devastating Mediterranean floods;
- risks affecting several coastal areas that could be vulnerable to a rise in the sea level (the Camargue delta in the Mediterranean region).

D.2 – FIGHT AGAINST DROUGHTS

Within the framework of the Law on Water of 1992, SDAGEs (Water Development and Management Schemes) have been implemented in each large basin; they set targets of minimum low water discharges for the main rivers subject to high draw-offs and they determine the areas of water distribution in places where water resources and needs are not balanced. In these sectors, any additional draw-off is forbidden or must be compensated by new reserves.

Lastly, the scheme aimed at controlling the working of irrigation has been strongly reinforced. The considerable rise in the price of water draw-offs and use has led to a kind of self-regulation of demand.

D.3 – AGRICULTURE

Agriculture is the major concern regarding the management of the various uses of water because of its impacts both in quantity (drying up due to irrigation) and in quality (eutrophication of rivers or coastal environments, contamination of water supply points by nitrates or pesticides). Irrigated areas only account for less than 8% of the Useful Agricultural Area in France (crops + fodder); consequently, a change in the water regime could impact the whole French agriculture.

Here and now, irregularities in rainfall and water regimes are materialised by a high vulnerability of farming activities to bad weather events (hail storms, floods…) that mobilise huge compensation funds and by the development of complementary irrigation aiming at securing output, especially for the crops connected with agro-industrial activities in the North of France.

Research institutes have initiated a considerable effort (Agrotech programme led by INRA[2]) in order to assess the impact of GHG increase on farming. The main results show a double effect: a positive impact due to carbonaceous fertilisation (increased productivity and reduced water needs), and a negative impact because warming shortens the vegetation cycle.

Significant changes in agricultural schedules have already been acknowledged.

Securing output is a major challenge for French agriculture: when considering the ups and downs recorded in output, however, it is difficult to determine what is attributable to the agronomic context (new varieties, etc…) and what to climate change.

D.4 – FIGHT AGAINST FLOODS

The French Government has decided:

– to speed up the implementation of Plans for the Prevention of Risks (PPRs),
– to improve flood warning systems through a better collaboration between the Water Services, Météo-France Services and the system of warning of the population.

In the Mediterranean regions, floods are difficult to predict. Forecasting systems regarding torrential rain warnings by Météo-France have been reinforced (in particular, thanks to the extension of the monitoring of storm phenomena by radar), and are subject to short-term warnings (24 hours) to the local authorities and general public, with a 4-level scale of risks. This warning system has properly worked during the floods of the Gard river in September 2002. It is still not possible to locate precisely the storm onset in small split-up watersheds, which hinders the forecasting of local floods likely to be disastrous in very small rivers of the Mediterranean type.

The recent catastrophic floods of the Gard river have led the Government to announce the reinforcement of measures for the protection of persons and goods:

1 – reduction of the rhythm of water runoff by developing regulative measures and decreasing the discharge upstream of the watershed: dry micro-reservoirs, setting up of flood expansion areas.

2 – reinforcement of flood warming systems. Within this scope, a National Technical Centre aimed at supporting Flood Warning Services will soon be established in Toulouse. It will gather the technical tools developed by Météo-France and the Ministry of Environment: HYDRO and PLUVIO databanks, distribution of flood simulation tools, publishing of flood monitoring maps to be used together with the meteorological monitoring maps already existing…

In parallel, measurement networks will be strengthened, especially the ARAMIS network that measures rainfall by means of radars and covers the whole metropolitan territory as well as large areas in the overseas Departments and Territories.

3 - speeding up of procedures for the establishment and approval of PPRs[3].

Generally speaking, specialised services have been asked to develop awareness and "risk culture" within populations, by a quicker and more direct circulation of the available information regarding risk

[2] National Institute for Agronomic Research
[3] Plans for the Prevention of Risks

forecasts (warnings of extreme events) and vulnerability (maps of areas liable to flooding), possible preventive measures and behaviours in case of flood onset.

Lastly, the Government has confirmed it intended to bring in a bill about risks.

The legal measures that deal with natural risks are stated in Section 2 of the bill that is in preparation, entitled “Preventive measures for natural hazards”. This section includes various chapters that focus respectively on the different elements of prevention:

- a better access to information for the population;
- land use and development: beyond the preventive measures concerning lands liable to risks, this chapter addresses the lands that contribute to worsening the risk or that could be used to mitigate it;
- works against natural hazards: in particular, to make easier the intervention of local authorities for the protection and maintenance of their own property;
- financial steps mainly aiming at favouring preventive measures, especially works but also out-of-court acquisition of threatened estates;
- actions of the RTM (Department for the Restoration of Mountain Lands) and the ONF (Forest Commission) regarding risk prevention.

TECHNICAL REPORT
in three sections:

1 – STATUS OF WATER RESOURCES IN FRANCE

2 - IMPACTS OF CLIMATE CHANGE ON THE WATER REGIME

3 – RECENTLY ADOPTED MEASURES

1 - STATUS OF WATER RESOURCES IN FRANCE

1.1 - An exceptional water potential

Thanks to its numerous water resources and to its highly diversified geographical environments, France benefits by a remarkable water potential from an ecological standpoint, although these resources are overexploited in some regions.

Rainfall reaches about 440 billion m^3 per year, of which 100 billion m^3 per year on an average are available for human use (60 billion m^3 during dry years, i.e. one in every decade), after taking into account evapotranspiration, problems of accessibility and losses during flood periods. However, these average figures mask the fact that these resources are irregularly distributed in time and space. The development of irrigated lands in the southern half of the country requires huge quantities of water that entail marked deficits at the local scale during dry years. The end of the 80's and the beginning of the 90's were characterised by long-lasting droughts.

The country counts more than 110,000 km of watercourses whose width is superior to one metre and that belong to private owners, as well as more than 12,000 km of bigger rivers that belong to the state and are managed by the Ministry of Environment.

France benefits by several vast sedimentary watersheds of interest for the use of underground water (the Paris Basin, the Aquitaine Basin) and of water tables accompanying the main rivers. Such ground water is a major resource for the supplying of drinking water.

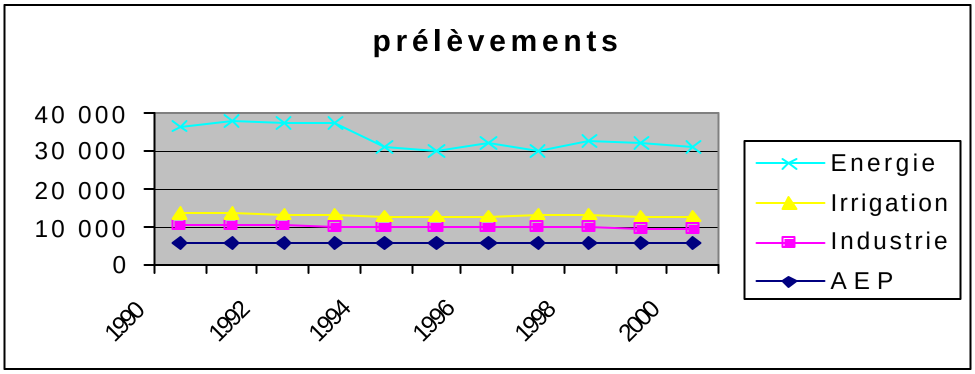
The water is usually taken from surface water; underground water only accounts for 15% on an average. Nevertheless, 56% of the water that feeds public supply networks come from ground water. Deep water tables are the main feeding system for large areas such as the Aquitaine and Paris regions regarding drinking water or the Beauce area regarding farming.

Big floods may cover vast plains for several weeks under the influence of the Atlantic climate, while violent and torrential floods characterise Mediterranean rivers.

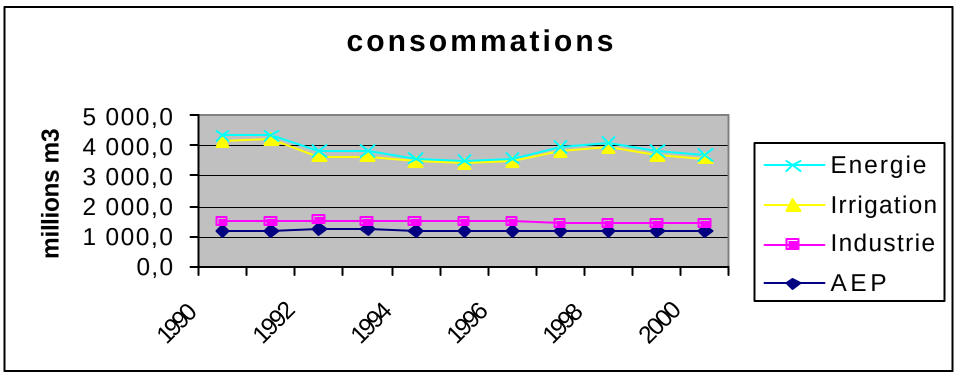
Lastly, France has a network of diversified lakes and wet areas, highly valuable for ecology. Wet areas cover about 2 million hectares. A report drawn up in 1994 by the Government evidenced a high degradation of this network of wet areas; and it has been assessed that more than half those existing 30 years ago have disappeared or are highly degraded.

1.2 – Many different pressures

In France, draw-offs for human needs are currently assessed to reach about 38 billions m^3, including 15% for domestic use, 19% for industrial activities, 64% for the cooling of power stations, and 12% for farming. Industrial and domestic uptakes have been steadied for several years, but the country has to face growing agricultural draw-offs induced by the quick development of irrigation during the 80's and 90's.



Draw-offs



Consumption

Figure 1 – *Draw-offs and consumption (expressed in million m^3)*

Most industrial and domestic draw-offs are restored to the natural environment, whereas the main part of the uptakes for irrigation are consumed. The needs for irrigation are the major part of the quantities taken from the natural environment in the South of France. The recent high increase of irrigation that is not compensated by the creation of water reserves entailed a serious drying up of many rivers in 1989 and 1990, especially in the South-West of France.

As in many developed countries, water consumption for industrial use has been decreasing for some years. The slackening activity in the mining and iron & steel sectors accounts for most of the decrease in the industrial demand. The modernisation of plants as well as water savings have also led to a reduction in the uptakes mobilised by the food-processing industry or the wood pulp paper industry. Draw-offs for power plants, that had been highly increasing from the beginning of the 70's, are now stabilised following the end of the nuclear power programme.
The consumption for domestic use increased by 15% between the end of the 70's and the beginning of the 90's. This increase is now stabilised: on the one hand, most supplying equipment are completed, on the other hand, important investments are devoted to reduce the leakage of networks. The rise in the water price and the recent legal measures according to which the water invoice depends on the volume consumed and is no longer a fixed amount have helped to accelerate water savings.

Uptakes for farming tend to increase. Irrigated areas cover 2,700,000 ha whose development mainly rely on sprinkling or drop-by-drop techniques, for which it is assessed that more than 80% of the water draw-offs, i.e. from 2,000 to 3,000 m^3/ha/year according to the year – are evapotranspirated. In the South-West of France, more than 60% of the water consumed are attributed to irrigation. To meet

these needs, it has been necessary to devote huge investments to the creation of water reserves and transfer structures.
Today, most people are suitably supplied through a conveyance network of drinking water. The main issues that concern consumers and authorities are nitrates, pesticides and lead.

1.3 – Irrigation in France

The major fact to be highlighted regarding France is a high increase in the South-West region during the 80's.

In 1997, the statistics of the Ministry of Agriculture count 2,700,000 ha of equipped areas and 1,900, 000 ha of irrigated lands.
Equipped areas include permanently or temporarily irrigated lands (complementary irrigation in the North of France). The equipment mobilised and the areas irrigated strongly vary between a dry year and a wet year.
These figures depend on the definitions used. Actually irrigated lands are subject to declarations that are not consistent according to the files used.

A high increase in irrigated lands is noticeable as of 1970, with an acceleration during the 80's.

(ha)	1970	1979	1988	1995	1997	2000
Equipped areas	767,000	1,325,000	1,796,000	2,510,000	2,700,000	2,634,000
Irrigated areas	539,000	801,000	1,147,000	1,630,000	1,907,000	1,576,000

Table 1 – *Evolution of equipped and irrigated areas in France.*

Provence (18% of the irrigated land) and Languedoc-Roussillon (7%) are old regions of irrigation (specific crops, fodder). The recent quick development of permanent irrigated areas has mainly concerned the South-West (Aquitaine, Midi-Pyrenees, Poitou-Charentes): 200,000 ha to 600,000 ha within 10 years, i.e. 30% of the irrigated land, as well as regions such as Pays de la Loire, Alsace and Val-de-Saône.

Such an increase is mainly due to the development of maize, a plant that reacts positively to water supply and which is sensitive to the droughts of recent years. Maize is the main crop of the irrigated land (45% for the whole France, 2/3 in the South-West), followed by vegetables and orchards (18%) and oil-producing plants (10%).

In the Mediterranean part of France, the rainfall deficit is high in summer; it implies a systematic use of irrigation for the main crops (orchards, market gardening, fodder). The hydraulic power of the Rhone, as well as important structures for water reserves and water transfers in the Rhone basin led in the 60's, ensure that water resources are well enough for the Provence (Canal de Provence) and Languedoc-Roussillon (Canal du Bas Rhône-Languedoc) regions.

In the South-West, as soon as 1988, the Adour-Garonne Water Agency had warned that the extension of irrigated lands was leading to a situation of chronic deficit of water resources. More than 800 million m^3 of water, 87 of which attributable to irrigation, have been taken from the natural environment as soon as the 90's. This figure corresponds to a discharge higher than the one brought by the Garonne, Adour and Charente rivers downstream their watershed in period of low waters. This induced shortage crises in 1985, 1986, 1988, 1991 as well as a situation of chronic deficit for rivers like the Charente or the main tributaries of the Garonne. Even in the recent years, which are comparably favourable in terms of rainfall, the river discharges evidenced have fallen below the baseline low water discharges.

According to the rainfall, the needs for irrigation water for maize can vary from 1,500 to 2,500 m^3/ha/year depending on the year. The extension of maize crops has generated serious water deficits and has led to implement a programme of dams and transfer structures.
The Basin Committee had proposed to realise an ambitious programme for the creation of water reserves in order to compensate the impact of the draw-offs: a creation of 600 million m^3 of water reserves within 10 years.
This programme was only partially implemented because of the very negative reactions of the ecologist circles who saw it as a never-ending race for irrigation. Because of the lack of financial backing, the Government has decided to progressively reduce its subsidies to this type of equipment.

The balance between supply and demand for agricultural water had then to be based upon a regulation of demand: a decrease in the growth rate of irrigated lands and a better management of their organisation (warning to farmers, water savings).

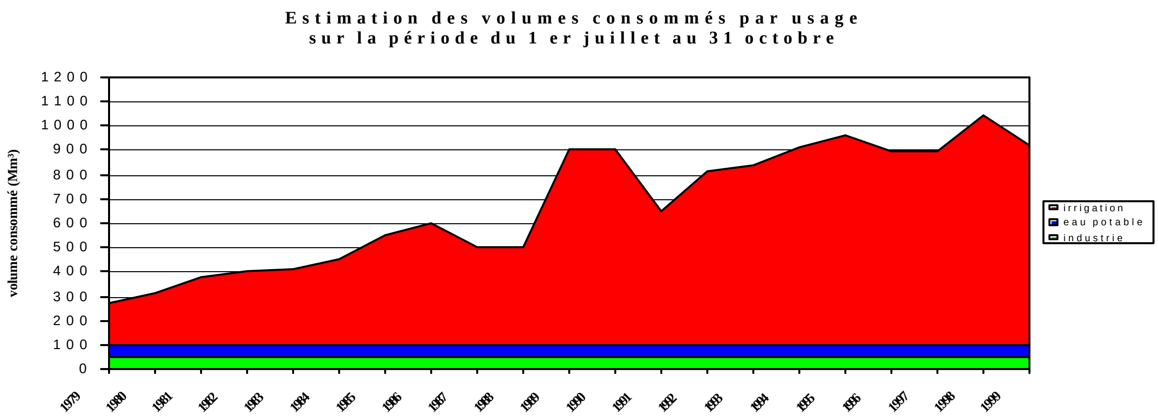


Figure 2 – *Estimate of the volumes consumed in relation to their use over the period 1st July to 31st October Adour-Garonne basin*

1.4 – Floods and high water in France

1.4.1 - Facts

Together with droughts, floods are the main natural hazard connected with water in France.

Three main types of floods and hazards exist in our country: floods of oceanic pattern (type: Seine, Loire, Garonne), which are long-lasting floods with high volumes of runoff; Mediterranean floods (type: Nîmes, Vaison-la-Romaine, Gard) which are short events but are violent and difficult to foresee; urban floods, connected with the saturation of drainage networks, which are usually due to storms.
To this list of water disasters, we should also add the cyclones that periodically hit Reunion Island and the West Indies. In 1998, Hurricane Mitch evidenced the devastating impacts of these phenomena in poor, ill-prepared countries (Nicaragua, Costa-Rica).

It is not easy to assess the measures to be taken in order to fight against floods. The classical technical and scientific approach (probability of floods and evaluation of overflows) has to be coupled with a socio-economic vulnerability approach (economic value and sensitivity of material goods to be covered by water). New methods, such as the “liability-to-flooding” method designed by the CEMAGREF have allowed to improve this knowledge.

Floods are natural events. The disorders they cause to human society are largely induced by men, as it has been diagnosed for a long time. The progress of knowledge (part of which relies on the study of

historical chronicles) today allows to improve the forecasting of such phenomena; we are now able to identify the human-induced causes that contribute to amplify them.
There has been a greater number of flood-connected disasters for the last 25 years than for the previous 100 years (the main reason being the increasing occupation of areas liable to flooding by vulnerable installations).

Year	Event	Casualties deaths (d) and disaster victims (v)
1875	Loire	
1910	The Seine in Paris	150,000 v
1930	The Tarn in Montauban	200 d +10,000 v
1930	The Garonne in Toulouse	171 d
1940	Eastern Pyrenees	50 d
1958	Cevennes rivers	38 d
1977	Lannemezan rivers	16 d
1987	Grand-Bornand torrent	23 d
1988	Nîmes	11 d + 50,000 v
1992	Vaison-la-Romaine	46 d
1993	The Lèze in Bollène	3 d
1993	Burst sea walls in Camargue	26 d
1994	South-East Corsica	4 d
1996	Béziers	3 d
1999	Aude – Eastern Pyrenees	29 d
2001	Breton rivers (Oder,…)	
2001	Somme	
2002	Gard	29 d

Table 2 – *Major floods in France*

These phenomena are accentuated by changes in land occupation (deforestation, consolidation of farming land, soil becoming impermeable in urban areas, reduction of flood expansion fields). Every year, about 40,000 hectares are gained by towns over forests and lands. They contribute to the quick acceleration of surface runoff. In rural environment, the removal of hedges and the increase of ploughed lands - in which soils remain bare in winter - to the detriment of meadows speed up surface runoff. Flood control has been highly beneficially helped by the works of restoration of mountain lands and programmes of reafforestation in order to fight against erosion that began at the end of the 19th century in the Alps and Pyrenees, and which have been carried on up to now.

Public action covers three main aspects in all countries: means for fighting against floods, prevention, and emergency aid. Organising the emergency aid is vital; but only prevention is likely to reduce the amount of damages. The distribution between these three public actions, as well as the main risks, vary according to the country (human victims in poor countries, material damages in rich ones).

Box – *Part played by the actors*

- Government:
- Météo-France: rainfall measurement and forecast
- Ministry of Environment: organisation of prevention (networks of warning and preventive management)
- Home Office: organisation of emergency aid
- Municipalities: protection structures, town planning, local warning.

Legal instruments

- Code of municipalities (1884): the Mayor has authority to exercise general law and order
- Law of 1982: insurance companies create a natural disaster compensation scheme
- Law of 1982/84: PERs (Plans of Exposure to Risks) are launched and implemented under municipal responsibility
- Law of 1995: simplifies the PER procedure by introducing PPRs (Plans for the Prevention of Risks) on governmental initiative and a scheme for expropriation in case of serious threat.

1.4.2 – Instruments for the prevention of flood-connected damages

The means to fight against floods are the following ones: creation of sea walls and dykes, erection of structures to mitigate floods, and preservation of flood expansion areas.

The oldest technique consists in creating dykes. Our main rivers (The Seine, Loire and Garonne) are dyked up over long distances in low valleys. These dykes that were erected upon governmental decision as soon as the 19th century have been extended or strengthened by local authorities or farmer associations. They are currently insufficiently maintained.

These dykes have openings in order to allow floods to expand over lands that are little exposed and are able to undergo flood periods without damages. Meadows are preferential lands for flood expansion. The fact that meadows are changed into cultivated lands and that some farming lands are built up with houses imply that it is more and more difficult to keep these flood expansion fields.

The maintenance of these structures is still a heavy financial charge for the Ministry of Environment, and few public partners are willing to grant huge funds for this upkeep, except towns as they see their opportunity to extend their urbanised areas. The dramatic bursting of the sea walls in Camargue in 1993, which were private walls that had in fact been variously tinkered (crossing of pipes) and abandoned by their owners, have shown that the Government and local authorities could hardly neglect to protect these structures.

The creation of reserves aiming at mitigating floods can only have a strictly limited impact in big watersheds. It is hardly possible to hope to suppress floods thanks to dams, considering the enormous volumes of water run off in relation to the capacities of the best sites. The programme that aims at partially erasing the floods of the Seine river could not be considered for the Loire or the Garonne whose floods are much more important (8,000 m^3/s for the Loire in Tours).

Priority must be given to a better management of runoffs in all the French watersheds, following the example of the works undertaken in the 19th century by the RTM (Department for the Restoration of Mountain Lands), in order to rehabilitate all the instruments used to slow down and store floods, by replanting hedges and mobilising all the techniques aimed at slowing down and infiltrating water. This policy alternative to the edification of big structures has already been initiated by several cities such as Bordeaux. In these cases, town planners are required by town planning regulations to store the discharges generated by new buildings in the developed areas themselves.

1.4.3 – A better anticipation of rises in river levels

Flood Warning Services are the entity responsible for forecasts, in collaboration with Météo-France. They are state-owned services, organised by large basins within the Ministry of Industry's DIRENs (Regional Offices). They deal with the most exposed part of the big rivers. The modernisation of measurement stations (automation), the setting up of radars intended to measure rainfall, the development of Hertzian or satellite transmission means and the improvement of computation methods have enabled to anticipate and actually improve the quality of the forecasts concerning rises in river levels for the main hydrographical systems, such as the Seine, Loire, Garonne, Dordogne and Rhone rivers.

Forecasting is more difficult for torrential floods of the Mediterranean type. Rainfall phenomena can bring considerable volumes of water within a short period of time, while it is not possible to foresee precisely on which watershed – often limited – the rain is going to pour. The consequences of these events affect very small rivers that tend to overflow quickly and that carry along mud and materials, thus worsening the disastrous effects of the flood. It is necessary to increase the collaboration between Météo-France and the Flood Warning Services, including the use of rainfall monitoring radars (ARAMIS network) set up by Météo-France with the financial backing of the Ministry of Environment.

Several cities (Paris, Bordeaux, Nîmes, Marseilles,…) and associations of communes have set up local forecasting systems complementary to those implemented by state services in order to face more localised phenomena likely to cause considerable impacts in vulnerable districts.

The organisation of the emergency aid, that depends on flood warning forecasts, comes under the authority of the Emergency Services, which belong to prefectures, and of the Mayors at the local scale.

1.4.4 – Prevention: municipalities hesitate to report risks

Mapping areas liable to flooding is a major prevention instrument. In addition to its function of warning, mapping aims at identifying the risk so as to avoid building vulnerable facilities in areas likely to be flooded. The Mayors are the main guarantors for the respect of these prescriptions, by means of PLUs (Local Town Planning Schemes) and planning permissions.

As soon as 1935, the French public authorities have drawn up plans of areas liable to flooding for the major rivers (Loire, Seine, Garonne, Rhone). But because of the scale (1/25,000) and the insufficient coverage area of these maps, these plans cannot be opposable to third parties and do not impose constraints.

The Law of 1982/84 has delegated to municipalities the drawing up of PERs (Plans of Exposure to Risks) that had to lead to the regulation of the authorisations to build in areas liable to flooding, corresponding to constraints registered in the Land Use Plans. Generally speaking, municipalities proved to be rather reluctant to institute these procedures that could entail strong constraints regarding POSs (Land Use Plans).

More than 10 years after their creation, there were only 347 PERs approved in 1995, whereas an inventory dating back to 1982 estimated that there were approximately 10,000 municipalities exposed. Municipalities are more willing to implement protection works than to report risks.

This situation has been remedied on the one hand, by the Law of 1995 that simplified the procedures for the laying down of these plans that became Plans for the Prevention of Risks approved by order of the prefect, and on the other hand, by the multiplication by 3, then by 6, of the budgets incurred by the State.

In 2002, the introduction of PPRs is prescribed in more than 8,000 municipalities out of the 10,000 communes identified as priority on account of natural disasters. More than 3,000 PPRs are now approved, and more than 500 new ones are passed every year.

It is difficult to decide what should be done with the buildings previously erected in areas liable to flooding: the Law of 1985 provides that the most vulnerable premises should be subject to an expropriation order, but of course this procedure may be reasonably undertaken only in exceptional cases. To complete this measure, the fund created in 1995 to finance these expropriations (the "Barnier" fund) will be mobilised as from 2003 to pay for the steps that aims at reducing the vulnerability of buildings located in areas liable to flooding, as imposed by PPRs.

1.4.5 – Emergency plans in every French Department

Today, emergency plans have not been designed as yet in every Department under prefects' authority. Whenever they exist, they provide for graduated means according to the importance of the disaster and for measures of protection to be undertaken regarding vital activities (water supply, traffic, activity of major plants). Emergency aid is organised upon Emergency Services' initiative, under prefects' authority who may appeal to exceptional means (army) if need be. The Home Office considers making compulsory the establishment of such plans. Without waiting for this obligation, State services have begun two years ago to work out an aid scheme shared by several Departments. This scheme is difficult to elaborate because of considerable existing risks (nearly one million inhabitants concerned) and of the extreme complexity of public services in the Paris agglomeration. Nevertheless, this is big challenge: the cost of damages that could affect the area in case of a flood like the one of 1910 is estimated to exceed 10 billion euros today, i.e. nearly ten times the cost of the damages suffered in 1910. At that time, the population exposed was five times less numerous and urban equipments were much easier to operate.

1.4.6 – Socialisation of risks and individual responsibility

After a disaster and the setting up of an emergency aid, the Law of 1992 regarding insurance enables to implement a scheme for the victims to get compensation, so long as the Prefect declared the flood to come within the scope of a natural disaster.

The French insurance scheme of 1982 provides that:

- all insured people are subject to a fixed rate additional premium which is compulsory;
- compensations are subject to an administrative order that recognises the event and states the municipalities concerned;
- insurances may be reinsured to the Caisse Centrale de Réassurance so as to benefit by a state guarantee.

These measures allowed to implement a quick compensation for the persons or activities affected by disasters. This scheme of systematic socialisation of risks has been established to the detriment of the individual responsibility of persons. Experience shows that many activities that chose to run the risk of settling down in exposed areas and suffered frequent floods have benefited by as many compensations.

The fact that the decision is distributed among the person who acknowledges the disaster (the Prefect) and the payer of the compensation (the insurance) and that insurances companies can be guaranteed by the Caisse de Réassurance leads to cover repetitive hazards, the risk of a major disaster being covered by the state-guaranteed fund.

Many actors agree that this system takes away too much responsibility from the main people concerned, and consider that a distinction should be made between a repetitive hazard, often connected with the use of a place identified as liable to flooding, and an exceptional risk, which should be the only one to deserve compensation.

In France, insurance costs for natural disasters are considerable (about one billion euros per year, all natural risks included), and are increasing (the rate of the insurance additional premium has risen from 9 to 12% in 1999). In comparison, the funds granted to prevention policy, and particularly to warning and the establishment of PPRs (15 million euros in 2001 for projects) appear to be low. Many experts have observed that it would be quite useful to rebalance the means between these two action policies.

This rebalancing has been progressively undertaken since 1994, with the creation in 1995 of the Barnier fund financed by a 2% levy from the additional premiums that finance compensation, which might be raised to 4% in the years to come, since the scope of this fund will be extended to the backing of works intended to reduce vulnerability.

2 - IMPACTS OF CLIMATE CHANGE ON THE WATER REGIME

2.1 – Hydrological impact of climate change on a major French watershed: the Rhone basin

Simulations of general circulation models (GCMs) designed according to the hypothesis of doubling the CO_2 atmospheric concentration (by the year 2050 according to various scenarios of GHG increase) agree about highly marked anomalies of the atmospheric variables near the surface, in relation to the current climate. Although the available scenarios regarding France are still dispersed, they all simulate significant disturbances of rainfall and air temperatures to be expected during the second half of the 21st century: increased winter rainfall and decreased summer rainfall, and a more marked rise in air temperature in summer than in winter. These anomalies will significantly impact the hydrology of the main French watersheds. It is consequently essential to implement hydro-meteorological modelling tools that should be able to integrate the climate anomalies expected, in order to assess their hydrological impact at a regional scale. The present chapter describes the methodology developed for the Rhone basin (project supported by the GICC programme) in order to assess the possible changes in various hydrological fields (snow, evaporation, soil water, runoff, discharges) in response to 6 scenarios of general circulation models interpolated on the basin. After a short description of the ISBA-MODCOU hydro-meteorological model developed for the Rhone, the monthly anomalies simulated in the 6 scenarios are discussed. The hydrological impact on snow, soil water, evapotranspiration and discharges for various sub-basins is briefly analysed in the last part.

2.2 - 'Gewex-Rhône' database and hydro-meteorological modelling of the current climate

The study of climate impact is based on the conclusions of the Gewex-Rhône co-operative project that led to set up an invaluable database regarding the basin and to develop an increasingly complex hydro-meteorological modelling over a long time period (1981-1996) (Habets et al., Etchevers et al.). This serves as a baseline of the present climate in order to assess the disturbances in various fields of the water system under a modified climate hypothesis. The field of interest covers the French part of the watershed (Fig. 3) thus including a high variability of climate and water regimes: a rather continental pattern in the Saône watershed, a mountain climate and snow water regime in the Doubs, Isère and Haute Durance watersheds, a Mediterranean climate for the Durance, and a Cevenol climate in the South-East of the area considered. The differential impact of climate change can then be examined in relation to the various hydrological contexts of the present climate. The meteorological database corresponds to 8 atmospheric variables interpolated on an 8-km uniform grid from all the measurements available for the period (more than 1,700 posts of daily rainfall): rain, snow, hail; specific air temperature and humidity, wind velocity, sun and atmospheric radiative flows, surface pressure. This meteorological database represents the climate of the watershed for the current period and is used to define the modified climate by combining the monthly anomalies simulated by various GCM scenarios (especially rainfall and air temperature).

A database of the daily discharges in a hundred stations (Fig. 3) is used to assess the performances of the modelling of the present climate and the monthly disturbances of discharges for the modified climates in different spots of the hydrographical network (computed from a 1-km resolution DTM). In addition to this hydrological base, records of snow heights obtained in 25 stations allow to calibrate various snow patterns. The last aspect of the base regards soil (1-km INRA soil database) and vegetation ("Corine Land Cover" database established from a classification of NDVI/AVHRR satellite indexes).

The hydro-meteorological modelling relies upon the ISBA-MODCOU coupled model (Habets et al. 1999, Etchevers et al. 2000) that allows to simultaneously simulate the interactions between surface-atmosphere (ISBA surface pattern) and surface-hydrology (MODCOU hydrology model). The ISBA surface model (Noilhan and Planton, 1989) used for operational atmospheric models simulate the diurnal cycle of water and energy budgets: snow at ground, evapotranspiration, surface runoff and drainage, distribution of temperature and soil water explicitly considering land occupation and soil texture. Runoff and drainage flows are transferred to the MODCOU distributed hydrological model that represents the discharge of each sub-basin established from the runoff in the surface hydrographical network (1-km resolution) and the evolution of the water table (in this application, ground water is limited to the Rhone and Saône valleys). In-depth studies led by Habets et al. (1999) and Etchevers et al. (2001) have shown that the coupled model was able to simulate very realistically the 10-day discharges for watersheds larger than 100 km^2 as well as the evolution of the snow cover over a long time period (1981-1996). By way of example, Figure 4 presents the comparison of monthly discharges observed and simulated in the main sub-basins and at the Rhone outlet in Viviers. The model consequently allows to consistently describe the various aspects of the continental water cycle and particularly to connect surface-atmosphere exchanges (rainfall, evapotranspiration) with hydrology (snow, soil water content, streamflow and discharges). This is an asset to analyse the hydrological impact of climate change.

2.3 – Climate change scenarios regarding the Rhone basin

Six scenarios derived from 4 general circulation models have been considered: LMD (IPSL), CNRM (Arpege-Climat), HC (Hadley Center) and UR (University of Reading) models. These scenarios correspond to “time-splitting” scenarios over the period 2050-2060 with a doubling atmospheric CO2 concentration and a 1% annual growth hypothesis. For each scenario, sea surface temperature fields have been computed from former simulations of the Ocean-Atmosphere coupled model of the Hadley Center. The six scenarios considered (table 3) are distributed in 4 “low resolution” scenarios for which 2 or 3 points of the general circulation model are located in the basin and 2 “high resolution” scenarios (LMD-HR and CNRM-HR – Dequé and Marquet 1997) giving a regional indication of the climate change within the basin (28 points for CNRM-HR and 10 points for LMD-HR). The 4 “low resolution” scenarios have been designed within the scope of the LSCPR European project (Polcher et al. 1999).

For each one of the 6 scenarios, 2 simulations were available for the current climate (1xCO2) and the modified climate (2xCO2).

1xCO2 simulations have been spatially interpolated on the 8-km uniform grid of the Rhone basin (Boone et al. 2000). In the case of low resolution general circulation models, the average of the 2 or 3 grid points within or near the basin has been considered. The realism of these 6 scenarios regarding the simulation of the current climate has been compared with the Rhone climatologies concerning rainfall and air temperature (Noilhan et al. 2001). As a rule, general circulation models are highly adequate to simulate the monthly cycle of air temperature whereas simulations of the monthly average rainfall are much less accurate regarding the present climate. Even though the seasonal rainfall cycle is generally well reproduced, monthly differences may be considerable. Besides, increasing the GCM resolution does not always correspond to improving the realism of the simulations performed.

2.4 – Monthly anomalies simulated in 6 GCM scenarios for the period 2050-2060

Considering the current limitations of the general circulation models to correctly simulate climate surface variables, it seems to be too early to directly use their results for the forcing of hydrological models. Obviously, the errors regarding the current rainfall that occur in several scenarios cannot lead to realistic simulations of the regional hydrology. This is why the monthly anomalies method has been selected in agreement with experts in climate modelling, since it is likely that the sensitivity of general circulation modelling to the increase of greenhouse gases is less subject to errors (even if this modelling is not perfect at our scale of interest). Consequently, for each scenario, mean monthly anomalies have been computed for each variable from both 2xCO2 and 1xCO2 simulations:

$$\mathrm{D}\ \mathbf{Ta} = \mathbf{T}_{\mathbf{a}\ \mathbf{(2CO2)}} - \mathbf{T}_{\mathbf{a}\ \mathbf{(1CO2)}}$$

$$\Delta P = (P_{(2CO2)} - P_{(1C02)}) / P_{(1CO2)}$$

Absolute anomalies are considered regarding air temperature (usually well simulated by general circulation models) while relative anomalies are taken into account regarding rainfall, which is less easily simulated by climate models. Snowfall anomalies are estimated from the total precipitation and the temperature of the modified climate by using the same critic temperature of rain/snow distribution as for the current climate (critic temperature = 0.5°C). These anomalies have been horizontally interpolated on the 8-km uniform grid.

Figure 5 shows the variation in monthly anomalies for the air temperature at 2m and the mean total precipitation over the basin. It evidences that winter temperature anomalies are quite homogeneous around +2 K whereas summer anomalies are extremely scattered, ranging from +8 K in September for HC to a moderate warming for the low resolution LMD. However, it is worth remarking that the two high resolution scenarios give comparable anomalies (+2 K in winter, +4 K in summer-autumn), however with a time lag in summer.

Regarding relative rainfall anomalies, the results of the general circulation models are still dispersed, even though a mean trend may be deduced: rainier winters (+20% on an average) and drier summers (-30% on an average). HC and LMD-HR scenarios are those which simulate the driest summers. In fact, the LMD-HR scenario shows a rainfall deficit all the year round, but for the month of February. Monthly variability is also high for most general circulation models, above all in autumn.

To sum up, the six scenarios are characterised by an increase in monthly temperature by about 2 K in winter and 4 K in summer, in spite of high month-by-month differences. On an average, winter precipitation increases by 15% and summer rainfall decreases by 20%. Two scenarios (HC and LMD-HR) differ in their low increase of precipitation in winter and their very high decrease in summer.

2.5 – Definition of climate scenarios for the period 2050-2060

The six scenarios are designed by combining the variables of the observed climate with the monthly anomalies simulated by the general circulation models:

$$\textbf{Ta modified climate} = \textbf{Ta observed climate (1981-1997)} + \Delta \textbf{Ta}_{\textbf{monthly GCM}}$$

$$\textbf{P modified climate} = \textbf{P observed climate (1981-1997)} * (1 + (\Delta \textbf{P / P})_{\textbf{monthly GCM}})$$

the other meteorological variables remaining at their current value. The modified climate is thus defined over the 16 years of basin climatology at a three hourly pace. The chronology of inter-annual variations (dry or wet year…) is not modified, nor is the monthly rainfall distribution. Rainfall intensity is simply adjusted by the monthly relative anomaly factor. In the future, it could be considered to modify rainfall distribution as suggested by some GCMs (the trend shown by the Arpège-Climat model is an increase in the number of days of heavy rainfall). Unfortunately, this information was available for only one GCM.

For each scenario, two series of forcing (present and modified climate) on the 8-km grid have been prepared for hydrological simulations. Only the monthly differences between the 2xCO2 and the 1xCO2 hydrological simulations are reviewed, in particular monthly anomalies regarding discharges, evapotranspiration, soil water content and snow.

Maps of vegetation and soil are the same as those of the current period. In the future, it should be worth considering the possible adjustments of vegetation-induced impacts within a context of enriched atmosphere (assimilation of atmospheric CO2 and adaptation of the biomass to the new climate and water context).

2.6 – Hydrological impact on the Rhone basin from the ISBA-MODCOU hydrological model

The ISBA-MODCOU model differs from simpler hydrological models in a rather precise description of surface processes, in particular in connection with the resolution of the diurnal cycle of surface energy and water budgets: detailed snow patterns, various elements of evapotranspiration, storage and distribution of water in the ground, surface runoff and drainage patterns.

The climate anomalies described hereabove strongly impact the surface budgets for the following reasons:

The rise in winter precipitation higher than the rise in the PET (potential evapotranspiration) increases the soil water content and therefore surface runoff and drainage. In mountain areas, the rise in air temperature occurs simultaneously with a decrease in snowfall and consequently with a reduction in winter accumulations (especially in medium mountain areas).

The decrease in summer rainfall increases the water deficit of the soil (the winter surplus being lost for reserves through runoff). The water deficit is still accentuated by the increase in PET (increase in air temperature) which entails a much earlier desaturation of the soil and harsher low water periods in autumn.

The rise in the air temperature entails an increase in real evapotranspiration during winter and spring since grounds are well supplied with water. Conversely, real evapotranspiration tends to be reduced in summer and autumn because of water stress. The flow of sensitive heat to the atmosphere is then reinforced. Within the scope of the ocean-atmosphere coupled exchanges, this is likely to induce a positive retroaction by accentuating the risk of a decreased rainfall. Snow is also a highly sensitive element, since it intensifies the melting and reduces accumulation as evidenced by Etchevers et al. (2001). The evolution of the snow layer has been computed from 2 physical snow models: the CROCUS detailed model and a simpler 3-layer snow model (Etchevers and Boone, 2001). Whatever the scenario, the height of the snow layer and the number of snowfall days decrease for every level of altitude, the highest reductions being found in the 2 extreme scenarios (HC and LMD-HR). Etchevers et al. (2001) show that this reduction strongly affects the medium altitude level (between 1500 and 2400 m) which is also the level where winter sport resorts are located: a –30 cm decrease in the mean snow height and a reduction by 50 days of the number of snowfall days on an average. Snow-covered surfaces decrease by 25 to 40% on an average according to the scenario. For high altitudes, the snow layer is a bit less affected because the mean temperature is significantly lower than the melting point (and is therefore less sensitive to the rise in temperature).

Anomalies regarding the snow layer are likely to have a considerable impact on the regime of Alpine rivers. This is shown in Figure 6, which displays the evolution of the snow layer and of discharges for the Haute-Durance basin (upstream of La Clapière). This part of the upper Alpine watershed includes no dams, which allows to directly connect the dynamics of the snow layer with the hydrological regime. For the current situation, modelling is able to remarkably reproduce monthly discharges. Climate scenarios evidence that the water-equivalent is reduced by about 50% and that the melting occurs much earlier, about 1 month sooner. The early snow melting entails a flood peak in May, a month ahead of schedule. It is worth underlining that this shifting is shown in all the scenarios. It induces much lower levels of water in July and August. In autumn and winter, there is a significant increase in discharges because of the bigger proportion of liquid precipitation (rainfall). Similar evolutions have been quantified for the Isère watershed in St-Gervais, the Drac watershed in Fontaine, the Ubaye watershed in Barcelonette and the Doubs watershed in Conclavon (Etchevers et al 2001).

Figure 7 illustrates the possible evolution of discharges, soil water content and evapotranspiration estimated from the ISBA-MODCOU hydrological model for 2 watersheds of different hydrological pattern: the Saône and Haute-Durance basins. The set of all the simulations with the 6 scenarios as well as the mean value are compared with the climatology of the current climate. For the Haute-

Durance basin, the increase in winter discharges and the reduction in summer discharges is actually connected with the increase in the soil water content in winter (under the present conditions, the snow is limiting winter infiltration) and with the high reduction in summer. Evaporation slightly increases in winter and spring (larger surface uncovered by snow) and decreases in summer when soil water becomes a limiting factor (in spite of the increased PET). Similar evolutions are recorded for the Saône basin, although they are more scattered as far as discharges are concerned. In this watershed, snow dynamics is not determining and climate change does not entail a marked time shift in the hydrological regime. On an average, i.e. if we consider every scenario as equiprobable, winter discharges increase by about 10% and low water discharges decrease a bit less. However, simulations regarding this basin are more uncertain since the GCM scattering diagram includes the present climatology while the simulation for the Haute-Durance basin does not. In fact, the two extreme scenarios (LMD–HR and HC) for this watershed simulate a decrease in discharges all the year round. Whatever the scenario of general circulation model, the soil water content of the Saône basin tends to decrease all over the year, very markedly in summer but also in winter because of the rise in PET.

Figure 8 shows that there may be high regional variations in hydrological impacts within the Rhone basin. They are annual anomalies concerning the high resolution CNRM scenario, which on an average are quite comparable with the 4 low resolution scenarios. The impact on discharges highly differs between the North (Saône) and South (Ardèche, Durance) of the area considered: increase in the yearly discharge of the Saône by about 10%, higher decrease in the Ardèche and Durance watersheds (reaching 15% for the latter). These contrasting regional responses are compensated at the Rhone outlet in Viviers, where a low reduction in the annual water volume is recorded (about 2%). Real evapotranspiration increases markedly in high areas because of the reduction of snow-covered surfaces. Evaporation also slightly increases in the North and is much more reduced in the South (5%) because of the soil water stress. The water content globally decreases over the whole area (since evaporation increases), especially in southern watersheds, thus accentuating their current vulnerability.

Table 4 presents a synthesis of the impact of these 6 scenarios over seasonal and annual discharges for the Durance, Saône, Ardèche rivers and all the Rhone basin. In spite of their dispersion, winter discharges increase on an average (the higher the current snowfall, the higher the increase), and summer discharges are significantly reduced. In fact, the agreement between the general circulation models is best in summer: no scenario foresees an increase in summer discharges of the Rhone in Viviers while 2 scenarios show a possible reduction in winter discharges.

2.7 - Extrapolation to other basins

The SIM model is now set up in the Adour-Garonne and Seine basins, for which hydrological simulations of the current period are satisfactory at the 10-day scale. The water regimes of these two basins are quite different from those of the Rhone, and may be more deeply affected by climate changes. A study being led regarding the Adour-Garonne basin (Morel, 2002) shows that its hydrological regime may be more sensitive, especially as regards low water patterns. In fact, the snow element would be more affected than for the Rhone basin because of the lower height of the Pyrenees and of the more moderated increase of winter precipitation. This could entail an earlier low water period in this basin where the use of water is already a problem since irrigated crops have been extending during the last years (more than 50% of the low water discharge of the Adour are currently used to irrigate maize). Moreover, the Adour and Seine basins have considerable aquifers (Landes water table, big aquifers of the Parisian basin) whereas this underground element is more limited in the Rhone basin. These subterraneous water reserves may be considerably affected by disturbances in their winter and spring water recharge, which could impact low water discharges. However, a better winter recharge of water tables could possibly counterbalance the summer water deficits of surface waters… But this is a subject for study in itself!

Case of small coastal watersheds in relation to climate change:

This issue is more difficult than for the large basins because of the difference of spatio-temporal scale between the GCM scenarios (100 km and monthly anomalies) and these small watersheds (several km) whose response time is quicker (several hours). Regarding the watersheds of the Mediterranean coast, we can assume that climate change will entail more severe floods in autumn and winter (the smaller the size of the watershed, the more sensitive the increase in rain intensity), and even more marked drought periods. The issue of the increase in the frequency of high floods cannot be dealt with through the "large basin" approach of the SIM model. First, it is necessary to be able to interpret GCM simulations in terms of modification of the rainfall distribution and of occurrence of extreme events, which is currently very difficult. In addition, breaking down tools aiming at expressing GCM information at the size of a watershed must resort to highly sophisticated methods, such as those being developed by the French community (analogous time type method, meso-scale climate modelling).

Nevertheless, forecasting flash floods in small watersheds is a topical problem, as frequently reminded by Cevenol events, independently of climate change. Forecasting such phenomena requires digital tools more detailed than GCMs, such as high resolution meteorological models (raster of several km) operating for a limited area and time periods of a daily scale. With the input of frequent atmospheric humidity field analyses (satellite and radar information), such research models have proved to be perfectly able to forecast extreme rain fields (Ducrocq et al. 2002). Experiments of coupling with hydrological models of sudden floods are also being tested by the community.

2.8 – Elements for conclusion

This study describes an example of regionalisation of the impact of climate change on a large French watershed and raises the problems connected with the extrapolation to other basins, especially with the case of small coastal basins. Six GCM scenarios under the hypothesis of twice the concentration of atmospheric CO_2 are used to force a hydro-meteorological model based on the current climate, and supply elements for extrapolating to other cases.

Considering the present limits of GCMs, only the monthly temperature and rainfall anomalies are taken into account and combined with the current climate in order to define the modified climate. The various elements of the continental water cycle appear to be significantly affected by the rise in mean air temperature (2 K in winter and 4 K in summer), by the increase in winter rainfall and decrease in summer. This leads to a reduction of the winter snow accumulation and a much earlier melting in spring, which induces a significant modification of the water regimes of snow-response basins. The South of the area considered seems to be the most affected region because of the higher conjunction between rainfall reduction and PET increase.

The present study does not deal with the impact of a modified occurrence of extreme climate phenomena under the modified climate hypothesis. The current limits of GCMs (physics and resolution) do not enable yet to make out a possible evolution of extreme phenomena, nor even to compute a statistical analysis of such events for the present climate. Regarding small watersheds, a consensus seems to emerge on the idea that the probability of extreme phenomena is the most likely hypothesis.

Model	**surface description**	**Resolution**	
		(deg)	**(km)**
HC	**MOSES**	**2.5 x 3.5**	
LMD	**SECHIBA**	**1.6 x 3.75**	
CNRM	**ISBA**	**3.8 x 3.7**	
UR	**TESSEL**	**2.8 x 2.8**	
LMD -HR	**SECHIBA**		**100**
CNRM	**ISBA**		**50**

Table 3 – *The 6 GCM scenarios interpolated for the Rhone basin: 4 low resolution scenarios (LSCPR project) and 2 high resolution scenarios (LMD and CNRM-HR).*

	Durance (La Clap.)			**Saône** (Le Chatelet)			**Ardèche** (Sauze)			**Rhône** (Viviers)		
	W.	S.	M.	W.	S.	M.	W.	S.	M.	W.	S.	M.
CNRM HR	1.06	0.78	0.87	1.09	1.09	1.09	0.91	0.67	0.85	1.07	0.87	0.98
CNRM	1.35	0.89	1.03	1.18	0.87	1.08	1.21	0.96	1.14	1.23	0.83	1.06
LMD – HR	1.05	0.67	0.79	0.85	0.80	0.84	0.95	0.64	0.87	0.91	0.66	0.80
LMD	1.00	0.86	0.91	0.88	0.94	0.90	0.89	0.93	0.90	0.93	0.87	0.91
HC	1.31	0.76	0.93	1.04	0.77	0.96	1.14	0.78	1.04	1.13	0.70	0.95
UR	1.32	0.96	1.07	1.20	1.03	1.15	1.16	1.07	1.14	1.25	0.96	1.12
Moyenne	**1.18**	**0.82**	**0.93**	**1.04**	**0.92**	**1.00**	**1.04**	**0.84**	**0.99**	**1.09**	**0.82**	**0.97**

Table 4 – *Comparative evolution of winter (W - October-March), summer (S -April-September) and yearly discharges (M – mean) computed by the ISBA-MODCOU hydrological model for the 6 scenarios regarding the Durance, Saône, Ardèche basins and the Rhone in Viviers.*

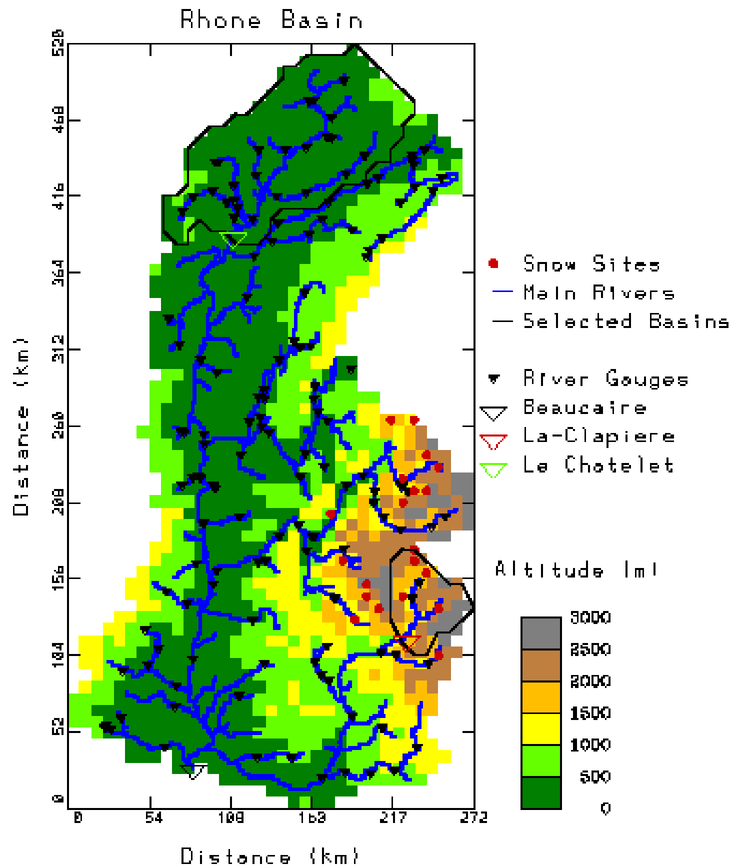


Figure 3 – *Modelled area of the Rhone basin showing the discharge and snow height observation stations used to validate the models as well as the topography on the 8-km uniform computation grid. The limits of the Saône and Haute-Durance watersheds which are examined more in detail in this study are indicated.*

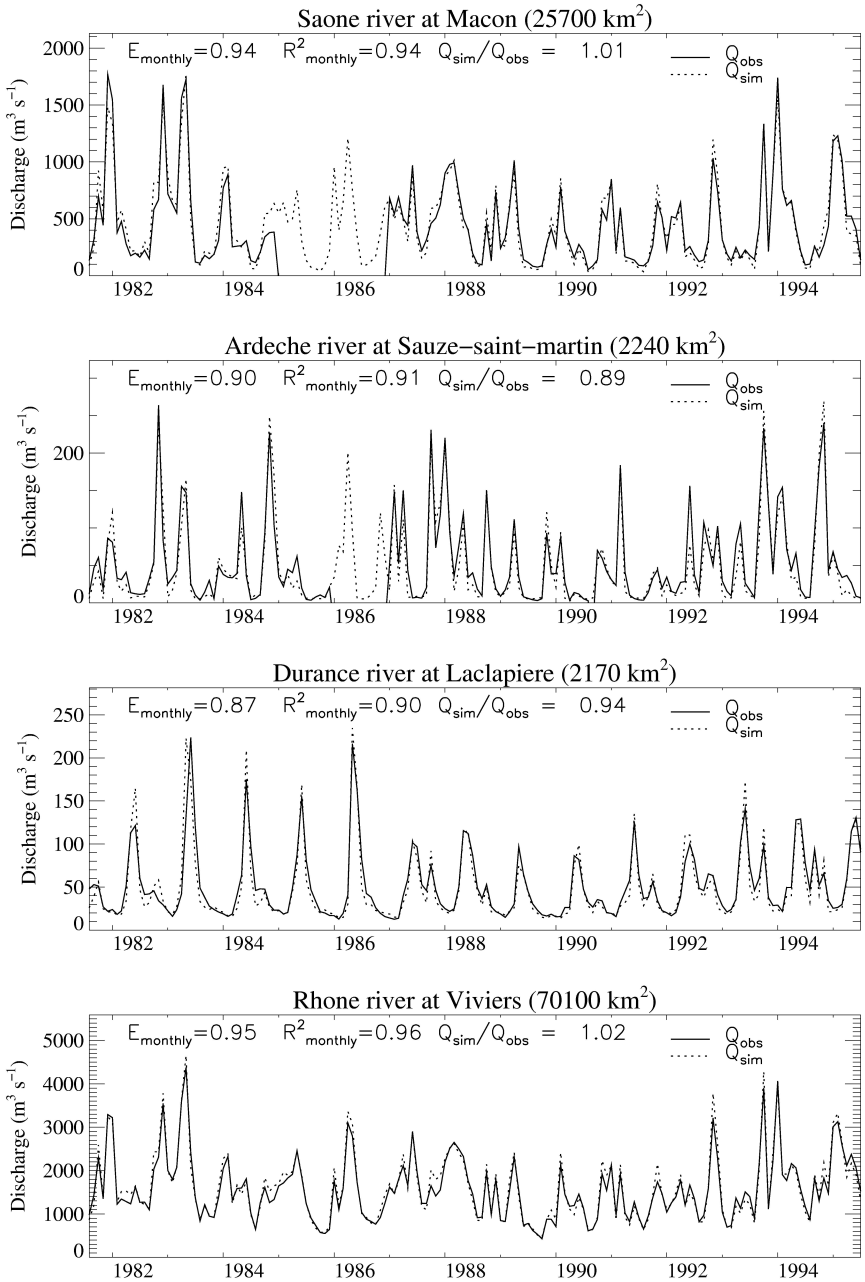


Figure 4 – *Comparison of the monthly discharges observed and simulated (ISBA-MODCOU model) of the Saône (Mâcon), Ardèche (Sauze), Durance (La Clapière), and Rhone (Viviers) rivers over the period 1981-1996 (Etchevers et al. 2001). Simulation statistic figures are indicated (Emonthly effectiveness, R2 correlation and Qsim/Qobs yearly ratio of depths of runoff).*

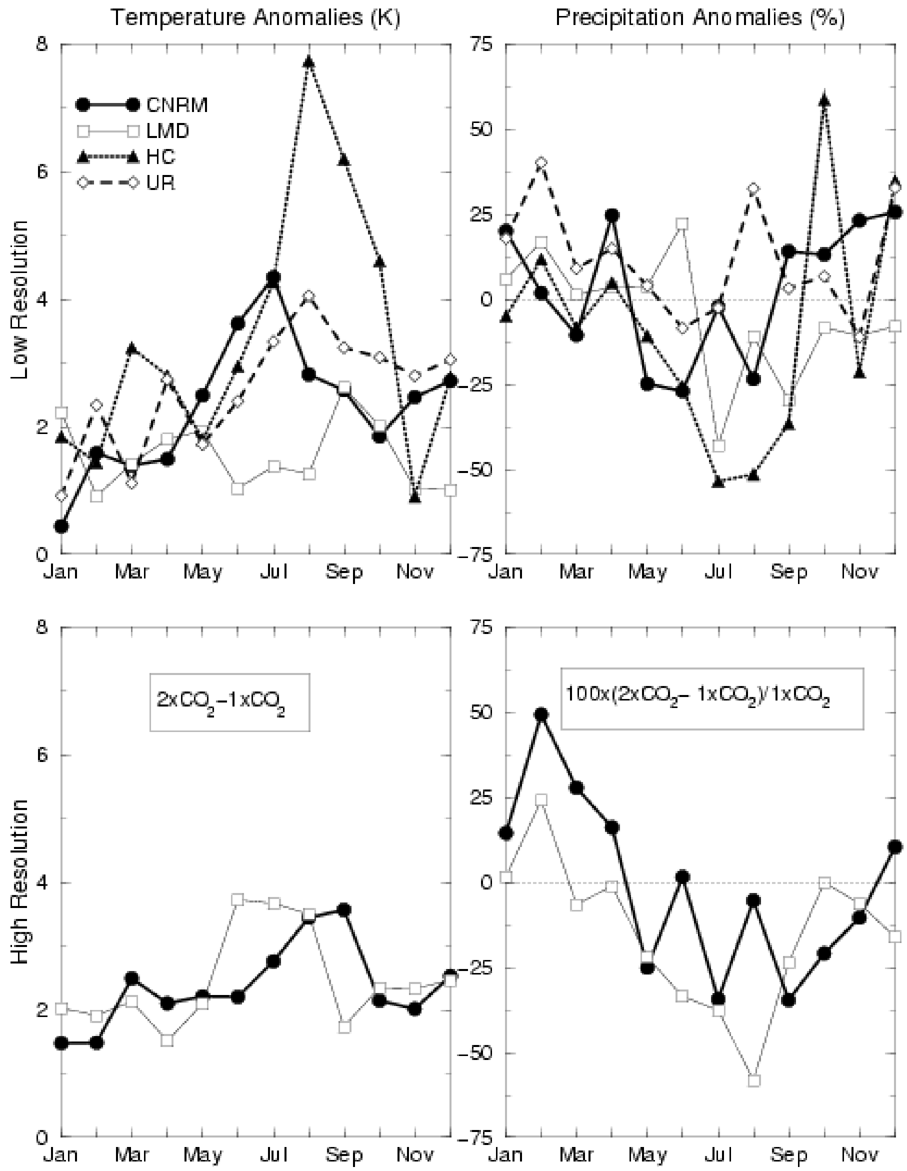


Figure 5 – *Rainfall (relative variation) and air temperature anomalies for the 6 scenarios regarding the whole Rhone basin. These monthly anomalies are computed from the 2xCO2 and 1xCO2 simulations of each GCM. They are then combined with the climate observed (1981-1997) to define the 6 scenarios of modified climate.*

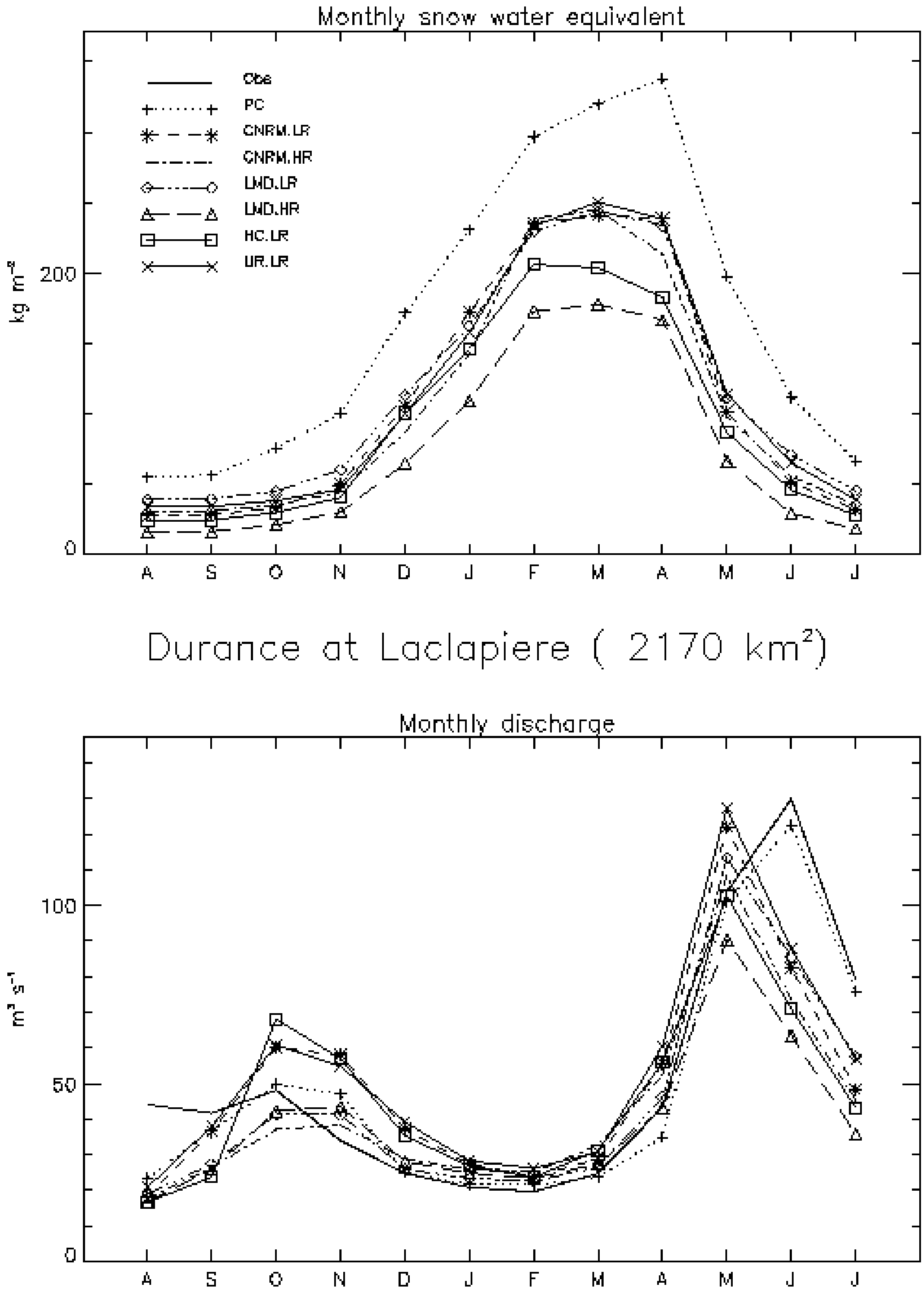


Figure 6 – *Evolution of the snow layer and discharges on the Haute-Durance watershed: the 6 scenarios are compared with the present climate (Obs and PC) (Etchevers et al. 2001).*

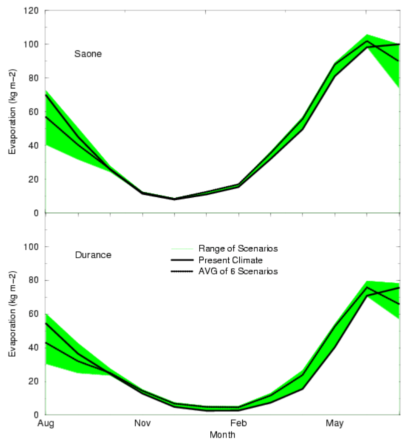


Figure 7 – *Evolution of monthly discharges (up left), of evapotranspiration (down left) and ground humidity (up right) of the Saône and Durance watersheds under the climate change hypothesis: the mean value is indicated as well as the set simulated by the 6 scenarios to be compared with the mean value of the present climate.*

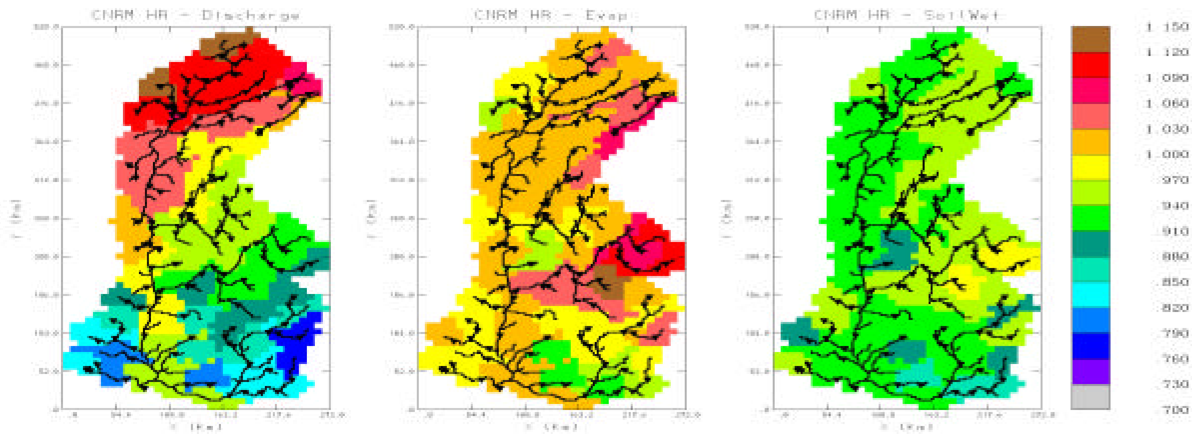


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Figure 8 – *Monthly anomalies of discharge (left), evapotranspiration (centre) and ground humidity under the hypothesis of the CNRM high resolution scenario. The anomalies correspond to differences in each term between the hydrological simulations under modified climate (2xCO2) and the current period (1xCO2).*

3 – RECENTLY ADOPTED MEASURES

3.1 – General considerations – Programmes and observatories

On 19th January 2000, France has adopted a National Plan to Fight against Climate Change (PNLCC) whose main objective is to organise an action plan in order to comply with the commitments made within the scope of the Kyoto protocol. For France, this undertaking consists in having stabilised greenhouse gases (GHG) emissions to their 1990 level by the year 2010, which requires a better control of the activities inducing GHG production. On this account, the activities especially concerned are those connected with energy production, tertiary housing, transports and farming output. The PNLCC provides for a hundred new measures or reinforcement of existing ones in the above sectors. The main principles of this Plan are: setting up of economic incentives, balance between domestic measures and market mechanisms, control and conservation of energy both at production and consumption levels, need for accurate information regarding the consequences of all decisions of public or private investment in terms of GHG emissions. The implementation of such measures is assessed every year through a review involving the civil society, within the framework of the National Conference on Greenhouse Effect, the last one being held in Lyons on 27th and 28th November, 2002. The programme and its developments are reviewed and approved by the CIES (Interdepartmental Commission on Greenhouse Effect) which involves all the ministers concerned, presided by the Prime Minister.

The PNLCC does not deal with issues regarding climate change effects and ensuing adaptation. The present state of research on such impacts can be found in the third national communication to the United Nations Framework Convention on Climate Change. Studies on these impacts are largely developed in France, mainly under the aegis of the GICC (Management and Impacts of Climate Change) research programme of the MEDD[4].

France has not (yet) defined a national programme of adaptation to climate change. However, there already exist laws about town and country planning and environmental protection, plans for the prevention of natural risks and schemes for an integrated management of natural areas, environments and resources.

The Law of 19th February 2001 has established the creation of the ONERC (National Observatory of Climate Warming Effects), in metropolitan France as well as in the French overseas Departments and Territories. This observatory aims at collecting information, studies and research works regarding the risks connected with global warming and extreme climate phenomena, in collaboration with the research centres and institutes concerned and the intergovernmental expert group on climate evolution. It may present proposals regarding adaptation.

As regards water regime, studies evidence the following concerns for the 50 years to come:

- early low water phenomena: one month ahead for the Rhone basin, study under way for the Garonne basin;
- increased evapotranspiration and change in farming schedules;
- multiplication of devastating Mediterranean floods;
- risks affecting several coastal areas that could be vulnerable to a rise in the sea level (the Camargue delta in the Mediterranean region).

On the whole, the current studies highlight that the risk of extension of extreme phenomena (droughts and floods) is higher than the risk of reduction of annual runoff, which could even increase.

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[4] Ministry of Ecology and Sustainable Development

As yet, the current PNLCC deals very little with adaptive measures concerning the consequences of climate change on the water regime. No significant correlation between climate change, water regime and evolution of needs can be established in France to date.

Many human-induced causes may explain the present difficulties met in the water management, which has led France to better prepare itself against these phenomena. Such measures will contribute to better protecting the country from the possible impacts of climate change on the water regime, even though such effects are still ill-known.

3.2 – Fight against droughts

Within the framework of the Law on Water of 1992, SDAGEs[5] have been implemented in each large basin; they set targets of minimum low water discharges for the main rivers subject to high draw-offs and they determine the areas of water distribution in places where water resources and needs are not balanced. Any additional draw-off - unless compensated by new reserves - is forbidden in these areas.

The grant of additional CAP[6] subsidies to irrigated maize crops has induced the considerable expansion of the irrigated area. The CAP reform of 1992 has mitigated this increase from the years 1995, by limiting the areas liable to subsidy. However, this reform has entailed a queuing of farmers for whom irrigation still offers prospects of increasing and stabilising their income.

Lastly, the scheme aimed at controlling the working of irrigation has been strongly reinforced: PURE [7] programme, development of counting, warning systems for vegetation needs made available to farmers. Counting has thus become a condition for the granting of CAP subsidies.

A progressive rise in the price of water draw-offs and use has led to a kind of self-regulation of demand. This rise aimed at involving farmers in water supply costs (up to then, they were quite totally borne by public funds).

3.3 - Agriculture

Agriculture is the major concern regarding the management of the various uses of water because of its impacts both in quantity (drying up due to irrigation) and in quality (eutrophication of rivers or coastal environments, contamination of water supply points by nitrates or pesticides). Irrigated areas account for less than 8% of the Useful Agricultural Area in France (crops + fodder); consequently, a change in the water regime could impact the whole French agriculture.

Here and now, irregularities in rainfall and water regimes are materialised by a high vulnerability of farming activities to bad weather events (hail storms, floods…) that mobilise huge compensation funds and by the development of complementary irrigation aiming at securing output, especially for the crops connected with agro-industrial activities in the North of France.

Research institutes have initiated a considerable effort (Agrotech programme led by INRA[8]) in order to assess the impact of GHG increase on farming. The main results show a double effect: a first positive impact due to carbonaceous fertilisation (increased productivity and reduced water needs), and a second negative impact because warming shortens the vegetation cycle.
Significant changes in agricultural schedules have already been acknowledged: earlier flowering of apple-trees in the South-East, earlier date of grape harvest (nowadays in Châteauneuf du Pape, at the beginning of September instead of at the end of the same month), anticipated first hay cuttings.

[5] Water Development and Management Schemes
[6] Common Agricultural Policy
[7] Programmes for a Rational Use of Water
[8] National Institute for Agronomic Research

With the CAP reform, France has resolutely initiated an incentive voluntarist policy to develop new non-food valorisations for vegetal production. The development of such outlets (vegetal fibres, specific oil-producing plants, and more recently, starch, potato flour, beet alcohol for chemistry – about 260,000 ha) corresponds to the principles of agricultural policy and rural development (creation of new sources of incomes and jobs, multi-functional farming, promotion of renewable raw materials), of energetic independence and control of GHG emissions. As such, these productions are granted tax breaks.

Within this scope, as soon as 1992, the public authorities have decided to grant tax breaks to biofuels, which are the first non-food outlet in terms of agricultural area.

Besides, the GIS AGRICE (Agriculture for chemistry and energy) has started an important effort of research and development in the field of biofuels, biomaterials and biomolecules.

Nowadays, the new non-food outlets cover 320,000 ha for the production of biofuels and 60,000 ha for the sectors of lubricants, surface-active agents, plasticizers, solvents and cleaning agents, cosmetic formulations, paints, aromatic and medicinal plants, and vegetables for the perfume industry.

Securing output is a major challenge for French agriculture: when considering the ups and downs recorded in output, however, it is difficult to determine what is attributable to the agronomic context (new varieties, etc…) and what to climate change.

Important reinforcements of the regulation have been implemented in accordance with the so-called "nitrates" European directive of 1995, so as to limit the effects of intensive crops (inputs of fertilisers and pesticides) or of intensive breeding. However, most experts agree that these measures will prove to be efficient only when farmers modify their behaviour, which would imply to deeply reform the CAP. The French farmers, who are worried about the degradation of their income, are strongly reluctant to the trend which was partially initiated with the CAP reforms of 1992 and 1999, that strengthens the rural section to the detriment of the section devoted to agricultural output.

The following tables and figures give some idea of the impact of climate change on farming output (after Bernard Seguin, INRA, in *Courrier de l'Environnement*, June 2002).

Crop	Place	Output	Water consumption
1 - Wheat	Versailles (not irrigated)	+5,7	- 1,7
	Avignon (irrigated)	+2,5	- 5,7
- Maize	Versailles (not irrigated)	+10,6	- 12,4
	Avignon (irrigated)	-16,1	- 16,2
2 - Wheat	Toulouse (irrigated)	+4,0	- 5,8
	Versailles (irrigated)	+2,9	0

Simulated variations of output and water consumption of wheat and maize crops in different places (expressed in percentage of the values simulated under the current conditions).
Results 1: transient GISS climate scenario, year 2030, CO_2 460 ppm, CÉRES models, average over 30 years simulated.
Results 2: ARPEGE-Climat scenario, temperature anomalies over seven years, STICS models, CO_2 effect not considered, average over 16 years simulated. Sources: Delécolle (unpublished data).

Table 5 - *Simulated impacts for various species and conditions*

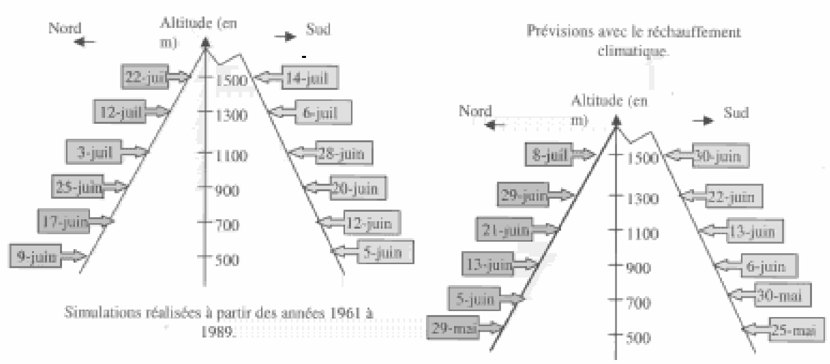

Figure 9 – *Meadows: Effects of climate warming on the first date of hay cutting in medium Alpine mountains (June, 2001)*

3.4 – Fight against floods

The French Government has decided, on the one hand to speed up the implementation of Plans for the Prevention of Risks, and on the other hand, to improve flood warning systems through a better collaboration between the Water Services, Météo-France Services and the system of warning of the population.

In the Mediterranean regions, floods are difficult to forecast.

By way of example, the disaster of November 1999 that affected part of the Aude and eastern Pyrenees Departments happened after rains whose volume exceeded 200 mm, with a peak rainfall of 350 to 500 mm within 12 hours in the wettest sectors (i.e. 5,000 m^3 of water per hectare, which is quite the average inter-annual rainfall recorded in these regions). The simultaneous occurrence of a storm in the Mediterranean impaired the normal runoff of rivers to the sea. As soon as Thursday 11th November, Météo-France had diagnosed the quick coming of an exceptional rainfall event in these areas, without being able to locate the point of impact of the biggest thunder-storms that were to rage on Friday night. It is quite impossible to guard against the consequences of such exceptional phenomena, even though part of the damages could actually have been reduced if the overflow areas of rivers had been better respected. This remains true regarding the latest events.

Forecasting systems regarding torrential rain warnings by Météo-France have been reinforced (in particular, thanks to the extension of the monitoring of storm phenomena by radar), and are subject to short-term warnings (24 hours) to the local authorities and general public, with a 4-level scale of risks. This warning system has properly worked during the recent floods of the Gard. It is still not possible to locate precisely the storm onset in small split-up watersheds, which hinders the forecasting of local floods likely to be disastrous in very small rivers of the Mediterranean type.

The catastrophic floods of the Gard river in October 2002 led the Government to announce the reinforcement of measures for the protection of persons and goods:

1 – reduction of the rhythm of water runoff by developing regulative measures and decreasing the discharge upstream of the watershed: dry micro-reservoirs, setting up of flood expansion areas.

2 – reinforcement of flood warming systems. Within this scope, a National Technical Centre aimed at supporting Flood Warning Services will soon be established in Toulouse. It will gather the technical tools developed by Météo-France and the Ministry of Environment: HYDRO and PLUVIO databanks, distribution of street simulation tools, publishing of flood monitoring maps to be used together with the meteorological monitoring maps already existing… In parallel, measurement networks will be strengthened, especially the ARAMIS network that measures rainfall by means of radars and covers the whole metropolitan territory as well as large areas in the overseas Departments and Territories.

3 - speeding up of procedures for the establishment and approval of PPRs[9]

Generally speaking, specialised services have been asked to develop awareness and "risk culture" within populations, by a quicker and more direct circulation of the available information regarding risk forecasts (warnings of extreme events) and vulnerability (maps of areas liable to flooding), possible preventive measures and behaviours in case of flood onset.

Lastly, the Government has confirmed it intended to bring in a bill about risks.
The legal measures that deal with natural risks are stated in Section 2 of the bill that is in preparation, entitled "Preventive measures for natural hazards". This section includes various chapters that focus respectively on informing population, land use and development, works, and financial steps, that are as many elements of prevention. A last chapter is devoted to the action of the RTM (Department for the Restoration of Mountain Lands) and the ONF (Forest Commission) regarding risk prevention.

The following measures have been taken so as to improve **access to information**, which is a right:

- mention of the status of real estate as regards risks when subject to transactions,
- municipal information about risks upon Mayors' initiative,
- laying of flood landmarks,
- flood forecast whose arrangement must me adjusted within the scope of flood forecast organisation schemes set up in every watershed district, after consulting local authorities.

Land use and development

Beyond the preventive measures concerning lands liable to risks, this chapter addresses the lands that contribute to worsening the risk or that could be used to mitigate it. Four steps are taken with this aim:

1. To implement state-approved constraints in order to facilitate:
    a) flood retention, by over-flooding specific areas so as to increase the capacity of storage of flood water,
    b) restoring the natural course of rivers when this course is necessary for the water supply of the solid discharge carried along by the river and for the maintenance of its morphological balance.
2. To prevent soil erosion by limiting or forbidding harmful agricultural practices in areas sensitive to erosion.
3. To replant hedges and rebuild embankments by allowing to set them up at the boundary of plots and no longer two metres farther as was the rule.
4. To provide for a dispensation from the statute of tenant farming for lands bought by local authorities in a main river bed within the scope of a general interest programme for the prevention of major natural hazards.

Regarding **works** against natural risks, the steps taken especially aim at making easier the intervention of local authorities for the protection and maintenance of their own property. This includes in

[9] Plans for the Prevention of Risks

particular the updating of lists of works for which municipalities are capacitated to act (avalanches, floods, fires,…), the simplification of intervention procedures in case of danger (suppression of the public inquiry) and the creation of easements in favour of local authorities to allow interventions.

The **financial steps** proposed mainly aim at favouring preventive measures, especially works but also out-of-court acquisition of threatened estates, either by contributing to financing their purchase, or by providing for tax exemption when arrangements are undertaken to make a building less vulnerable to risks, or else by providing for higher insurance premiums or excesses when preventive works are not executed. These measures deal with:

- Considering compensation for natural disaster for the computation of expropriation allowances for risk.

- Extending the use of the fund for the prevention of major natural risks that will be usable to contribute to financing studies and preventive works in private estate for properties covered by the guarantee against natural disasters, when these studies and works are made to enforce approved Plans for the Prevention of Risks.

- Considering flood prevention within the scope of departmental policies for the protection of natural areas, by allowing Departmental Councils to use the TDENS (departmental tax for sensitive natural areas) for the conservation of flood expansion areas.

- Exempting of town planning taxes for preventive works.

- Allowing municipalities or associations of communes to expropriate on account of a major natural risk.

- Enabling prefects and the President of the CCR (Central Reinsurance Fund) to submit a case to the BCT (Office in charge of fixing insurance prices), so as to revise the amount of the additional premium for natural disaster when policyholders refuse to implement basic preventive measures.

3.5 – Mediterranean ecosystems

Two types of ecosystems appear to be particularly threatened in the French Mediterranean coasts: wetlands and forest ecosystems.

As regards wetlands, the main current menaces connected with agriculture and town planning have induced the public authorities to give the status of nature reserve to the main coastal ponds and to the Camargue delta. The main threat linked to climate change could be an invasion of sea water, but the latest studies about the Rhone delta evidence that these problems depend more on a risk of subsidence of these environments due to a lack of water supply upstream than on a risk of a rise in the sea level.

Regarding forest ecosystems, the main threat is fire hazards, in connection with demographic growth and with insufficient rainfall in summer. A climate warming of about 3° could entail a contraction of natural vegetation areas due to aridity and a slight rise in levels of vegetation with a decreased productivity. However, such modifications will be perceptible in the long term only, since many Mediterranean species such as holm oaks are highly adapted to drought phenomena. Fire-connected risks would nevertheless increase because of longer drought periods.

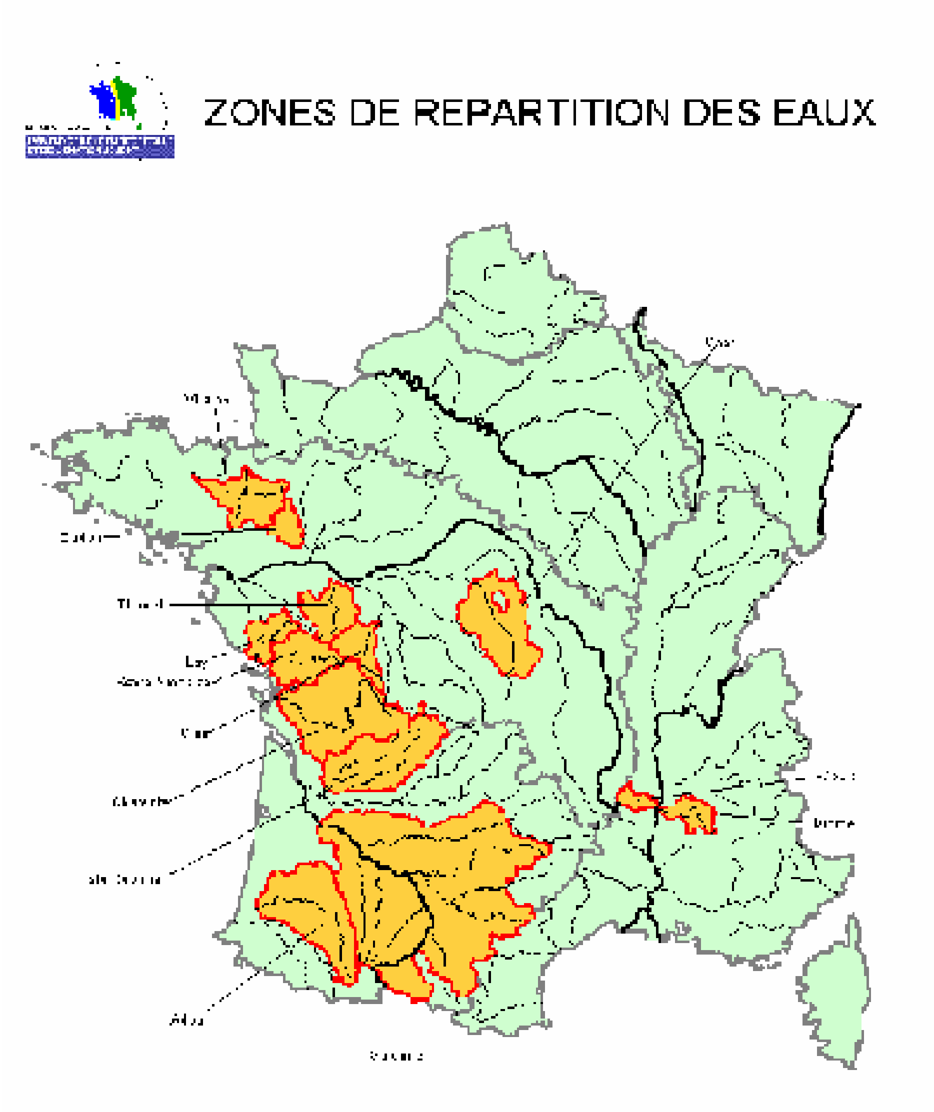

Figure 10 – *Synthesis: Water distribution areas in France*

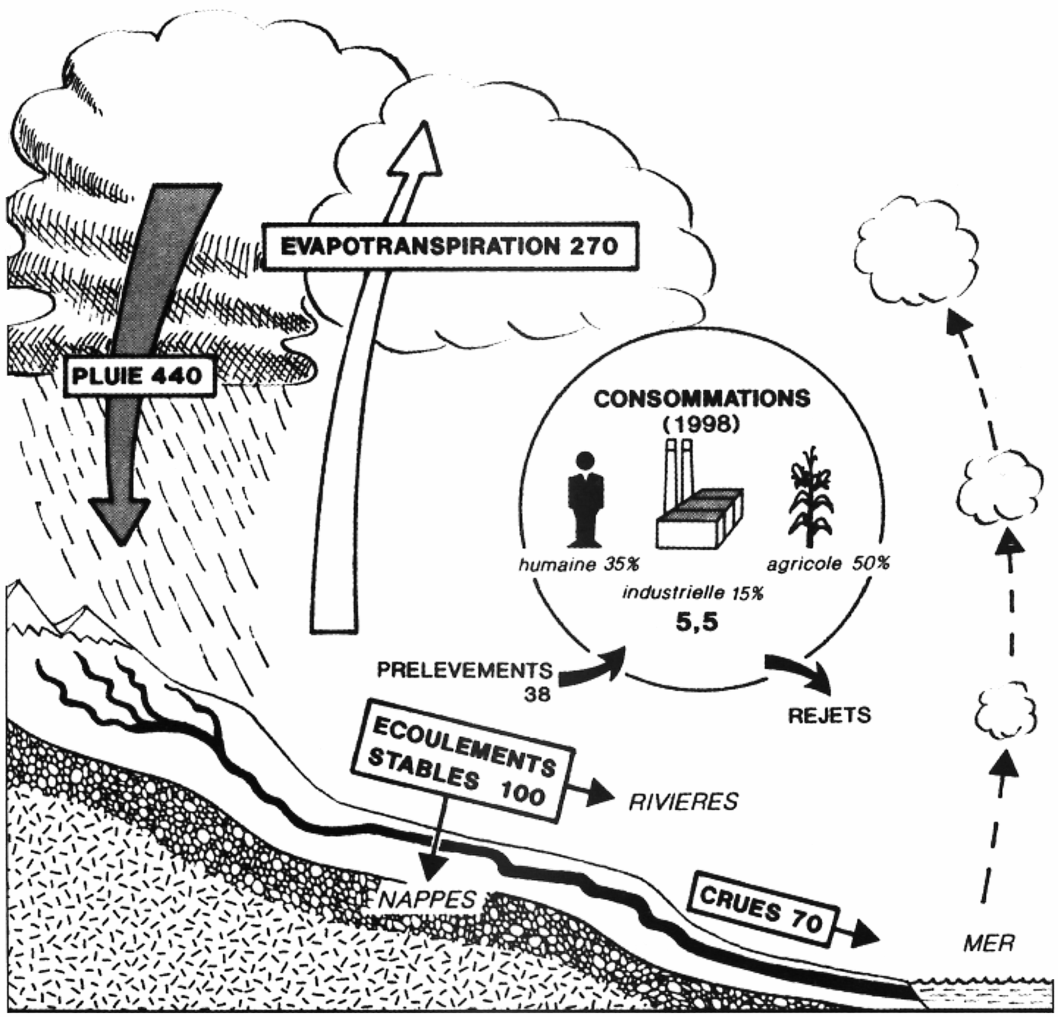

Figure 11 – *Synthesis: the water cycle (including uses) in France – quantitative aspects*

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