IMPACTS OF CLIMATE CHANGE ON THE MANAGEMENT OF UPLAND WATERS : THE RHONE RIVER CASE

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Summary

The Rhone river watershed covers a surface of 98 000 000 km^2, including 10 000 km^2 in Switzerland. Most of the discharge originates in the Alps, but a significant contribution is provided by the Jura Mountains and by the western Massif Central. The main river are the Rhône, the Saône, the Isère and the Durance. The total discharge at the sea 1700 m^3.s^{-1}.

Since 10 years, several models have detailed the General Circulation Model proposed by the IPCC (1996 and 2002) and predicted changes of the natural components of the hydrological cycle, from temperature and precipitation, to ice and snow cover and to river discharge. They anticipate on a decrease of total discharge, a marked decrease of summer discharge, an increase of winter discharges and winter storms, a decrease of ice and snow cover inducing a change in the river regime.

However, one of the main characteristics of the Rhône is the high level of economic development which has triggered complex impacts on river and lake hydrosystems. High altitude reservoirs have affected the river regimes since at least 50 years, to the detriment of summer discharge, altering the pristine mountain discharges. While the temperature of Geneva Lake increased during the last 20 years for climatic reasons, the temperature of the French river course of the Rhône was affected by the impact of nuclear power plants. These documented changes anticipate on the changes predicted during the XXIth century and provide most interesting insights into the the future of aquatic ecosystems.

At last, an attempt was made to summarize the possible impacts of climate and river changes on the future uses of water and on humans. Hydropower and thermal power will be affected, as well as tourism and agriculture through an increase of pressures on the consumptive uses of water. Human health may be affected as well as the level of risks in valley bottoms.

1 - Introduction

During the last 10 years, many detailed studies and general reports (IPCC, 2002; Deneux, 2002; Renaud et al., 2002; Pont, 2003; Husting, 2005; OcCC, 2003) have been devoted to the impacts of predicted climate change in Europe, and notably in the Alps and on the Rhône River. These reports deal mostly with the probable changes in the hydrological regime of the Upper Rhone River in Switzerland, and with the hydrological and ecological changes of the Rhone River downstream of Geneva. This report will present a summary of the main results obtained by specialists of the question, which combine past, present and future changes of natural components of hydrosystems, as well as the complex interactions of natural and human induced changes. The approach will take the complete hydrosystem into account, from upland ecosystems down to the delta of the Rhone, with some insight into the tributaries. We decided to follow the proposal made by Leblois et al. (2005), i.e. making a distinction between "effects" and "impacts". "Effects" are changes, or direct consequences of climate change on hydrosystems, while "impacts" are consequences of the latter on human uses of water or instream uses of water (ecological requirements).

While much research has been done on river discharge, few studies have dealt with water as a resource, prone to locally intensive uses and sensitivity to climate change. At a broader scale than the rivers, and considering combined criteria, an interdisciplinary study has considered past situations to check the causes and effects of "degradation", "desertification" and human "desertion" in selected areas of the Mediterranean, notably in the Southern Rhone valley during the Holocene and the XIXth c. (Van der Leeuw, 1998). We will not address this broader perspective below.

2. Studied area and methods

2.1. The Rhone River basin

The Rhone river watershed covers a surface of 98 000 km^2, including 10 000 km^2 in Switzerland (Fig. 1). The Swiss Rhone in Valais is influenced by mountain climate. Its natural regime is characterised by low winter discharge due to snow detention, by high spring and summer discharge due to the melting of snow and ice. Like other subalpine lakes, Geneva Lake smoothens flood peaks downstream, similar to Annecy Lake for the Fier River, and Bourget Lake for the Rhone. The tributaries of the Rhone between Geneva and Lyon (notably, the Arve, Fier, Guiers and Ain rivers) drain lower ranges but preserve the snow-melt regime, while the glacial influence is strongly attenuated. Due to the oceanic influence on the Jura Mountains, the 200 km Ain river may peak at 2400 m^3/s, which is as much as the upper Rhone. The Saône River, which joins the Rhône in Lyon, has a typically oceanic regime with high discharge during the cold season and low discharge during the warm season, due to evapo-transpiration. As a consequence, downstream Lyon, the "compensated" type regime is more regular (Pardé, 1925). Flowing from the Alps, the left bank tributaries regenerate the snow-melt influence, while right bank tributaries and the Durance deliver high discharges during the fall and the spring, under Mediterranean influence. At Beaucaire, the regime is characterized by low flow from September to November, along with risks of marked low flow.

2.2. Observed climate and hydrological change since the XIXth c.

Climate is widely considered to have changed since the Late XIXth century and during the last decades. Climate change may have affected both temperatures and precipitations. Change in temperature is not documented since the late XIXth in the hydrosystem of the Rhône. Temperature of large subalpine lakes, such as Lake Geneva, is proved to have increased by 1°C since the 1960's. Concerning river discharge, statistical tests applied to 8 gauging stations of the Rhone river downstream Geneva demonstrated that hydrology is stationary. However two types of ruptures are apparent, one locally in 1891, due to artificial developments at the outlet of Lake Geneva, the second one at the end of the 1970's, with the occurrence of wet decades throughout the basin, following a period (1940-1975) of lull. A new cycle rich in strong floods has occurred in recent years, similar to the late XIXth period, but no effect of global change having been detected yet (Sauquet et Haond, 2003). This study introduces an important point. This report deals with the impact of climate change on the Rhone River hydrosystem. Traditionally this question is dealt with, using predicted climate data and expected induced changes in the different compartments of natural systems as well as predicted impacts on human uses. In this report, the registered changes since ca 20 years will be presented because their occurrence is documented and because they provide tested useful insights of expectable changes in the future.

Moreover, changes in hydrological hydrosystems incorporate human induced changes, particularly in highly developed watersheds. Indeed, the control on upland hydrology has been a long term process in the Alps, changing the hydrology of rivers. Also, thermal plants have been located along the Rhone River to benefit from cooling by its waters, thereby inducing an increase of water temperatures and consequences on aquatic ecosystems.

Fig.1 The watershed of the Rhône River

2.3. Modelling the changes

The assessment of climatic change has been traditionally based on general circulation models (GCM) which typically have a resolution of 2.5° latitude and 3.75° longitude. At the basin scale, the General Circulation Model (IPCC, 1996, 2002) projects that the expected climate warming will enhance the hydrological cycle, with higher precipitations in winter, higher rates of evaporation and decreased precipitations in summer and during the fall, and a proportion of liquid to solid relatively greater at high altitude. Two scenarios have been tested:

- B2: average temperature would increase by 2-2.5°C in one century
- A2: average temperature would increase by 3-3.5°C

This model having been recognized to be unable to reproduce the characteristics of variables at the regional and short time scales, different projects have been launched in order to address this issue. Computations were made in the Suiss Alps, using a high resolution model (20 km x 20 km) under a hypothesis of a doubling of CO^2 concentration. The MEDALUS Project (1996-1999) was funded by the EEC to explore future changes, such as desertification of the Mediterranean domain. In this programme, Palutikov J.P., Goodess C.M. (2000) applied downscaling procedures to develop scenarios in Spanish and Italian regions. The ECLAT-2 project (1998-2001) was funded through the Climate and Environmental Program of the DGXII of the EEC to complement the IPCC, IGBP and HDP Programmes. Downscaling techniques were applied to the Rhone basin (Noilhan et al., 2000), using selected GCM ouputs in the basin for doubled $C0^2$ concentration conditions. These studies explored the sensitivity of the production functions of the hydrological model to anomalies in precipitations and temperatures for selected sub-basins during the period 1981-1985. The ECLAT-2 programme provided the first evaluation of predictable climate change impacts in the basin in different components of the water budget, such as runoff, snow and soil moisture availability for the interface between soil and atmosphere. It was based on the GEWEX-Rhone programme which used the macroscale Coupled ISBA MODCOU (CIM) model for the 1981-1998 time series. This model was calibrated with present day conditions using atmospheric forcing, land surface types, soil freezing, surface runoff, evapotranspiration, river flow series and snow depth in the Alps. This model was run over 15 years for spatial resolutions ranging from 1 to 8 km. Indeed, it was recognized that the model could be used for testing the GCM anomalies (Habets et al., 1999; Etchevers, 2000). Research was continued through the programme GICC-Rhône (1999-2004) with the hypothesis of a doubling of CO^2 concentrations in 2050 (Leblois and Grésillon, 2005).

3. Predicted changes of the natural components of the hydrological cycle

3.1.Climatic change

3.1.2. Present and predicted changes in air temperature

During the XXth century, the average temperature of the globe increased by 0.6 +/-2°C (IPCC, 2002). The Alps experienced a warming of temperatures comprised between 1° and 2°C. However, more than 1°C out of the strong recent increase, which occurred since 1990 (along with a decrease in precipitations), could be related to positive values of the NAO (North Atlantic Oscillation, a measure of the intensity of westerly flow and associated storms tracks) according to Beniston and Jungo (2002). These authors propose that warming would have been weaker without the NAO effect and suggest that we should “improve the performance of models in simulating NAO decadal-scale variability”.

During the XXIth c., global temperature should increase by 1.4 to 5.8°C (IPCC, 2002). In the Suiss Alps, the worst scenario is that winter temperatures could increase by up to 4°C and summer temperatures (July) by 6°C (Beniston et al., 1995). Horton et al. (2005) proposed a scenario of +1°C (expected for 2020-2049) and two scenarios considering two increased green house gas emissions (period 2070-2099: + 2.4 to 2.8 °C and +3.0 to 3.6°C, with rates higher in summer than for annual averages). In France, the ECLAT-2 programme models predicted warming for all the months, but temperature increases were greater from July to September, ranging from 2.5°C to 7.5°C according to the different models tested. The GICC-Rhone study, using the ARPEGE-CLIMAT model, predicts an average yearly increase of 2.5°C and an increase in July of 4°C for the doubling of CO^2 concentration.

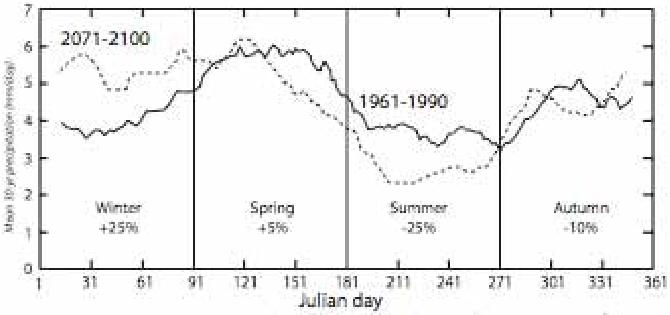
3.1.3. Changes in precipitations

According to GIEC models applied to France, with the B2 scenario, precipitations would increase in the winter, while they would be reduced by 5-25% in the summer. According to the A2 scenario, summer droughts would be more severe with a decrease of 20-35% in summer rainfall, associated with severe episodes. In the Swiss Alps, Beniston et al. (2003) have shown that “milder winters are associated with high precipitations levels than cold winters, but with more solid precipitations at elevations exceeding 1,700 – 2,000 m above sea-level, and more liquid precipitations below”. With expected climate warming, the average predicted precipitations would not change, but summer precipitations should decrease, while winter precipitations would increase (Fig. 2-A). Modelling of winter storms suggest a stronger frequency of southern flows from the Mediterranean and heavy storms, like 1999 Lothar storm (Beniston, 2004). Also, periods of drought could be more frequent as well as periods of heavy rainfalls. Higher snowfalls at high altitudes would not compensate for increased ice-melting. According to Beniston et al. (1995), winter precipitations would increase by 15% in the Western Alps. In France, the ECLAT-2 programme predicted a minimum of precipitations in summer months (from -45% to +8%), and increased precipitations in winter, up 5-30% according to the models.

The changes associated with an increase in global temperature are rendered more complex by interactions with the NAO shifts. Indeed, the amounts of precipitation are influenced by the Northern Atlantic Oscillation. Beniston (1997) has correlated thick snow cover and long duration in the Swiss Alps with high NAO index because during these episodes, winter temperatures shift toward higher values (« the frequency of temperatures exceeding the freezing point is more than doubled above 1000 m, thus enhancing the potential for early snowmelt »).

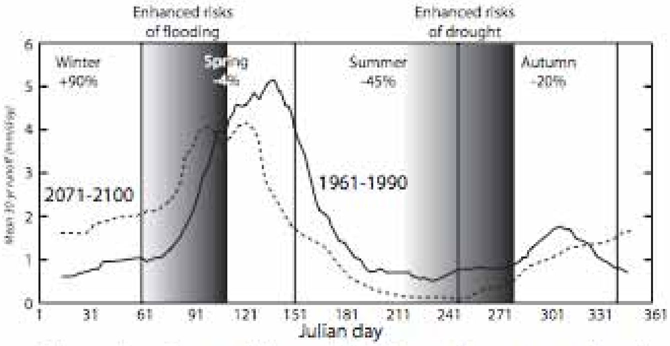
3.1.4. Changes in the depth and duration of snow cover

The depth of snow cover is influenced by temperature. At Portes Pass (Northern French Alps, alt. 1,320 m), snow depth from February 11th to 20th has decreased during the last 40 years (fig. 3). The strong reduction in the last ten years is “probably related to climate warming” (Etchevers & Martin, 2002; Martin & Etchevers, 2002). This reduction in the duration of snow cover has been hypothetised by Föhn (1991) and documented in the low altitude zones of the Swiss Alps. Using satellite imagery, Baumgartner & Apfl (1994) observed a reduction of snow cover by 3-4 weeks during the late 80’s and the early 90’s. An average increase of 4°C in temperatures, forecasted by several regional models for this area of Europe, would reduce the volume of snow by ca 50% in the Swiss Alps. For every °C increase in temperature, the snow line will rise by about 150 m so



A

Changes in precipitation in the Alps, averaged over the1961-1990 reference period (solid line) and the 2071-2100 future simulated period (dotted line). Figures refer to the schifts in precipitation amounts by season, in %.



B

Changes in surface runoff in a typical alpine catchment area, such as the Rhône and the Rhin, averaged over the1961-1990 reference period (solid line) and the 2071-2100 future simulated period (dotted line). Figures refer to the schifts in runoff by season, in %.

Fig.2 Predicted precipitations (A) and surface runoff (B) changes in the Swiss Alps. (after Beniston, 2005, modified) that "regions where snowfall is the current norm will increasingly experience precipitation in the form of rain. » (Beniston, 1997).According to the scenario of Météo-France (Martin & Durand, 1998), assuming an increase in temperature of +1.8 C°, at an elevation of 1,500 m, the average length of snow cover, presently comprised between 160 and 180 days in the Northern French Alps, could decrease down to 125-135 days. In the Southern Alps, it could decrease from 130-100 down to 80-55 days/yr (Fig.3). This means one month less of snow cover that today (SAFRAN-CROCUS snow model, in French ARPEGE GCM - Equipe Climate Modelling and Global Change). According to the GICC-Rhone study, the depth may be reduced by 50% at low altitudes, but is less affected at higher altitudes (1800-2000 m). In the different scenarios, the areas covered by snow decrease by 25-40% (Etchevers & Martin, 2002; Lebois et Grésillon, 2005).

As a result of climate change, glaciers have already retreated because they stand close to the freezing point. Haeberli (1994) considers that past and present fluctuations of glaciers and pergelisol are proofs of past and present climate changes through the changes in energy balance. Due to the green house effect, the velocity of observed changes exceeds the changes monitored during the Holocene. Haeberli (1995) and Haeberli and Beniston (1998) have shown that « the glaciers of the European Alps have lost about 30 to 50% of their surface and about half of their volume. 30-50% of existing mountain glacier mass could disappear by 2100 if global warming scenarios in the range of 2-4°C indeed occur ». With an upward shift of 200-300 m in the altitude of the line of equilibrium , the reduction in ice thickness could reach 1-2 m per year (Maisch, 1992). The sensitivity of the line of equilibrium to temperature is between 60 and 120 m/°C according to different authors (Green et al., 1999; Maish, 2000; Vincent, 2002). According to Vincent (2002), glaciers of the French Alps retreated during two periods :

- From 1942 to 1953, due to low winter snow falls and to a high rate of retreat in summer
- From 1982 to 1999, due to a high level of summer ablation (from 1.9 m to 2.8 m at 2800 m at the elevation of 2800 m). This is due to a strong increase of the energy balance.

The difference in mass balance between 1800-1850 and 1970-1980 is comprised between 0.50 and 1.00 m in water equivalent for the glaciers of the French Alps (Vincent, 2002). Six et al. (2002) proposed that the mass balance of alpine glaciers could be negatively correlated to the oscillations of NAO index, as Beniston et al. (1995) proposed for periods of warm temperature and low precipitations.

3.2. Present and predicted changes of discharge

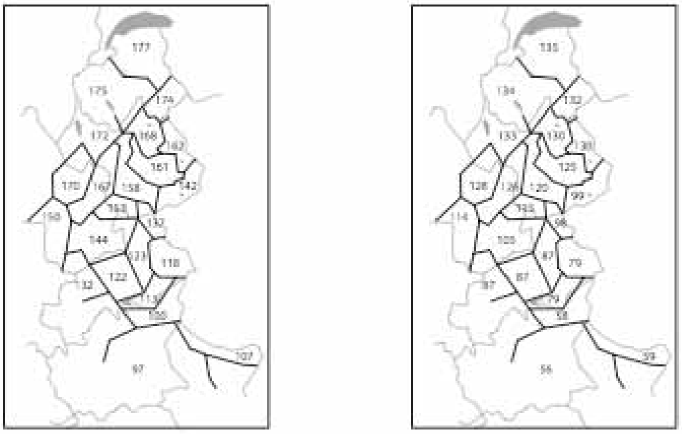


Fig. 3 Simulated number of average snow cover at the elevation of 1500 m in the French Alps in day / year
Left : present situation. Right : prediction using SAFRAN & CROWS models. (After Etchevers and Martin, 2002, modified)

3.2.1. Vegetation, soils and water balance in mountain ecosystems

Changes in direct water consumption by existing vegetation will occur. They will be due to changes in forest cover and to changes in the amount of evapotranspiration. If an increase in water consumption can be predicted, then a decrease of river flow is logical. At the basin scale, the GICC study predicts that the pattern and the spatial extension of natural vegetation would not change significantly, so hydrology would not be affected by this parameter. However, on the long term, vegetation will colonize the upper slopes of the Alps. In the Southern regions, the decrease of water content in soils and vegetation will increase the stress on vegetation, may induce a higher sensitivity to fires during the driest periods of the year, and increase exposition to soil erosion (IPCC, 2001). For instance, the 2003 summer drought provoked several fires in the Vercors, a wet massif of the Northern Prealps, which had not experienced any fire during the last decades.

3.2.2. River discharges

The statistical study of river discharges in France did not detect any significant change in the number and the intensity of floods since the mid-XXth c. Also, it is impossible to confirm any change in low discharges, mostly because of heavy human impacts on rivers (Lubès-Niel & Giraud, 2003; Lang et al., 2005). However, the situation may be different concerning the regimes of mountain rivers. Indeed, the specific annual discharge of mountain rivers is higher than the specific discharge of extended watersheds including lowland areas. This results from higher precipitations, low evaporation rates, and by conditions favouring runoff. “The hydrological regime is strongly influenced by water accumulation in the form of snow and ice and the corresponding melting processes resulting in a pronounced annual cycle of the discharge. A modification of the prevalent climate and especially of the temperature can therefore considerably affect the hydrological regime and induce important impacts on the water management” (Horton et al., 2005). The recent increase in temperatures has probably already had consequences on river regimes.

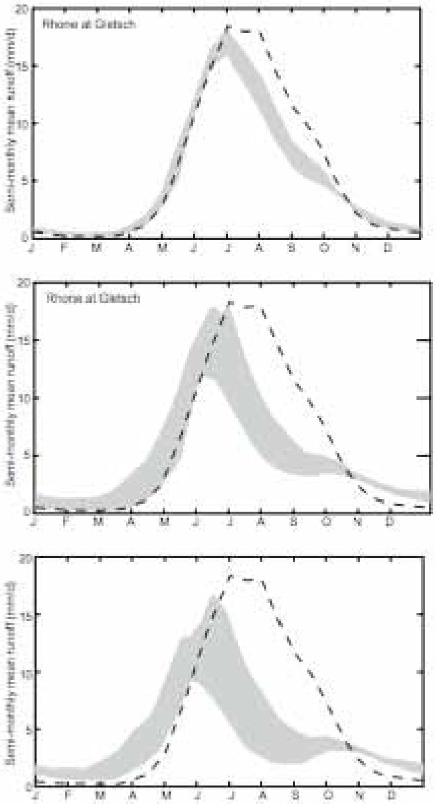
In Switzerland, “shifts in snow-pack duration and amount will be crucial factors in water availability » for runoff according to Beniston et al. (2003). The increase in winter temperatures will have clear consequences on the beginning of snowmelt and on the reduction of flow during the spring at low altitudes and on summer flow at the highest altitudes. The rarefaction of snow cover below 1000 m will reduce runoff. These shifts will affect river regimes with higher winter discharges (Fig. 2-B). However, increased evaporation in winter may partly reduce runoff and river discharge. Climate warming will increase the average discharge of rivers flowing from glaciers at first during the period of retreat, but then will decrease summer discharge, as rivers will progressively lose their glacial-type hydrological regime. A detailed study has been performed on the potential impacts of climate change on the runoff regimes of 11 small catchments having glacier surfaces comprised between 0 and 50%, at altitudes ranging between 1340 and 2940 m, under different hydrological regimes (Horton et al., 2005; Schaeffli, 2005). Predictions were developed for a scenario of +1°C (expected for 2020-2049) and two scenarios considering two increased green house gas emissions (period 2070-2099: + 2.4 to 2.8 °C and +3.0 to 3.6°C, with rates higher in summer than for the average). The conclusion are the following for the +1°C scenario:

- A decrease of annual precipitations
- An increase of winter precipitations, with the risk of higher flood peaks
- A decrease of summer precipitations
- A strong decrease of ice-covered areas, due to the strong increase of summer temperatures. The regimes will be mainly driven by snow-melt during the Late XXIth c.
- A decrease in the amplitudes of discharge
- A significant decrease of annual discharge (5-15% for the +1°C scenario) due to the reduction of precipitation, the increase of evapo-transpiration, the long term decrease of glacier surface and discharge.

Horton et al. (2005) predicted “a significant decrease of the total annual discharge and a shift in the monthly maximum discharge to earlier periods of the year due to the temperature increase and the resulting impacts on the snow melt processes”. At lower altitudes, “the influence of precipitations is more pronounced and the variability of the predicted climate change impact is mainly due to the large range of predicted regional precipitation change” (Fig. 4).

In France, a statistical analysis of discharges at 140 gauging stations from 1975 to 1990 show a reduction of snow-melt regimes to the benefit of “transitional” regimes and to a marked irregularity in the seasonality of regimes. With the warming of climate, “minimal and maximal discharges will be observed more frequently than in present times during other periods of the year than it is presently expected”. In others words, prediction will be more difficult and the authors recommend the adoption of a probabilistic approach (Krasovskaia et al., 2002). However specialists consider that discharge regimes have not changed enough to justify any change in the policy of dam management (D. Duband, oral comm.). The coupled ISBA-MODCOU model was used in three sub-watersheds and on the entire Rhone basin for a selected warm year, then tested for the prediction of change (Noilhan et al., 2000; Etchevers et al., 2001; Etchevers & Martin, 2002; Leblois, 2002; Leblois & Grésillon, 2005) (Fig. 5-6-7).

Fig. 4 Predicted changes of the hydrological regime of the upper Rhône at Gletsch, Switzerland (glacial discharge regime). (After Horton et al., 2005, modified)



A + 1°C scenario (2020 - 2049)

B B² scenario (2070 - 2099)
Simulation for low emission of greenhouse effect gaz

C A² scenario (2070 - 2099)
Simulation for high emission of greenhouse effect gaz

- in grey : zone of tested models
- bold dashed line : regime of the controled period (1961 - 1990)

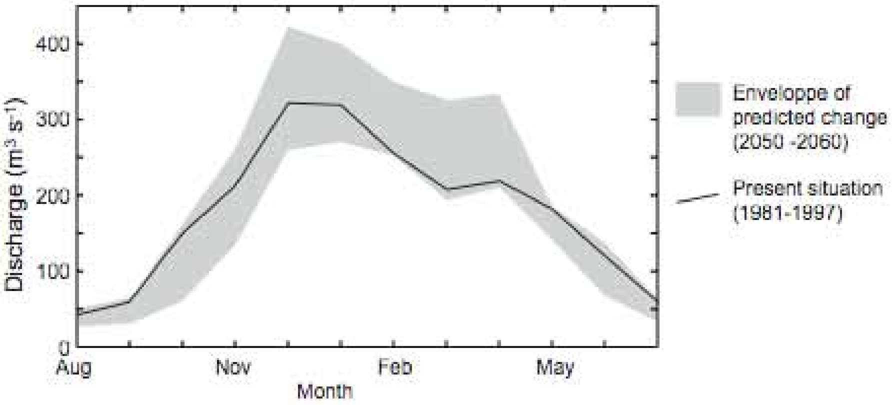


Fig. 5 Predicted change of the discharge of the Saône River at Mâcon
(source : Leblois et coll., 2002, modified)

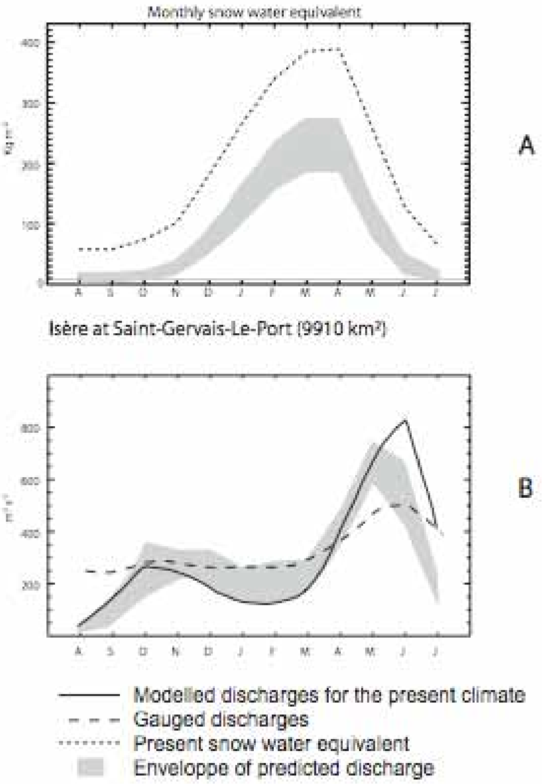


Fig. 6 The watershed of Isère River. A - Monthly snow water equivalent. B - Monthly discharge at Saint-Gervais-Le-Port (9910 km²). (After Etchevers & Martin, 2002, modified)

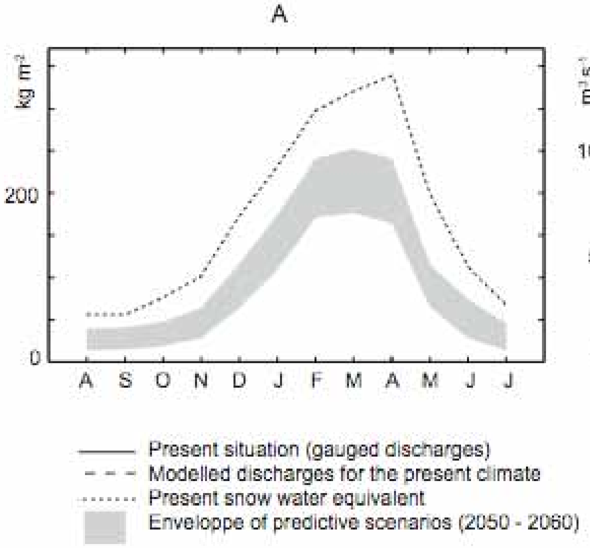


Fig. 7 The upper watershed of the Durance River. A - Monthly snow water equivalent. B - Present and predicted monthly discharge of the Durance at La Clapière (2710 km²) (after Etchevers & Martin, 2002, modified)

- In the Doubs basin, the snow-rain regime shifts to rain regime with an increase of discharge in December and January, and a decrease in spring, without a significant change of the total yearly discharge.
- In the Saône basin (Mâcon), the rain regime remains the same, but discharges decrease in summer (Fig. 5).
- In the Isère basin (Northern Alps), the maximum shifts from April to March, the winter maximum increases, and the summer minimum decreases by 50% (Fig. 6).
- In the Southern Alps, during contemporary dry years, the Durance basin experiences a "precocious and excessively rapid snow melt… resulting in an early peak and correspondingly very weak summertime flows". The simulated change forecasts "an annual reduction of river discharge and of the soil moisture, decreasing by as much as 30% below the present values" (Fig. 7).
- However, if "the reduction of snowfall and earlier snow melting (increased air temperature) induced a decrease of the average snow depth by 50% and of the snow duration by more than one month", snow pack at high altitude is less affected because even with the air warming, the average air temperature would remain below 0°C.
- The Ardèche river basin experienced a "significant reduction in summer flow" and a strong reduction of the soil water content, … "reflecting the heavy reduction of precipitation in that area"

The GICC-Rhone programme extended these conclusions drawn from sub-waterheds to the larger area of the French part of the Rhone basin (Leblois et al., 2005):

- Average yearly discharge and low flows decrease (from May to November), but high discharges increase. Low flows may be reduced by 40-50% close to the outlet of the Rhone.
- Spring flow related to snow-melt decreases since the warming of the climate reduces snow depth and the duration of snow cover, and snow melt occurs one month earlier.
- The behaviour of rivers in the winter depends on the different scenarios, but generally the increase of winter rainfall induces an increase of winter discharges

3.2.3. Interactions between sediment supply and floods

Considering winter peak flows, they should interact with changes in sediment fluxes and, locally, with the hydraulic geometry of rivers, increasing waterborne risks. The increased elevation of pergelisol due to increased temperatures will decrease the cohesiveness of soils, and trigger mass movements (Haeberli et al., 1990). Extreme rainfalls and increased average winter temperatures, increased alternations of freezing and warming in weak rocks, will increase landslides and rockfall hazards. However, recent catastrophic events in the Mattertal (Valais region) in 1987, 1993, and 2000, and above-average concentration of events have been proved to be caused by insufficient and short archival data (Stoffel et al, 2005).

These changes in slope processes will increase sediment inputs into rivers, will induce deposition and will raise the level of floods, interacting with land occupation issues along valley floors. This trend could affect northern regions of the basin, as predicted by Beniston et al. (1995).

4. Observed current human impacts on the hydrological variables

4.1. Hydrological impacts of high altitude reservoirs on the river regimes

The effects of the ongoing natural climate warming up of climate on river regimes are rendered more complex by the impacts of the management of Lake Geneva and of upland reservoirs. The economic use of Lake Geneva has slowly changed since the Late XIXth century to the benefit of tourist activities predominantly, which require a constantly high water level during the warm season. The development of the tourist industry has imposed a reduction in the amplitude of vertical variations in Geneva Lake, inducing a reduction in flood control and difficulties for the optimal use of water at the outlet (Coulouvrenière dam). The Rhone at the outlet of Geneva Lake was initially developed to maximize the efficiency of energy production, through strong variations in the level of the lake, and then unpredictable variations downstream. However these variations have decreased with time, since the conservation volume of the lake, which peaked in the 1850's (810 hm3), was reduced to meet the needs of tourism (i.e. stability) of the Vaud and Valais cantons (330-340 hm3 after 1892). The artificial regime of the lake decreased the discharge of the Rhône from July to October (to preserve a capacity of storage in case of a summer flood) and increased it in the winter for the production of energy (Bravard, 1986).

These changes interfered with the impacts of the development of energy production in the Alps. Indeed, the fast development of water storage in high altitude reservoirs of upper Valais since the 1950's has impacted the filling up of Lake Geneva because more and more water was used in the inner Alps during the spring. This delays the filling up of Lake Geneva and affects the hydrology of the Rhone downstream Geneva, high summer discharges being reduced when compared to natural discharges. At the end of the 1960's, the cumulated conservation storage was up to 1400 hm^3, i.e. three times the conservation storage of lake Geneva (Bravard, 1986). H. Vivian (1983, 1989) insisted on the impacts of Valais dams on the regime of the Rhône River. During the winter season, the production of high priced energy in Valais increases river discharge (deep waters of reservoirs do not freeze and may be turbined). These impacts trigger a change in the regime of the Rhone River at Porte de Scex, which loses part of its mountain characteristics (ice-fed and snow fed regime toward a regime artificially similar to a rain-fed regime). This change, which is still visible at Valence, allowed Vivian (p. 66), to state that "the hydrological regime has become an oceanic type". Upstream of Lyon, low flow no longer occurs in winter but during the fall, while the winter high flow downstream of the confluences with the Ain and the Saône increases ("exaggeration of the natural regime"). Similar changes have been noticed in the Isère watershed since modelled discharges differ significantly from gauged discharges. It is worth noticing that reservoir construction upstream of Saint-Gervais strongly decreased spring discharges to the benefit of all the winter months. Thus, the predicted increase of winter flow is already anticipated by the artificial increase linked to the production of hydro-energy.

In conclusion, the impacts of Lake Geneva and mountain reservoirs cumulated since they store water in spring and summer and decrease the Rhône discharge during these seasons and increase the discharge during the cold season. These artificial changes have anticipated the ongoing and expected impacts of climate warming, even if a higher degree of complexity in engineered flow could be taken into account. This complexity would deserve more interest and international collaborative research, considering the economic consequences along the French course of the river (running of the nuclear power plants).

4.2. Human impacts on water temperature

The temperature of Lake Geneva increased by 1°C since the 1960's, while temperature of Annecy lake increased of 1°C since the late XIXth c. The temperature of the Rhone river increased by 1.3 to 3°C in the different stations between 1977-1987 and 1988-1999. They increased notably during the spring and the summer. The former temperature at Orange is then the present temperature at Lyon (Poirel, 2004). This warming up is distributed between natural and human-induced causes.

The CNR had estimated the yearly average warming up impact of the chain of hydroelectric schemes at 0.14°C due to the slower velocity of flow in the 16 reservoirs (Cottereau, 1989). A far more important part of the warming up must related to the impacts of nuclear power plants. Indeed, the influence of these plants on the thermal regime has been demonstrated by Electricité de France (Desaint, 2004). 90% of time, the theoretical impact is less than 3°C just below the plants, while the average warming up is 1.72°C (Bugey plant), 1.03 (Saint-Alban plant), and 1.34°C (Tricastin plant). Temperatures have a strong seasonal behaviour, depending on the meteorology, on the discharge of the Rhone, on the input of cool water from the tributaries (Isère River), and on the energetic production of the plants. The artificial warming up decreases downstream of the plants, but the warming up due to the upstream Bugey plant is still noticeable on the lower Rhône, only it is delayed in time. The residual artificial warming up is comprised between 1° and 1.5°C on the downstream course.

5. Complex changes of water ecosystems

5.1. Changes in river ecosystems : upland rivers and foreland rivers

Considering a reduction of discharges by of 30-40% and an increase in temperature during the dry months throughout the basin, biologists (Pont et al., 2003) working in the GICC programme propose the following preliminary results :

- The potential reduction of cryophilous and rheophilous fish species, such as the trout, the bullhead, the loach, the Planer lamprey, and the introduced sun perch. The main threshold will be a 2°C increase in temperature. This trend would enhance the already noticed reduction of these species already noticed in Europe, which has been caused by river training. Considering the impact of decreased discharges on river hydraulics and river habitat for fish, models predict the negative impact of lower summer discharges on reophilic species, such as grayling, dace and barbel. Their abundance could decrease by 20% due to this factor.
- Some Cyprinids will be positively affected, such as the chub, the bleak, and the perch. The most rheophilous Cyprinids will colonise the upstream river reaches
- Some families of macroinvertebrates are negatively influenced by increased temperature (Perlidae, Odontoceridae, etc…). In fact, several physical and chemical factors interact in a complex manner with temperature increase.

These tendencies reinforce the negative impacts of river training monitored since the XIXth c. along rivers of Europe.

The response of exotic vegetal species has been studied in south-western France and the conclusions may be extrapolated with caution. Competitiveness of the most thermophilous species will be positively affected by an increase in temperature of 1°C (Tabacchi & Planty-Tabacchi).

At last, it is of major concern to look at the effects of the recent warming of the rivers. Two types of studies have documented these changes:

- The average yearly temperature of the Saône River increased by 1°5C between 1987 and 2003. The 2003 summer heat wave could exemplify future years since temperature at the highest since 1500 at least. Mouthon & Daufresne (2006) studied the response of mollusc communities between 1996 and 2004. The resilience of these communities to high temperatures is low, particularly for *Pisidium*. As much as “more than half the mollusc species currently inhabiting the potamic area of the Saone and Doubs rivers, and probably other large rivers, are probably directly threatened with extinction".

- The effects of a 1°C increase since 1985 has been studied on macro-invertebrates of the Rhône. While improvement in water quality did not introduce significant changes in community structure, temperature was proved to be a major factor all along the river whatever the constraints linked to local development schemes may have been (hydropower schemes, nuclear power plants). The period was characterised by the progressive development of invasive species and progressive changes in native community structure, due to gradual environmental changes (Daufresne et al., 2004). Moreover, large recent floods (pulse disturbance) and 2003 heat wave triggered rapid shifts. They were beneficial to eury-tolerant and invasive taxa in the downstream and middle river reaches. No sign of recovery was observed after disturbances and the sensitivity of community structures seem to increase with time, due to catastrophic bifurcations (JF Fruget, oral comm..).

5.2. Changes in lake ecosystems

The impacts of the increase in temperature in the large subalpine Lake Geneva has been studied for the current conditions, which provide some insights into predictable changes linked to global warming. Temperature increased by 1°C along the vertical profile since 30 years ago (Fig. 8). The thermal stratification sets up one month earlier in the epilimnion, along with the primary production and the growth of herbivorous zooplankton. Complementing the human-controlled decrease in the concentration of phosphorus, the spring mixing of water, then the availability of nutrients, and the structure of phytoplankton and grazers, were influenced by the winter warming up of the lakes, which in turn is linked to the NAO (Anneville et al., 2005). The different fish species were also affected by the warming of water (Gerdeaux, in press; Gerdeaux, 2005):

- The arctic chars (*Salvelinus alpinus* and *Coregonus lavaretus*) are endemic species adapted to the cold deep waters of the hypolimnion since the Late Glacial Period, alike in Arctic areas. They have a strong importance in fishing economy of the lake. These species spawn in winter when photoperiod and temperature both decrease. The warming of the lake delays spawning in December, reducing the development of embryos so that larvae are hatching a few days earlier than before, and are benefiting warmer waters and plenty of food from plankton. Then moderate warming benefit the artic chars whose

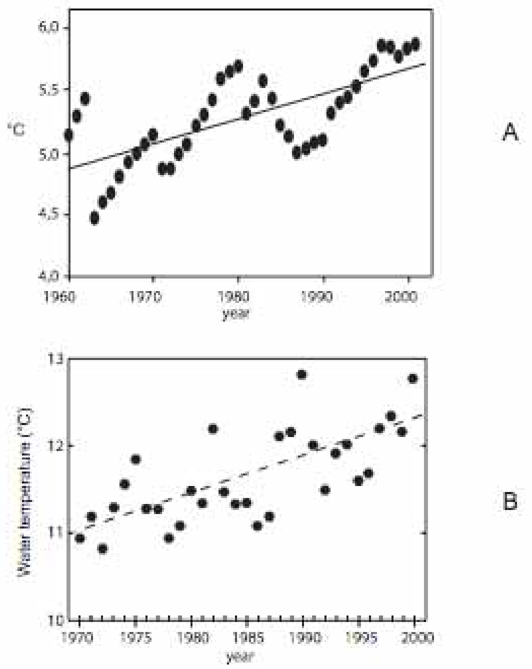


Fig. 8 Mesured changes in water temperature of Lake Geneva. Bottom from 1960 (A). 5 m depth from 1970 (B).
(after Gerdeaux, 2003 & 2004, modified)

catches increased from 50 tons in the 1970's to 300 tons since the late 1990. Bottom temperature increased from 4.5°C to 5.5°C during the last 30 years. When temperature will be as high as 7°C, ovogenesis of females will be halted and these species will not be able to adapt.

- The roach is a cyprinid living in the warmer epiliminion and spawns in May, one month earlier than before. Generally speaking, white fish have benefited the recent warming of the lake through better survival of larvae due to increased plankton food supply
- The perch, which lives deeper (below the epilimnion), does not benefit from the earlier warming of water. Since the reproduction of perch does not occur earlier, the alevins no longer benefit from the presence of roach larvae and experience a slower growth.

In the future, the lakes will experience a warming up from warmer air temperature and tributary waters. Earlier snow melting and earlier peak flows from the Alps will increase spring warming of the lakes. Also, the reduction of glacier mass will reduce the cooling by tributaries in late spring and summer. This impact of warmer waters on the vertical profile will depend on the future conditions of mixing influenced by changed conditions of stratification and by tributary inputs. Danis et al. (2004) have particularly studied the future conditions of water mixing behaviour, using a thermal model. Annecy lake is a monomictic lake experiencing one full mixing when air temperature cools surface waters down to the maximum density of 4°C. The mixing of Annecy Lake will be preserved. The epilimnion temperature would increase of ca 2.2°C in one century. The hypolimnion temperature will experience the same change thanks to the high transparency of water, which allows the absorption of solar radiation. The regular overturning will then be preserved. However, like in Geneva Lake, the arctic char will disappear due to the increase in temperature above 7°C.

6. Predictable impacts on the uses of water and on humans

6.1. Energy

6.1.1. Hydropower

The general reduction in runoff will affect the production of hydraulic energy throughout the Alps, particularly in the Southern Alps which will be submitted to the strongest reduction. In Switzerland, the scenarios of change predict a reduction of the mean annual hydroelectricity potential due to a significant decrease of mean annual discharges. After 2050, the reduction of summer discharge will reduce the differences in seasonal discharges, inducing an easier management of energy production. The winter discharges will increase in response to earlier snow-melt and to increased precipitations. Spring discharges will increase, but the change will be more limited. The modelling the Mauvoisin hydropower plant production allowed B. Schäfli (2005) to predict a 36% decrease between 1961 to 1990, and 2070-2099. The same behaviour is predictable in the Northern French Alps (cf the regime of the Isère River, fig. 6).

Since the future hydrological regimes will be driven more by precipitations than by snow-melt and glacier-melt processes, the “inter-annual variability of mean annual discharge is expected to increase”, and possibly “the year-to-year hydroelectricity potential” (Horton et al., 2005). The filling up of high elevation reservoirs will occur earlier in the season thanks to earlier snow melting and to increased winter temperatures.

Economically, this change may fit with the highest values of energy during winter peaks of demand. However, the recent increase in summer consumption of energy observed during the hot months of 2003, due to the use of electric coolers, has triggered peaks of prices on the European market. This unexpected peak of demand will value summer production and may change the conditions of water storage in the Western Alps to the detriment of summer storage, considering that increased precipitations in winter decrease the importance of summer storage for winter production.

6.1.2. Thermal power cooled by rivers

Increased temperature of the Rhone will reduce the production of thermal energy, following the Carnot rule. The cooling of nuclear power plants of the Rhône in France requires differences in temperatures between the river and the cooling system. Any warming of the river decreases the potential of energy production since the maximum temperatures of the releases are controlled by strict rules. However, it is probable that these regulations will be softened to the detriment of aquatic ecosystems, as it occurred in August 2003,. This policy will be all the more probable that energy prices will increase during the hot season.

6.2. Tourism

Climate change will have impacts on tourism through the status of water. Beniston (2003) proposes to make the distinction between direct impacts (through conditions for specific activities) and indirect impacts (through changes in landscapes and the modified pattern of economic demand). We will consider herein the direct impacts upon tourism based on snow and lakes.

6.2.1. The challenge of snow cover reduction

According to Abegg and Froesch (1994), an increase of temperature of 2-3°C by the year 2050 would adversely affect ski resorts located at low altitude (below 1,200-1,500 m). Warmer winters will bring less snow at these altitudes, and snow will melt faster, reducing the probability of practicing skiing, a sport requiring a snow cover of 30 cm during at least 100 days. A 2°C warming would reduce the reliability of resorts in Switzerland from 85% in the late XXth c. down to 63%, affecting in particular the low altitude resorts (Koenig and Abegg, 1997). In Isère department, France, the Conseil Général ordered a study dealing with the last 29 winters. The results point to the vulnerability of the resorts whose ski runs are lower than 1,500 m in elevation, the snow cover being more and more uncertain. In the Drôme department, the Conseil Général finances the yearly financial deficit of 4 small ski resorts. In 2003, it granted the construction of the upper ski-lift of Rousset resort, above 1,400 m, into the perimeter of a protected natural area.

To avoid the headlong pursuit of the communes in charge of developing winter sports, the Conseil Général of Isère Department proposed a new type of contract to the lowest resorts in order to avoid being financially sollicited in case of a series of winters deprived of snow. Indeed, these changes in snow cover and in the duration and quality of the winter season will have economic consequences, such as in Morzine-Avoriaz resorts complex (Frangialli & Passaquin, 2003). The lack of snow is being compensated for by costly investments in snow-making equipments, better vegetation cover on the runs, by the development of resorts at higher altitudes, and by investments in other types of activities. If over-frequentation may be predicted in high altitude resorts, Christmas and Easter periods will generate less incomes and the value of estates will decrease at lowest altitudes. The heavy past investments may not be refunded, which affects the finances of communes or private investors. Thousands of seasonal workers will have shorter seasons and reduced incomes.

The development of artificial snow has been precisely documented in the French Alps (Dugleux, 2002). In 2002, 85% out the 162 ski resorts of the French basin of the Rhone were able to produce artificial snow, on 15% of surfaces, mostly between 1,500 and 2,000 m, but at higher and higher altitudes. This is detrimental to local water resources since making 2 m^3 of snow requires 1 m^3 of unfrozen water, while the torrents are at low flow. In 1999-2000, 10 hm^3 of water were used in 119 resorts in Savoy, i.e. the same amount that a city of 170 000 inhabitants, or 20% of the volumes used for domestic uses. In terms of specific consumption, artificial snow requires 4000 m^3/ha, to be compared with 1700 m^3/ha for the irrigation of corn in the Alps. Water for artificial snow has three origins:

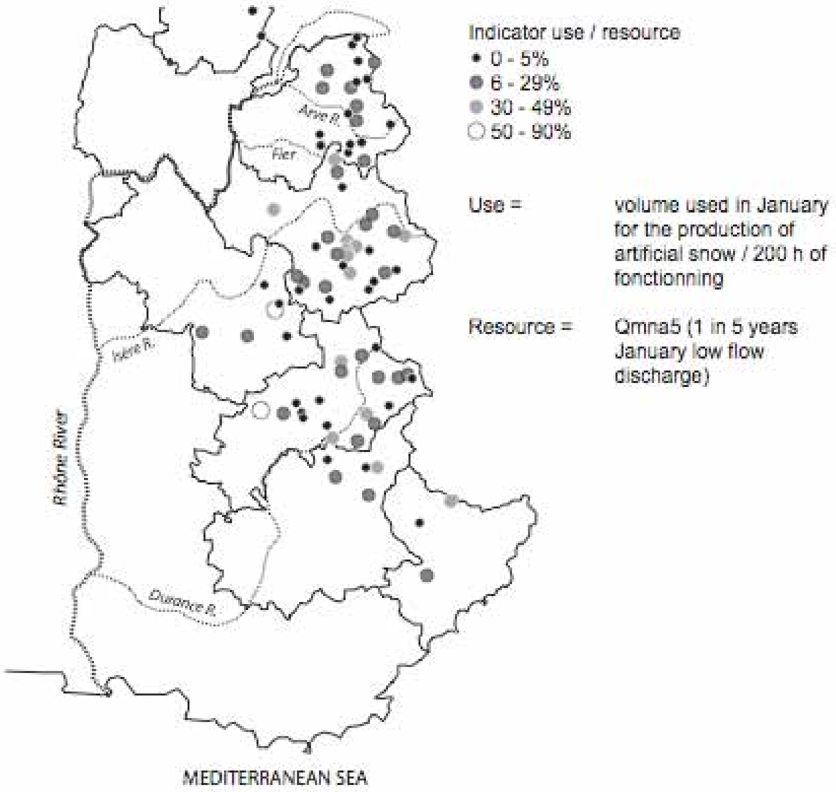


Fig.9 Pressure of the production of artificial snow on the upland water resources (after Dugleux, 2002, modified)

- More than one third of resorts experience shortages in water supply for domestic uses, because in 25% of resorts, snow production competes with human uses (total volume : 2 hm^3 per year).
- 50% of ski resorts have built artificial tanks storing 20 000 to 150 000 m^3 (total volume: 5 hm^3 per year)
- 25% of resorts withdraw water from rivers during the cold season.

Making artificial snow has impacts on the aquatic environment :

- Tanks are harmful to wetlands, have no hydrological impacts on rivers during the cold season, but are filled in during the summer season, and may be prone to destruction by floods
- Direct winter withdrawals impact rivers at low flow, from November to February (January represents 30% of the total consumption).

Dugleux (2002) proposed an indicator of pressure upon low flow discharges. For 60% of resorts, withdrawal represents less than 10% of low flow discharge. For 11 resorts it represents from 30 to 49% of this discharge, for 2 of them, more than 50% (Fig. 9). It has been underlined that, if the present impacts are not too harmful, they will develop in the future. Since artificial snow meets major economic objectives (the survival of the resort in some cases, the maximum snow depth on all the tracks during the complete season), the phenomenon must be strictly monitored and controlled.

6.2.2. Water supply to southern resorts

Water supply to resorts (swimming pools, lawns), and for leisure (golf courses) will be reduced if summer precipitations decrease and if evaporation increases, notably in the Southern part of the watershed (Ceron & Dubois, 2003). Mountain reservoirs will be solicited, as it is presently the case in the Ardèche basin where a minimum discharge guarantees the practice of canoeing in the downstream gorges, in July and August.

6.2.3. Maintaining levels of large subalpine lakes

Tourism on large lakes will be impacted by climate change in a complex way. Coupled with the early reduction of discharge, it will probably impact the conditions of the seasonal filling up of Lake Geneva. Annecy and Bourget Lakes have small tributaries which will be affected by earlier snow-melt and by decreased summer discharge, in a context of increased evaporation, like in 2003. Due to water withdrawal for domestic uses from Annecy Lake, and withdrawal of used water collected around both Annecy and Bourget Lakes, the natural inputs into the lakes have been artificially reduced. Maintaining high water levels in summer, for the sake of aesthetics and tourism is a challenge, which precludes any variation for the sake of the sustainable ecology of banks in Annecy Lake. In the case of Bourget Lake, maintaining a high and constant level would require supplying water from the Rhone to the lake, as in July 2003.

6.3. Pressures on the consumptive uses of water

6.3.1. Present consumptions in the Rhone watershed (France) and along the Rhone River

The total withdrawals at the watershed scale have a total amount to 15 800 hm^3/year (table 1), but do not exceed 4600 hm^3 if one excludes withdrawals from the Rhone River (most of this withdrawal is just a diversion to the cooling systems, since a small proportion is lost in cooling towers, most of the cooling systems being “closed” systems). This yearly volume must be compared with the yearly discharge of the Rhone River at the outlet, i.e. 54 000 hm^3 (95 000 hm^3 are stored in lakes and 15,5 hm^3 stored in the decaying alpine glaciers.

Domestic uses	Industry	Thermal energy	Irrigation	Total
1900	950	11 200	1750	15 800

Table 1 : Withdrawals in the Rhone watershed for the different water uses, France only (hm^3/year)

Excluding energetic uses,

- The withdrawal from the Rhone River alone stands below 850 hm^3/year (Table 2), i.e. the represents less than 1,6 % of the total discharge into the Mediterranean.
- The withdrawal at the watershed scale (4600 hm^3/y) represents 8,5 % of the discharge into the Mediterranean.

Part of these withdrawals devoted to domestic uses, agriculture and industrial processes are not consumed and go back to the ground waters and to the river.

	Domestic uses	Industry	Thermal energy	Irrigation by gravity	Irrigation pression	Others
Superficial water	10,4	112,1	11 200	45,6	134,8	0
Ground water	212,6	277	0,1	4,3	13,7	15,4
Total	223	390	11200	49,9	150	15,4

Table 2 : Withdrawals from the Rhone River only (hm^3/an)

6.3.2. Irrigation in the perspective of climate change

The GICC-Rhone study (Leblois et al, 2005), using the STICS model, predicts that the doubling of CO^2 concentration will induce a shorter seasonal cycle for corn cultivation (reduction by 21%), and a 15% loss of yield. The shorter cycle induces an increase of irrigation rates which cumulate with increased plant requirements due to climate warming. However, the earlier growth reduces the intakes in August, the most difficult periods for river hydrology. The Drôme river case study provided interesting insights into future climate change, since the average yearly temperature increased by 0.9°C and the temperature of July by 2°C, with marked consequences on hydrological resources. The GICC study predicts that agriculture will probably adapt through a reduction of irrigation practices to the benefit of crops less dependant on water resources.

The pressure upon water resources (superficial water and groundwater) will change in a complex way. Industrial consumptive uses are decreasing, while domestic uses are stagnant, partly due the rise of prices. Global water consumption by agriculture will be influenced by EEC policy and by the global market, in ways that are difficult to predict today. It is clear that different ecoregions have different potentialities and that a unique set of rules is not recommended to overcome periods of water shortage. Beyond the modelling of river discharges, the GICC-Rhone study recommends to investigate the different components of water balance at the scale of the geographical units. The variations of precipitations from year to year, and the variation of water volumes should be computed for a better management of resources in situations of potential conflicts.

It is worth considering the present responses of farmers to drought, such as they occurred in 1989, and in 2003 and 2004, because they may announce future massive forms of adaptation to situation of crisis:

- In the “ecoregions” prone to the drying up of rivers and deprived of subterraneous resources, i.e. mainly in the crystalline regions of the basin, farmers were granted to built tanks intercepting the headwaters and the hypodermic flow. Hundredths of tanks have been built along the eastern rim of the Massif Central since 30 years (Lyon Mounts, Vivarais). They induce severe reduction of summer flow and decrease winter floods during the period of infilling. As such, they have been proved to induce so severe impacts upon river hydrology and ecology that they are no longer a priority of public authorities, even if they are economically efficient.
- A kind of adaptation is the development of wells into the alluvial aquifer bordering the river. This practice is detrimental to small rivers, which are fed by the aquifer and are prone to severe and long-lasting drying up. Authorities are reacting by delineating the

riparian aquifers and by limiting the authorisations of pumping from the wells (Bonhomme and Nicolas, 2005).

- Most of the recent developments concern the aquifer included inside the deep and rich mollassic sandstones of the Alps and Jura foreland. Water extraction is so intense that the groundwater levels are declining due to a negative balance between the refilling by the precipitation and the extraction during the warm season. Public authorities have recently decided to develop a network of piezometers in threatened areas, because they are sensitive to the over exploitation of water resources (in some rare cases, water for domestic uses was no longer available due to the lowering of the groundwater level). Undoubtedly, controlling the volumes that are really extracted from aquifers will be a challenge.

As it has been presented in the above developments, human interference with the effects of climate change is increasing as far as agricultural uses are concerned. The more river discharges will be affected by water withdrawal from aquifers, the more it will be difficult to make the distinction between anthropogenic impacts and changes induced by climate change, even along large rivers like the Rhône.

While admitting that French agriculture will need more security, Redaud et al. (2002) recommended to reinforce regulations aiming at controlling irrigation in order to better respect the low flow objectives of the Watershed directory schemes (SDAGE) in heavily impacted basins.

6.3.3. Massive withdrawals from large rivers

Water intakes from large rivers in Southern France is quite a story. In the mid-fifties, the Durance and the Rhone rivers were affected by large withdrawals with different purposes. The average yearly discharge of the Durance River was 210 m^3/s at the confluence into the Rhone River. On the upstream course of the river, the Serre-Ponçon dam (1955-1959), along with a complex hydraulic system on the Verdon (a left bank tributary), allowed the diversion of 0.7 km^3 for energy production and 0.2 km^3 for agriculture into a lateral canal designed for carrying up to 300 m^3/s. Also, part of the discharge was diverted to the cities of the Mediterranean coast in order to secure water supply in a period of growth of tourism. The lower reach of the canal pours into the Etang de Berre, to the detriment of the Rhone discharge. Downstream Serre-Ponçon, the minimum discharge of the river is no more than 2 m^3/s during most of the year (when the canal discharge is not exceeded), while the absolute minimum was 25 m^3/s before 1960. R. Warner (2000, 2001) described the artificial river corridor as case of “desertification”. The vast array of upstream developments ensured “exotic” areas (the irrigated and coastal regions): “with further effective reductions in precipitations and increase in temperature, sustaining these enterprises will be very difficult. The opportunity for further exploitation is virtually nonexistent. So the trends for desertification already apparent will continue and promote greater concern" (Warner, 2000).

The Languedoc canal (1957-1960) was dug to divert up to 75 m^3/s from the Petit Rhône, the eastern branch of the Rhone in the Camargue delta, for the sake of irrigated agriculture. However, withdrawals have never exceeded 15-20 m^3/s, due to lack of consumption in the low coastal plains, which remained widely devoted to non-irrigated vineyards. In 1995, the company ruling the canal and a society delivering drinkable water to the city of Barcelona proposed to divert 10-15 m^3/s from the Rhone to Barcelona, using the same intake. The purpose was to secure water delivery to Barcelona and provide better quality. The development of tourism, and the increase of summer discharge of coastal rivers in Languedoc were other objectives. This project failed for complex political reasons but it reveals the renewal of pressure upon the Rhone River.

6.4. Risks

6.4.1. Floods

The major apparent risk is linked to increased flood hazards. If winter floods occurring on rivers in Switzerland have negative influences on discharges in downstream countries, then these countries may ask for improved retention in the Swiss lakes and reservoirs, along with political consequences (Schädler, 2003). In the last 15 years, severe floods occurred in the Upper Rhone downstream Geneva (1990 was the 1 on 100 years flood), and in the lower Rhone (for instance:1993, 1994, 2003). As stated above (Sauquet & Haon, 2003), they may be just a cycle of high discharges as many occurred in the past. Also, they may be the first signals of changed climate towards higher peak floods. Anyhow, they revealed the strong vulnerability of the Rhone valley to flooding. In 1995, the French government launched a large study called "Global Rhône study", combining hydraulics, sediment transport and land occupation, as these different topics having been recognized as complementing each other. The 2003 flood, approximately the 1 in 100 years flood for the downstream gauging stations, motivated the French government to launch the so-called "Rhône Masterplan" (2005) which includes a series of measures to mitigate the human consequences of flooding, the reduction of hydrological hazards being recognized as quite impracticable. The expected risk explicitly refers to the largest past floods (1856), to extremal scenarios combining several meteorological origins (the so-called "general flood" in the sense of Pardé, 1925), and to the negative impacts of the occupation of the floodplain. It is thus worth noting that the possible effects of climate change on the intensity of large flood is not taken into account, despite the possible increase in extreme winter events. Also, to face the expected changes, the French Ministry of Environment and Sustainable Development recommended to extend the number of the “Plans de Prévention des Risques” and to improve forecasting procedures (Redaud et al., 2002).

6.4.2. The Camargue delta and the mouth of the Rhone River

In the perspective of sea level rise, the coast dunes protecting the Camargue delta will be threatened and brackish water may extend upstream, changing the ecological conditions of the lower river. According to Provansal and Sabatier (2000), the main cause of present coastal retreat is not sea level rise but the decrease of sediment supply from the Rhône River which has complex causes (sediment retention in reservoirs, impacts of embankments of the Rhône, reforestation of the watershed, etc…). The velocity of the coastal retreat should increase, in particular if sea storms and surges get more intense.

Also, the intrusion of brackish water will affect the Grand Rhone itself. In the 1990’s, an outcrop of bedrock has been suppressed for the sake of navigation downstream the city of Arles, making easier the intrusion of marine water at low flow. It is probable that the expected reduction of low flow and sea level rise will induce longer periods of brackish conditions between flood pulses upstream of the present limit, to the detriment of human uses (domestic uses and irrigation of paddy fields inside the delta).

6.4.3. Increased temperatures and pathologies

The warming up of water temperature should increase the sanitary risks through better conditions for hosts of virus (West-Nile virus, bird influenza, etc…), such as horses, mosquitoes and birds. The Workshop Zone “Rhône Watershed” (P. Sabatier) launched a research programme on the environmental parameters controlling the sanitary conditions in marshland areas.

Conclusion

Changes have begun on the hydrosystem of the Rhône River due to the direct impacts of recent climate warming. These documented changes interfere with human-induced changes in a highly developed watershed. Predicted changes linked to modelled climate change may have significant hydrological, ecological and economic impacts in the next decades.

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