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Impacts of climate change on water resources: a case-study for Portugal

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Abstract The paper briefly analyses the impacts of climate change on water resources and identifies, in general terms, the specific impacts related to different hydrological variables and different characteristics of the water systems. A case study of the impacts of climate change on Portuguese water resources developed within the SIAM project, is introduced. The climate scenarios considered, corresponding to selected climate models, show a small increase of annual precipitation for the northern region of Portugal and a decrease for the central and southern regions. The models also predict an increase of seasonal asymmetry with relevant decreases in summer precipitation. The annual average temperature appears to increase, particularly in southern Portugal. These climatic scenarios lead to a probable trend towards a concentration of river runoff in winter and an increase in the current seasonal asymmetry of water availability in Portugal. It also appears that the concentration of rainfall in winter and the estimated general increase in the frequency of heavy precipitation events is likely to augment the magnitude and frequency of flooding, particularly in the northern part of the country. The predicted decrease of river flow in southern Portugal, during the next century, associated with an increase in the spatial and temporal asymmetry of water resources distribution, may have very serious consequences and be a cause of major concern. It may, in fact, have strong implications for the water resources management strategies and policies to be designed for Portugal. Finally, how the consideration of climate change on water resources should influence the future planning and management of water resources, both in general terms and in the specific case of Portugal, is analysed. In particular, the joint study of climate change impacts on the water resources shared by Spain and Portugal is proposed as a major focus for scientific and technological co-operation of the two countries of the Iberian Peninsula.

Key words adaptation measures; climate change; impacts; water resources

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

In recent years, and particularly since the outcome of the second and third assessment reports of the Intergovernmental Panel on Climate Change (IPCC, 1996, 2001), it has become clear that global climate change is a scientific reality. An increasing awareness that global climate change will affect water resources has also clearly emerged and this has been reflected in a rapidly growing body of scientific literature.

Water resources are in fact arguably the most important domain to be considered in a climate change impact assessment study. This importance stems from the fact that climate change has direct impacts on the availability, timing and variability of the water supply and demand, and is also related to the significant consequences of these impacts on many sectors of our society. Water is used for human consumption, industrial purposes, irrigation, power production, navigation, recreation and waste disposal, as well as for the maintenance of healthy aquatic ecosystems. Its availability and the occurrence of extreme events, such as floods and droughts, condition the location of urban, industrial and agriculture areas, power generation plants and trading centres.

Several hydrological variables and characteristics of the water resources systems may be affected by global climate change. A brief reference to these variables and characteristics is made below.

(a) *Temperature* Impacts of global climate change on temperature are perhaps the most obvious ones and are particularly important because temperature is a driver of many other hydrological variables.

(b) *Precipitation* Together with temperature, precipitation is the second hydrological variable considered in global climate models to express the impact of global climate changes.

(c) *Evapotranspiration* An increase of temperature normally leads to an increase of potential evapotranspiration, although actual evapotranspiration is conditioned by the amount of water available in the soil and plants. Transpiration of water by plants is affected by a number of variables, including stomatal behaviour and concentration of CO_2 in the atmosphere.

(d) *Soil moisture* Temperature, precipitation and evapotranspiration directly affect soil moisture. But the strongest influence is normally due to precipitation. Soil moisture changes strongly influence crop growth and water needs for irrigation.

(e) *Runoff* Runoff is clearly affected by the abovementioned hydrological variables and, in particular, by precipitation. However, future runoff is also conditioned by several other climatic factors and human influences, such as streamflow diversions and regulation or interaction between surface and groundwater, which makes it difficult to predict future runoff.

(f) *Groundwater* Changes in the magnitude and seasonal distribution of precipitation will cause changes in the patterns of seasonal aquifer recharge with consequences for the groundwater stock and flow, and for the quality of groundwater. The interaction between surface water and groundwater is also expected to be modified.

(g) *Floods and droughts* In parallel with the impact of climate change on the average values of hydrological variables, the impact on extreme phenomena, such as floods and droughts, is relevant. Several studies indicate a tendency for an intensification of climate variability in situations of climate change and offer, for some regions, apparently paradoxical scenarios of increase in both floods and droughts.

(h) *Aquatic ecosystems* Climate change may affect aquatic ecosystems in many different ways as the health of these ecosystems depends on many climate-sensitive factors, including temperature, water quantity and quality, and timing of water availability. These impacts may be particularly serious in lakes and reservoirs, where important changes in the dynamics of the water bodies may lead to alterations of nutrient exchanges or to invasions of exotic species.

(i) *Water quality* Climate change may affect the quality of water bodies as a consequence of changes in runoff, changes in the pattern of transport of agricultural, industrial or domestic pollutants, or modification of the assimilation capacity of pollution by the water bodies related to changes in water temperature.

(j) *Water demand* The changes in temperature associated with global climate change will not only have an impact on water availability but, also, on water demand. This impact will tend to be particularly relevant in the case of water use for agriculture, as a result of changes in evapotranspiration and soil moisture, but may also be significant in the case of industrial and domestic uses.

(k) *Sea level rise* The temperature increase associated with global climate change will cause a rise of sea level as a consequence of thermal expansion of the ocean waters and melting of glaciers and polar ice. This will have negative impacts on water resources, causing saline intrusion in coastal aquifers and affecting coastal and estuarine ecosystems.

The IPCC Third Assessment Report (IPCC, 2001) estimates a global increase of mean annual temperature of 0.8°C to 2.6°C by 2050, and 1.4°C to 5.8°C by 2100. The study also reports results that indicate an increase in annual precipitation induced by climate change in high and mid latitudes and most equatorial regions, as well as a general decrease in the subtropics. Results also show that flood magnitude and frequency is likely to increase, due to the concentration of precipitation in winter in most areas of the globe. Simultaneously, the decrease of low flows in many regions, associated with higher temperatures, constitutes a serious threat to the quality of water resources.

As regards the impacts of climate change in Europe, the IPCC studies suggest that Southern Europe, and the Mediterranean region, will be particularly affected in a negative way. This will be especially true in the Iberian Peninsula, south of the River Tagus, where a considerable increase in temperature and a reduction in precipitation and runoff are expected by 2100.

A report, recently published, by the Joint Research Centre of the European Commission (EC, 2005) confirms these IPCC predictions. The report presents a detailed analysis of the impacts of climate change on water resources in Europe and proposes adaptation measures. It should be noted that the results of the report are also in line with the conclusion of the Portuguese case study referred to in the following section of this paper.

A CASE STUDY OF THE IMPACTS OF CLIMATE CHANGE ON PORTUGUESE WATER RESOURCES

This section briefly describes the first national study of the impacts of climate change on Portuguese water resources (Cunha *et al*., 2002). This study is part of a general study on "Climate Change in Portugal: Scenarios Impacts and Adaptation Measures" (SIAM Project) (Santos *et al*., 2002). The SIAM Project is currently being developed into a second phase, SIAM II, which involves an extension to Madeira and the Azores

Islands, and also a broader thematic scope as regards water resources, by considering not only surface water resources, but also groundwater resources. This groundwater part of the study has already been briefly presented in a preliminary paper (Nascimento *et al*., 2004).

To evaluate the impacts of climate change on water resources, the study by Cunha *et al*. (2002) compared two sets of statistics of climate and hydrological variables. The first set assumes a steady climate scenario and the second assumes a given scenario for greenhouse gases emission.

The current global climate models (GCMs) and regional climate models (RCMs) are able to produce time series for a set of climatic variables under different emission scenarios. The basic scenario, commonly referred to as the *control run*, consists of simulating the conditions in the absence of any CO_2 increase, thus producing a stationary climatic scenario, where each climatic variable varies throughout the simulation periods but its overall average is not expected to change. The other scenarios, referred to as *perturbed scenarios*, simulate the climate trend and variability associated with a given greenhouse gas emission scenario. These emission scenarios assume different CO_2 increase rates and may also include the combined effect of greenhouse gases and aerosols.

To evaluate the impacts of climate change on water resources one must go beyond temperature and precipitation and also assess the changes in runoff. Unfortunately, the scale used by both GCMs and RCMs is too coarse to allow for an appropriate simulation of hydrological processes at the basin level.

To overcome this difficulty, most studies have used the climate models' results as the input to a hydrological model that simulates the mechanism of interception, infiltration, aquifer recharge and runoff at the basin scale. This approach, followed by a number of authors, was also adopted in the SIAM study. The climate change impacts on water availability were evaluated by comparing the results from a hydrological model, which was run under different climatic scenarios. Historical monthly precipitation and temperature records describe the current climate. Future climatic scenarios were built by perturbing the historical records with expected changes predicted by GCMs or RCMs.

The hydrological model used in this study is a continuous, aggregated and deterministic monthly precipitation–runoff model that simulates the transformation process of precipitation into runoff on a given river basin. It assumes a monthly time step and since it is an aggregated model, it assumes a uniform spatial distribution of the conditions that affect the transformation process. The model produces runoff, aquifer recharge and effective evapotranspiration monthly time series as output.

To characterize the present climate conditions, the historical precipitation and temperature records of about 500 raingauge stations and about 200 climate stations, from the Portuguese Meteorological Institute and the Portuguese Water Institute, were analysed. Data from the Spanish Meteorological Institute covering the Spanish territory in a region surrounding Portugal, and, particularly, in the Galicia region, north of Portugal, were also included in the data set. The period of analysis was 1961–1990 and monthly values were used.

To provide a nationwide picture of the hydrological regimes in Portugal, 62 river basins with no major human intervention and with areas ranging from 15 to 1000 km^2

were selected. The hydrological model was calibrated for each river basin. The length of observed records used for calibration ranges from 5 to 50 years.

In order to identify the climate models that better reproduce the actual climatic conditions in Portugal, the output of six different global and regional climate models were compared with the observed records.

The six models considered were the following: three from the Hadley Centre for Climate Prediction and Research (HadCM2, HadCM3 and HadRM2); one from each of three institutions, the "Deutches Klimarechenzentrum" (ECHAM4), the Canadian Centre for Climate Modeling and Analysis (CGCM1); and the "Grupo de Modelado Atmosférico" of the Complutense University of Madrid (PROMES). This includes the two types of climatic models referred to above, the GCMs and the RCMs, which have quite different spatial resolutions. All these models are referred to by the Intergovernmental Panel on Climate Change (IPCC, 2001), with the exception of the PROMES model, and a thorough description of their capacities and limitations can be found at the IPCC Data Distribution Centre site.

The conclusion of the comparison of the results of the six models was that the HadCM3 and HadRM2 models from the Hadley Centre provide the most accurate results. They were, therefore, selected to serve as the basis of the future climate scenarios adopted in this study. A detailed reference to the process leading to the selection of these two models is provided by Cunha & Oliveira (2003).

Climatic scenarios

Figure 1 summarizes the changes put forward by several climatic models for the northern, central and southern regions of Portugal. Four sets of results are presented from the HadCM2 model corresponding to four different runs of the same model, which assume slightly different initial conditions. Two sets are presented for the HadCM3 model, with the HadCM3+S run corresponding to a HadCM3 run that includes the effect of aerosols. The temperature change values for the 2050 scenario were computed as the difference between the average values for the 2030–2064 period of the perturbed run and the average values for 1960–1994 period of the perturbed run. Similarly, the temperature change values for the 2100 scenario were computed as the difference between the average values for the 2065–2099 period of the perturbed run and the average values for 1960–1994 period of the perturbed run. The precipitation change values were computed as the ratio between the average values of the same future periods of the perturbed run and the average values for 1960–1994 period of the perturbed run.

The first conclusion to be drawn is the highly consistent results indicating an increase of the annual mean temperature, mostly of between 2.0 and 3.0°C by 2050, and between 3.5 and 5.0°C by 2100. The results for the central and southern regions are approximately 0.5°C higher than for the northern region.

Model results, not presented in this paper, show that the increase in annual mean temperature is likely to occur all year round, pushed by a strong increase of summer temperatures of 3.0 to 5.0°C and a more gentle increase of about 2.0°C by 2050, in the winter. Summer temperatures are expected to increase between 5.0 and 7.0°C by 2100.

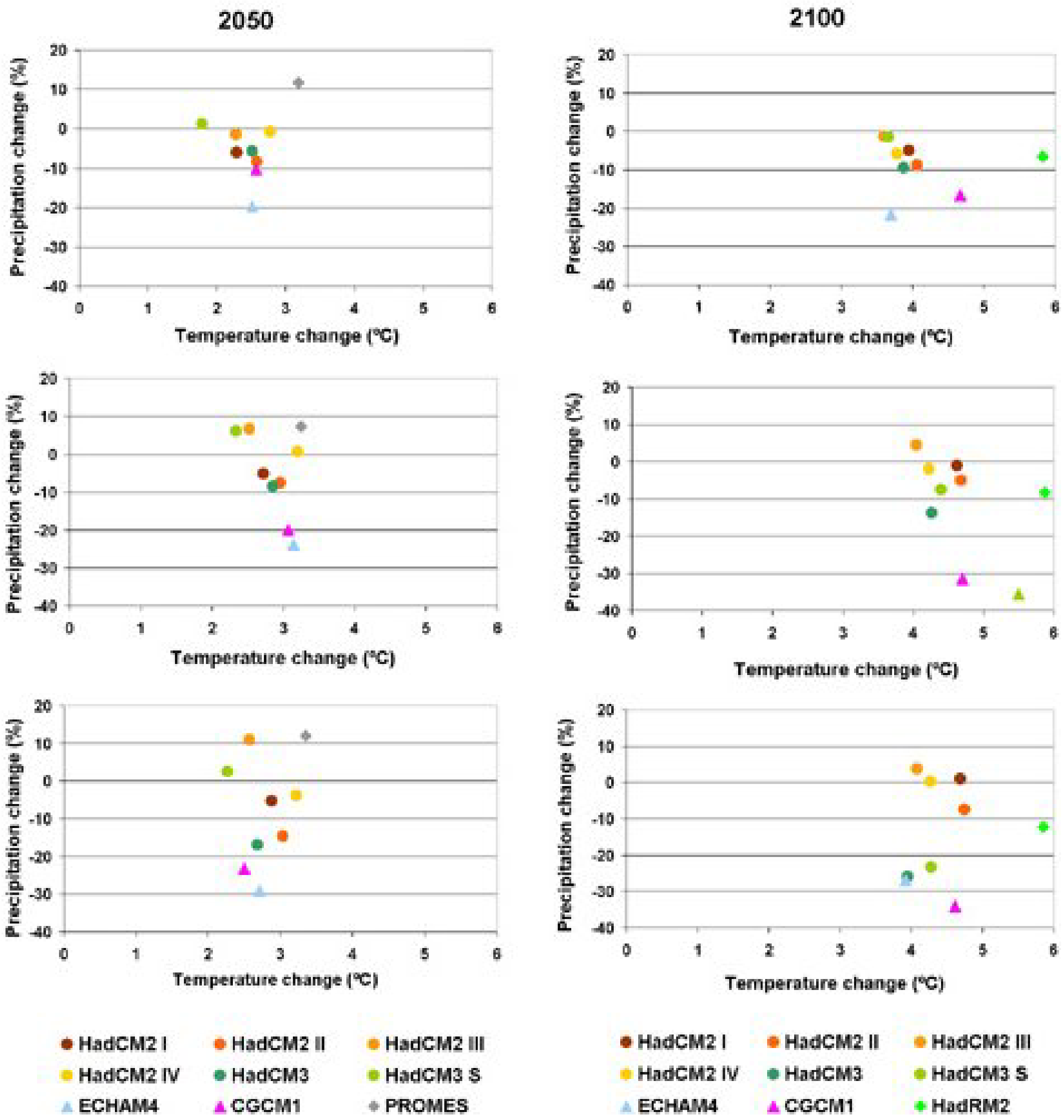

Fig. 1 Temperature and precipitation annual change for 2050 and 2100 in northern, central and southern Portugal.

The precipitation results show a lower agreement, but the general trend indicates an annual decrease up to 10% in the northern region, which could be as great as 30% in the southern region. Some results indicate a small increase in precipitation by 2050. These positive values almost disappear by 2100.

Table 1 presents the annual average precipitation and temperature changes from 1960–1994 average values, predicted by the two models that offered the results most consistent with the historical record. HadCM3 results include values for 2050 and 2100, assuming two extreme social and emission scenarios. Scenario B2a assumes a return to smaller regional communities, with weaker international links, where the resolution of social problems takes precedence over economic development. Scenario A2c assumes a world increasingly global with strong economic activity and with diminishing environmental concerns. The HadRM2 results only include values for 2100.

Table 1 Annual average precipitation and temperature changes from 1960–1994 average values.

Model	North Precip	Temp	Centre Precip	Temp	South Precip	Temp
HadCM3 B2a 2050	0%	+2.1 ºC	+6%	+2.7 ºC	+6%	+2.3 ºC
HadCM3 A2c 2050	+11%	+2.5 ºC	–18%	+2.8 ºC	–28%	+2.6 ºC
HadCM3 B2a 2100	+1.6%	+3.2 ºC	+2%	+3.7 ºC	–1%	+3.5 ºC
HadCM3 A2c 2100	–13.6%	+4.5 ºC	–28%	+5.1 ºC	–42%	+4.9 ºC
HadRM2 2100	–7%	+5.8 ºC	–8%	+5.9 ºC	–12%	+5.9 ºC

The results in Table 1 show a consistent increase of temperature of around 2.5ºC for 2050 and between 3.2 and 5.9ºC for 2100. At a seasonal scale, results not presented in this paper show an increase of average winter and spring temperature of between 2 and 5ºC by 2100. The average summer temperature may increase by between 4 and 8ºC and the average autumn temperature may increase by between 3 and 7ºC.

Regarding precipitation, the scenarios shown in Table 1 present some disparity, for the north of Portugal, but almost all predict a decrease of precipitation for the south. At the seasonal scale (results not included in this paper), the winter scenarios present some variety, but all models indicate very consistent results towards a reduction in precipitation for spring, summer and autumn. By 2100, spring precipitation is expected to decrease by between 0 and 20%, in the north, and by between 10 and 50%, in the south. In the summer, a precipitation reduction of between 30 and 50% is expected in all regions. Finally, autumn precipitation may decrease by between 0 and 25%, in the north, and between 0 and 50%, in the south.

Runoff scenarios

With diminished precipitation and increased potential evapotranspiration, directly linked to a temperature increase, water availability is likely to decrease in annual terms. Nonetheless, the predicted seasonal changes in precipitation and temperature may constitute a much more severe constraint to water management.

River runoff was simulated for 62 selected river basins using a hydrological model. The results obtained from these basins are expected to represent the variety of runoff regimes existing in Portugal.

Three major scenarios are presented in this paper (Fig. 2). HadCM3 results include values for 2050 and 2100, assuming the two different emission scenarios mentioned above. The HadRM2 results only include values for 2100.

The results do not fully agree with each other. Some scenarios indicate an increase in runoff, whereas others show a progressive reduction in the annual river runoff during the 21st century. According to this latter scenario, the runoff reduction appears to be small in the northern region of Portugal, but increases progressively towards the south, where it reaches some alarming values.

Despite these inconsistent results regarding annual runoff, all models predict a significant increase of the seasonal asymmetry of runoff. Results, not presented in this paper, show a decrease in runoff for spring, summer and autumn. There seems to be a systematic trend towards a concentration of the river runoff in winter, induced by a similar pattern of change in the precipitation distribution.

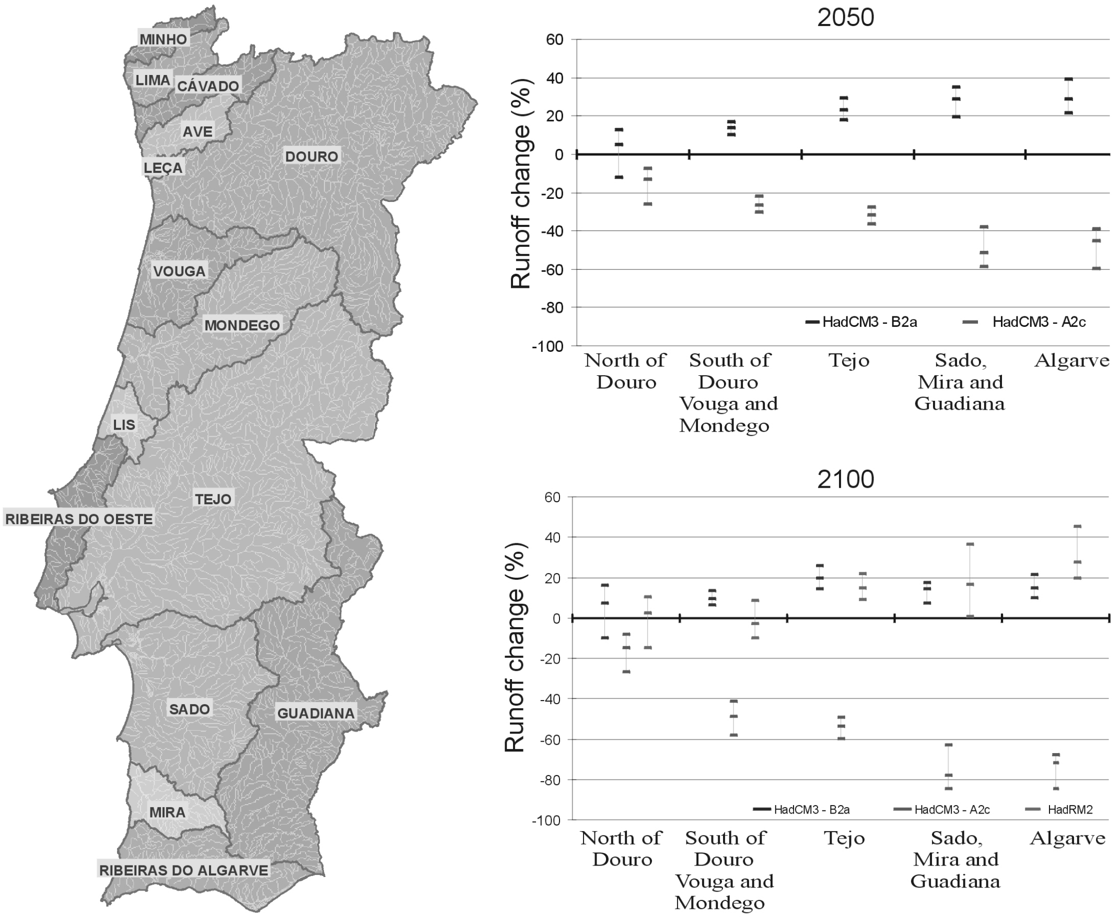

Fig. 2 Annual runoff changes predicted by HadCM3 and HadRM2.

The winter runoff projections for 2050 and 2100 vary widely depending on the different models and emissions scenarios, but there is consistent indication of a runoff reduction in the spring, summer and autumn. By 2100, the spring runoff is expected to decrease by 0 to 80%, while summer and autumn runoff may decrease by 20 to 80%.

If this trend towards an increase of spatial and seasonal asymmetry of water availability is confirmed, the challenge for water managers in Portugal to meet water needs will become increasingly more difficult.

The existence of large river basins shared by both Portugal and Spain implies that the Spanish climate also affects the Portuguese hydrological regime. Model results show that temperature and precipitation changes are expected to be similar on both sides of the border. The likely decrease of precipitation will lead to a reduction of the runoff generated to both sides of the border, which will accentuate even further the expected decrease of water availability in the Portuguese part of the transboundary river basins.

In conclusion, a general decrease in water availability, an increase of seasonal and spatial asymmetries, an increase of flood risk and an increase of water quality problems should be expected. The decreased runoff in the Spanish part of the transboundary river basins is likely to accentuate even further the expected decrease of water availability in the Portuguese territory. The impacts of climate change on sea level may also affect groundwater levels and groundwater quality, thus influencing water resources availability.

HOW SHOULD CLIMATE CHANGE INFLUENCE WATER RESOURCES MANAGEMENT IN THE FUTURE?

Water managers have not yet fully perceived what is changing and do not assume the need to take climate change into account for long-term planning and managing of complex water systems. However, some professional water organizations have already recognized the new reality and have made recommendations to water planners and managers to take climate change into full consideration in their professional work.

The American Water Works Association, for example, has stated that water agencies "should explore the vulnerability of both structural and non-structural water systems to plausible future climate changes and not just to climatic variability" and also that Governments "should re-evaluate legal, technical and economic approaches for managing water resources in light of possible climate changes" (AWWA, 1997).

A major challenge facing water managers is to evaluate how changes in water systems' reliability, resulting from climate changes, may differ from those resulting from natural variability. This new form of evaluation should be taken into consideration, in particular when dealing with the design and implementation of water supply infrastructures.

Some studies have shown that relatively small changes in the inflow to reservoirs may cause large changes in the reliability of water yields from these reservoirs. Changes in the operating rules might improve the ability of the systems to meet delivery requirements.

Changes in precipitation amount or pattern will also have a direct impact on hydropower generation and, again, operation rules may need to be changed.

The net impact of climate change on agriculture will depend on many factors whose relative influence varies for different regions and for different crops, but in general it can be stated that relatively small changes in water availability could have large impacts in the agricultural sector.

In order to succeed in modifying the behaviour of the water managers of the future, the scientists working in the area of climate and water have already, in some cases, produced recommendations addressed to water managers for adaptation to the impacts of climate change on water resources. They have also suggested "win-win" or "no-regrets" strategies, which are strategies with net social benefits which are independent of the scope and severity of anthropogenic climate change. Three good examples of such sets of recommendations are those prepared in the United States by Waggoner (1990), AWWA (1997) and Gleick *et al*. (2000).

It is clear that the impacts of climate change must be considered with an increased attention on water resources management strategies and policies. The argument that the impacts of climate change are not yet fully known and that a number of uncertainties still exist should not be a reason to postpone action. The results of different studies have already identified some trends with a high probability of occurrence, which should be considered in future water management strategies and policies.

Furthermore, it must be realized that a sound water management policy has always required, in the past, a capacity for decision under uncertainty. Policy makers and water managers currently forecast the hydrological regime and the water resource systems demands for future situations and act upon these forecasts. They try to plan in advance the response to future scenarios, usually selecting flexible and adaptable policies to enable quick reactions to specific situations.

From this perspective, taking climate change into consideration does not require any drastic change to the approach currently adopted by water managers, as it only constitutes an additional source of uncertainty that will condition future values of both water supply and demand. The main conceptual change is the rejection of the traditional engineering assumption that considers the historical climate as a reliable indicator of future conditions. In fact, water management agents must start considering climate change as a source of uncertainty.

The results presented in the Portuguese case study briefly presented here, also show that the task of managing Portuguese water resources is likely to become increasingly more challenging. The potential decrease of water availability and the increase of the hydrological seasonal asymmetries, associated with more stressing conditions related to water quality and flood risk, underline how important it is to have water management policies based on a sound and in-depth knowledge of Portuguese water resources, as modified by climate change. This emphasizes the need for further studies of impacts of climate change on Portuguese water resources in order to make the consideration of climate change information in water management practices possible.

The predicted decrease of river flow in southern Portugal, if confirmed, may have dramatic consequences, and therefore, be a cause of significant concern. Thus, it does not seem wise to ignore the impacts of climate change in Portuguese water resources planning and management.

Climate change will influence not only the average values of runoff, but will also condition its extreme values, affecting the flood and drought regimes. In particular the timing of the occurrence of floods and droughts and their magnitude and duration are likely to be modified.

In the Portuguese study referred to above, the impacts of climate change on floods and droughts have not been studied in detail. But the results of the study show a general tendency for a future increase (relative to present) of precipitation during the wet season and for a decrease during the dry season, in particular in the north of Portugal. The runoff regime should normally follow this general tendency, thus a future intensification of both floods and droughts as a consequence of climate change is expected.

This strengthening of floods and droughts risk as a consequence of climate change is in agreement with the results of several studies conducted elsewhere (see, for instance, IPCC, 2001). In addition, it should be expected that river flooding in coastal regions will be intensified by the rise of sea level associated with climate change.

Another aspect deserving particular attention within the climate change research to be developed in the future in Portugal is water quality. In fact climate change may have direct and indirect impacts on water quality.

The indirect impacts of climate change may result of an increase or a decrease in runoff. The increase in runoff may cause an increase in pollution due to different reasons, such as erosion and transport of sediments, pollution by fertilizers and pesticides used in agriculture, or urban and industrial pollution. A decrease in runoff may also have indirect consequences on water quality, which are related to changes in the pollution assimilation capacity of water bodies.

Moreover the possible increase of water temperature as a consequence of climate change will also have direct impacts on water quality, causing a decrease in the levels of dissolved oxygen in water and interfering with the chemical and biological processes occurring in water bodies, with consequences, for instance, for eutrophication processes and the ecosystem's health.

The impacts of climate change on water demand should also be the object of due consideration. In reality, the changes in temperature associated with climate change will not only condition the supply of water, but may also have impacts on the water demand, which will normally increase as temperature increases.

These impacts may be particularly relevant in the case of agricultural water use, as the water needs for crop production increase as a consequence of the intensification of evapotranspiration or of the reduction of soil moisture caused by climate change. The selection of different crops, more adaptable to the new climate conditions, may also significantly affect water use.

The impacts on water demand for industrial uses may also be significant in certain conditions, as for instance in the case of water cooling systems. Similarly the water demand for domestic and municipal water uses, such as those related to water drinking, bathing, street washing and irrigation of parks and gardens may also increase when the temperature increases. Finally an increase in temperature may also imply an increase in the amount of water required by aquatic ecosystems.

It should be noted, however, that in certain cases a tendency for a reduction of water demand with increased temperatures may also occur. For instance in situations of drought there is often a reduction in water demand resulting from the adoption of more rational strategies for water management, including the development of technologies aiming at more efficient use of water.

The Portuguese case study presented previously has shown a reasonable agreement in the predictions of the impacts of climate change on temperature and precipitation in neighbouring regions of Portugal and Spain. However, the studies on the impacts of climate change on water resources which have been conducted in Spain appear to be less refined than those carried out in Portugal. The Spanish studies include the brief analysis presented in the Spanish Hydrological Plan and in the Spanish White Paper on Water (MMA, 1998, 2000) and the more consistent work developed by Ayala-Carcedo (1996, 2000), Ayala-Carcedo & Iglésias-Lopez (2000) and, also, by Fernandez-Carrasco (2000, 2002). The latter studies follow a similar approach to the work carried out in Portugal (Cunha *et al*., 2002) but were not sufficiently developed to allow an extrapolation of the results to the whole Spanish territory, as is the case with the Portuguese study.

This seems a strong recommendation for, in future, making joint studies in Portugal and Spain on the impacts of climate change on Iberian water resources. The Iberian Peninsula is a clearly defined physiographic unit and it would be most sensible to have the two countries working together, applying common methodologies, in particular to the shared hydrographic basins. The shared Iberian river basins are natural laboratories where the scientists of the two countries should unite their efforts and work together. These joint studies would cover the scientific and technical problems of the shared water resources in general and, in particular, study the impacts of climate change on water resources. This issue should be considered with reference to the framework of bilateral scientific and technological cooperation between the two countries.

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