GLOBAL WARMING AND VARIABILITY ON IRRIGATION REQUIREMENTS IN THE MEDITERRANEAN ENVIRONMENT

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SUMMARY

It is nowadays widely accepted that the increasing concentration of the so-called greenhouse gases in the atmosphere is altering the Earth's radiation balance and causing the temperature to rise. This process in turn provides the context for a chain of events which leads to changes in the different components of the hydrological cycle, such as evapotranspiration rate, intensity and frequency of precipitation, river flows, soil moisture and groundwater recharge. All these problems will become more pronounced in the years to come, as society enters an era of increasingly complex paths towards the global economy. In this context, European and global environments are closely linked by global processes such as climate patterns, hydrological conditions and socio-economic factors transcending regional boundaries. Consequently, achieving sustainable development in Europe will depend on the above factors and on the basic policies adopted by our society in the decades to come.
Within the Mediterranean environment, water availability and irrigation development already pose a growing problem under today's climatic conditions and anatrophic pressure and will pose even more challenges under the expected future climatic trends. The present Mediterranean climate is characterised by hot dry summers and mild wet winters. The region frequently suffers from years of scant rainfall and many areas are afflicted by severe drought.
Concerning irrigated agriculture, most of the current 16 million hectares of irrigated land were developed on a step by step basis over the centuries. Many structures of these systems have aged or are deteriorating. They are, moreover, under various pressures to keep pace with changing needs, demands and social and economic development. Therefore the infrastructure in most irrigated areas needs to be rehabilitated, renewed or even replaced and consequently redesigned and rebuilt, in order to meet the goal of improved sustainable production. This process depends on a set of common and well-coordinated factors, such as new advanced technology, environmental protection, institutional strengthening, economic and financial assessment, research thrust and human resources development. In relation to these issues and based on available information, this report gives an overview of current and future (time horizon 2050) irrigation development in the Mediterranean environment. Moreover, the paper analyses the results of the most recent and advanced General Circulation Models for assessing the hydrological impacts of climate change on crop water requirements, water availability and the planning and design process of irrigation systems. Finally, a five-step planning and design procedure is proposed that is able to integrate, within the development process, the hydrological consequences of climate change.

Key words
Global warming, water resources, crop water requirements, irrigation systems

INTRODUCTION

Global climate change has become an important area of investigation in natural sciences and engineering, and irrigation has often been cited as an area in which climate change may be particularly important for decision- making. According to the Intergovernmental Panel on Climate Change, IPCC (1996), climate change would affect precipitation patterns, evapotranspiration rates, soil moisture and infiltration rates, the timing and magnitude of runoff and the frequency and intensity of storms. Subsequently, changes in evapotranspiration rates can, substantially, alter rainfall-runoff processes, adding uncertainty to the understanding of important links between the hydrological cycle and ecosystems behaviour. The level of atmospheric carbon dioxide (CO_2) may, also, affect both water availability and demand, through its influence on vegetation.

Although climate change is expected to have a significant impact on water availability and irrigation requirements, the extend and effect, at the geographic scales of interest, on the water resources planning and management process, remains largely unknown. Though a major effort has been devoted to analyzing the potential impacts of global climate change on water resource systems, by contrast, relatively little has been done to review the adequacy of existing water planning and evaluation criteria in the light of these potential changes.

In this context, the lack of consistent understanding and application of basic evaluation principles in the agricultural sector has, so far, hindered the prospects for devising an integrated assessment to account for the linkages between climate change and irrigation development. The challenge today is to identify not what is the best irrigation development over the next four of five decades, but rather, what is the best development for the next few years, knowing that a prudent hedging strategy will allow time to learn and change course.

All these problems will become more pronounced in the years to come, as society enters an era of increasingly complex paths towards the global economy. In this context, European and global environments are closely linked by global processes such as climate patterns, hydrological conditions and socio-economic factors transcending regional boundaries. Consequently, achieving sustainable irrigation development in Europe will depend on the above factors and on the basic policies adopted by our society in the decades to come.

Within a Mediterranean context, the focus of the current report, water availability and irrigation development already pose a growing problem under today’s climatic conditions and anthropogenic pressure and will pose even more challenges under the expected future climatic trends.

CLIMATE AND CLIMATIC CHANGE

Present-day Climate

In very general terms, Europe’s climate regime can be divided into two types: those dominated by rainfall and those dominated by snowmelt. Rainfall-dominated regimes, with maxima in winter and minima in late summer, are found in the west and south, whereas snow-dominated regimes, with maxima in spring and minima in summer or winter, are found in the north and east. There are differences between the rainfall-dominated regimes of western Europe, which are controlled by the passage of Atlantic depressions, and those of southern and Mediterranean Europe. These latter regimes are characterized by winter rainfall that is at least three times the amount that falls during the summer. Indeed, over much of the Mediterranean summer rainfall is virtually zero. This strong summer-winter rainfall contrast is echoed by a pronounced seasonal cycle in almost all climate variables. Rainfall varies from about 1000 mm in the far northerly areas and in those above 800 m, to 250 mm in the southern dry lands where the sequence of wet and dry years is also a characteristic feature of the region. Generally speaking, rainfall has decreased overall since the end of the 19th century, and this can be related to changes in atmospheric pressure and sea surface temperatures. Climate behaviour may vary greatly over short distances in the Mediterranean, due to the nature of the landscape and the influence of the sea in coastal areas.

Climate Change Scenarios

Current scientific research is focused on the enhanced greenhouse effect as the most likely cause of climate change in the short-term.
Until recently, forecasts of anthropogenic climate change have been unreliable, so that scenarios of future climatic conditions have been developed to provide quantitative assessments of the hydrologic consequences in some regions and/or river basins. These scenarios can be classified into three groups:

- hypothetical scenarios;
- climate scenarios based on General Circulation Models (GCMs);
- scenarios based on reconstruction of warm periods in the past (paleoclimatic reconstruction).

The scenarios of the second group have been widely utilized to reconstruct seasonal conditions of the change in temperature, precipitation and potential evapotraspiration at basin scale over the present and next centuries (IPCC, 1999). GCMs, representing physical processes in the atmosphere, ocean, cryosphere and land surface ,are the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. They are coupled atmosphere-ocean models (AOGCMs) which link, dynamically, detailed models of the ocean with those of the atmosphere and are able to simulate the time lags between a given change in atmospheric composition and the responses of climate.

The Hadley Centre's General Circulation Model

The UK Hadley Centre's GCM has been used to examine climatic changes over the Mediterranean Basin due to enhanced greenhouse effect (Viner and Hulme, 1997). The Hadley Centre has often led the field in the development of GCMs. To date results from version two (Had-CM2) of the AOGCM have been extensively used to assess the impacts of greenhouse gas forcing over the region (De Wrachien et al., 2002a; 2002b). Version three (Had- CM3) accounts for both CO_2 and aerosols impacts. The model comprises 19 layers into the atmosphere with a horizontal resolution of 2.5° x 3.75 degrees . The model represents the radiative effects of minor greenhouse gases as well as CO_2, water vapour and ozone, and also includes a simple parameterization of background aerosol. A land surface scheme includes a representation of the freezing and melting of soil moisture, and evaporation takes account of the dependence of stomata resistance on temperature, vapour pressure and CO_2 concentration. The ocean component of Had CM3 has 20 levels with a horizontal resolution of 1.25° x 1.25°. Moreover, the new version has a much improved sea-surface temperature and sea-ice climatology compared to earlier generations of the model.
Both versions two and three of the Hadley Centre GCM have been run on a monthly basis for the Mediterranean countries to predict changes in rainfall and temperatures (Ragab and Prudhonmne 2002). Both the IS92a and IS95a forcing patterns were used. All the scenarios analyzed are for the time horizon 2050. They are expressed as percentage change (rainfall) or temperature change (in °C.) compared to the average values of the baseline period 1961-'90. The results show that by the year 2050 for the wet season (October-March), rainfall could increase in central and eastern Spain, southern France, northern Italy and the Alps by up to 15% ,while in the southern Mediterranean rainfall will decrease by about 10% to 15%. For the same period, the

temperature in the northern Mediterranean will increase by 1.25° to 2.25°C against an increase of between 1.5° and 2.5°C in the southern Mediterranean. Temperature in coastal areas will usually increase to a lesser extent than in inland regions. Results also show that for the dry season (April to September), by the year 2050 rainfall is likely to decrease over much of the Mediterranean especially in the southern parts where it could diminish by up to 25%. Decreased precipitation is predicted to be accompanied by a rise in temperature of between 1.5° and 2.75°C in the northern regions and 1.75° and 3.0°C in the southern Mediterranean, again coastal areas being affected to a lesser extent than regions inland. Reduced precipitation during the summer has a major impact on irrigation and tourism which both increase the pressure on water supplies during the dry period.

ENVIRONMENTAL AND ECOLOGICAL IMPACTS OF CLIMATE CHANGE

Ecosystems are likely to be the most vulnerable to climate changes because the natural response time is slow and adaptation mechanisms are limited. The assessment of the vulnerability of these systems is complicated by the reality that population growth and economic development contribute to their degradation in complex ways.

Changes in vegetative cover and evapotranspiration rates can also substantially alter rainfall-runoff processes, adding uncertainty to understanding important links between the hydrological cycle and ecosystems. The level of atmospheric CO_2 may affect water availability through its influence on vegetation. Controlled experiments indicate that increased concentrations of CO_2 increase the resistance of plant stomata to water vapour transport, resulting in deceased transpiration per unit of leaf area. CO_2 has also been shown to increase plant growth, leading to a larger area of transpiring tissue and a corresponding increase in transpiration. The net effect on water supplies is uncertain but would depend on factors such as vegetation, soil types and the climate.

While much is known in general about the potentially large ecological impacts of climate change, our inability to forecast these impacts more exactly contributes to the uncertainties confronting land and water planners. Added to this, it should be noted that our ability to model hydrological and biological baseline decades into the future is even more limited. Linking GCMs to hydrological and biological models as part of an integrated assessment of the impacts of climate change on environmental and ecological resources remains, nowadays, a formidable challenge.

Climate Change and Water Resources

The issue of water resources represents an important element in assessing the hydrological impact of global warming. Global warming could result in changes in water availability and demand, as well as in the redistribution of water resources, in the structure and nature of water consumption, and exasperate conflicts among water users. These impacts may be positive or negative depending on the climate scenario adopted, the water management sector concerned and the environmental conditions (De Wrachien et al. 2003).

Recently, climate forecasts from state-of-the-art GCMs were used to assess the hydrological sensitivity to global warming of different river basins (Nijsses et al., 2001). The river basins were selected on the basis of the desire to represent all the geographic and climatic conditions of the world. Four models have been used:

- The Hadley Centre's GCMs (Had-CM2), UK (Johns et al., 1997);
- The Hadley Centre's GCMs (Had-CM3), UK (Gordon et al., 2002);
- The Max Plank Institute for Meteorology GCM (MPI- ECHAN4), Germany (Rockner et al., 1996);
- The Department of Energy's GCM (DOE-PCM3), USA (Washington et al, 2000).

Changes in basin-wide, mean annual temperature and precipitation were computed for three decades, cantered on 2025, 2045 and 2095, and hydrological model simulations were performed for decades cantered on 2025 and 2045.
The main conclusions, related to the Mediterranean environment are summarized below.

- The largest changes in the hydrological cycle are predicted for the snow-dominated basins of the Alpine Europe, as a result of the warming that is predicted for this region. The presence or absence of snow fundamentally changes the nature of the land surface water balance, because of the effect of water storage in the snow-pack. Water stored as snow during the winter does not become available for runoff or evapotranspiration until the subsequent spring melt period. Because of this cumulative process, the largest hydrological changes are manifested in the early to mid spring melt period. In general, the streamflow regime in snow melt dominated basins is most sensitive to increases in temperature during the winter months.
- The hydrological response predicted for most of the basins in response to the GCMs predictions is a reduction in annual streamflow in southern Europe. For example, an increase in mean annual air temperature by 1-2°C and a 10% decrease in precipitation could reduce annual runoff by 40-70%.

Climate Change and Irrigation Requirements

In the last decade, Global Irrigation Models (GIMs) have been developed that include parameterizations of physiological processes such as photosynthesis, respiration, transpiration and soil water in-take (Bergengren et al., 2001). These tools have been coupled with GCMs and applied to both paleoclimatic and future scenarios (Doherty et al., 2000). The use of physiological parameterizations allows these models to include the direct effects of changing CO_2 levels on primary productivity and competition, along with the crop water requirements. In the next step the estimated crop water demands could serve as input to agro-economic models which compute the irrigation water requirements (IR), defined as the amount of water that must be applied to the crop by irrigation in order to achieve optimal crop growth. Adams et al. (1990) and Allen et al. (1991) used crop growth models for wheat, maize, soybean and alfalfa at typical sites in the USA and the output of two GCMs to compute the change of IR under double CO_2 conditions.
On the global scale, scenarios of future irrigation water use have been developed by Seckler et al. (1997) and Alcamo et al. (2000). Alcamo et al. employed the raster-based GIM of Döll and Siebert (2001), with a spatial resolution of 0.5^0 by 0.5^0. This model represents one of the most advanced tools today available for exploring the impact of climate change on IR at worldwide level.
More recently, the GIM has been applied to explore the impact of climate change on the irrigation water requirements of those areas of the globe equipped for irrigation in 1995 (Döll, 2002). Estimates of long-term average climate change have been taken from two different GCMs:

- ♦ the Max Planck Institute for Meteorology GCM (MPI-ECHAM4), Germany
- ♦ the Hadley Centre's GCM (Had-CM3), UK

The following climatic conditions have been computed:

- ♦ present-day long-term average climatic conditions, i.e. the climate normal 1961-1990 (baseline climate);
- ♦ future long-term average climatic conditions of the 2020s and 2070s (climatic change).

For the above climatic conditions, the GIM computed both the net and gross irrigation water requirements in all 0.5^0 by 0.5^0 raster cells with irrigated areas. "Gross irrigation requirement" is the total amount of water that must be applied such that

evapotraspiration may occur at the potential rate and optimum crop productivity may be achieved. Only part of the irrigated water is actually used by the plant and evapotranspirated. This amount, i.e. the difference between the potential evapotranspiration and the evapotranspiration that would occur without irrigation, represents the “net irrigation requirement”, IRnet.
The results show that irrigation requirements increase in most irrigated areas in the north of the Mediterranean Basin, which is mainly due to the decreased precipitation during the summer. In the south, the pattern becomes complex. For most of the irrigated areas of the arid northern part of Africa and the Middle East, IRnet diminishes. In Egypt, a decrease of about 50% in the southern part is accompanied by an increase of more than 30% in the central part. The decrease in IRnet depends on the fact that the cropping patterns and growing seasons of an irrigated area are strongly influenced by temperature and precipitation conditions (Doll, 2002). In GIM, temperature determines which areas are best suited for multicroppings and the growing seasons are identified based on optimal temperature and precipitation conditions. In Egypt, for example, modeling of the cropping patterns results, for the baseline climate, in two crops per year in the southern part and only one crop per year in the central part, and vice versa for the 2020s.

Climate Change and Irrigation Systems

Uncertainties as to how the climate will change and how irrigation systems will have to adapt to these changes, are challenges that planners and designers will have to cope with. In view of these uncertainties, planners and designers need guidance as to when the prospect of climate change should be embodied and factored into the planning and design process (De Wrachien, 2003). Frederick et al. (1997) proposed a five-step planning and design process for water resource systems, for coping with uncertain climate and hydrologic events, and potentially suitable for the development of large irrigation schemes.
If climate change is recognized as a major planning issue (first step), the second step in the process would consist of predicting the impacts of climate change on the region’s irrigated area. The third step involves the formulation of alternative plans, consisting of a system of structural and/or non-structural measures and hedging strategies, that address, among other concerns, the projected consequences of climate change. Non-structural measures that might be considered include modification of management practices, regulatory and pricing policies. Evaluation of the alternatives, in the fourth step, would be based on the most likely conditions expected to exist in the future with and without the plan. The final step in the process involves comparing the alternatives and selecting a recommended development plan.

CONCLUDING REMARKS

- Agriculture is a human activity that is intimately associated with climate. It is well known that the broad patterns of agricultural growth over long time scales can be explained by a combination of climatic, ecological and economics factors Modern agriculture has progressed by weakling the downside risk of these factor through irrigation, the use of pesticides and fertilizers, the substitution of human labor with energy intensive devise, and the manipulation of genetic resources. A major concern in the understanding of the impacts of climate change is the extent to which agriculture will be affected. The issue is particularly important for the Mediterranean countries, where water availability and sustainable irrigation development pose a growing problem under today’s climatic conditions and entropic pressure. Thus, in the medium and long terms, climate change is an additional challenge that agriculture has to face in meeting national food requirements.

- Climate change has many effects on the hydrological cycle and thus, on water resources systems. Global warming could result in changes in water availability and demand, as well as in the redistribution of water resources, in the structure and nature of water consumption, and exasperate conflicts among water users. Scenarios based on GCMs forecasts do not provide sufficiently reliable information for the assessment of the hydrological consequence of climate change at the scale of the Mediterranean region. Nevertheless, it is reasonable to assume that the largest changes in the hydrological cycle are expected for the snow dominated basins of the Alpine Europe, while annual streamflow is likely to decrease over the river basins in the southern part of the region.
- Impact of global warming on crop water requirements plays a role of paramount importance in assessing irrigation needs. In the last decade, global vegetation models have been developed that include parameterization of physiological processes such as photosynthesis, respiration, transpiration and soil water in take. These tools have been coupled with GCMs and applied to explore future scenarios at both regional and world-wide levels. In the context of the Mediterranean environment the models outcomes show that irrigation requirements are likely to increase in most irrigated areas in the north of the basin, while in the south the patter becomes complex.
- Concerning irrigated agriculture, most of the current 16 million ha of irrigated land, in the Mediterranean, were developed on a step by step basis over the centuries, and were designed for a long life (50 years or more), on the assumption that the climatic conditions would not change. This will not be so in the future, due to global warming and the greenhouse effect. Therefore, engineers and decision-makes need to systematically review planning principles, design criteria, operating rules, contingency plans and water management policies
- Uncertainties as to how the climate will change and how irrigation systems will have to adapt to these changes are issues that water authorities are compelled to address. The challenge is to identify short-term strategies to cope with long-term uncertainties. The question is not what is the best course for a project over the next fifty years or more, but rather, what is the best direction for the next few years, knowing that a prudent hedging strategy will allow time to learn and change course.
- The planning and design process needs to be sufficiently flexible to incorporate consideration of and responses to many possible climate impacts. The main factors that will influence the worth of incorporating climate change into the process are the level of planning, the reliability of the forecasting models, the hydrological conditions and the time horizon of the plan or the life of the project
- The development of a comprehensive approach that integrates all these factors into irrigation project selection, requires further research on the processes governing climate changes, the impacts of increased atmospheric carbon dioxide on vegetation and runoff, the effect of climate variables on crop water requirements and the impacts of climate on infrastructure performance.

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