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GLOBAL WARMING WATER SCARCITY AND FOOD SECURITY 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. Mankind is expected to respond to these effects by taking adaptive measures including changing patterns of land use, adopting new strategies for soil and water management and looking for non-conventional water resources (e.g. saline/brackish waters, desalinated water, and treated wastewater). 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 anthrophic 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 affected by severe drought. Concerning irrigated agriculture, most of the current 16 million hectares of irrigated land were developed over the centuries on a step by step basis. 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. Most of these factors are well-known and linked to uncertainties associated with climate change, world prices and international trade. These uncertainties require continued attention and suitable action on many fronts, in order to promote productivity and facilitate flexibility in agricultural systems. Therefore, water system engineers and managers should begin to systematically review existing design criteria, operating rules, contingency plans and water allocation polices. To this end, strategies need to be developed that ensure maximum productivity per unit of water and land, while reducing the use of fertilizers and pesticides to improve efficiency in order to preserve the environment. 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.

Keywords: global warming; agricultural development; irrigation systems; food security

1. 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 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 short-term uncertainty. The question is not what is the best irrigation development over the next four or 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 anthropic pressure and will pose even more challenges under the expected future climatic change.

2. AGRICULTURE AND ENVIRONMENT: DEVELOPMENT AND SUSTAINABILITY

2.1. The concept of sustainability

To meet the future challenges posed by food security, further agricultural development is necessary in order to guarantee increased agricultural output while conserving the natural resources. Natural resources conservation is of paramount importance as these are the very resources on which agriculture depends. This means that the natural environment should be managed in such a way to assure food security for the present and future generations. So, food security is not only a matter of quantity but also of continuity. Thus agriculture must strike the appropriate balance between development and conservation. In this context the responsible use of natural resources plays a primary role. Among the basic natural resources upon which life depends are soil and water.

The responsible use of the soil and water can be described in terms of sustainability or sustainable development. Sustainability has been defined in many different ways and there is no single, universally accepted definition. According to the Brundtland Commission "sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional changes are all in harmony and enhance both current and future potential, to meet human needs and aspirations". (WCED, 1987).

FAO has formulated its own definition of sustainability, specifically in the context of agriculture, forestry and fisheries "sustainable development is the management and conservation of the natural resource base and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for the present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, is environmentally non – degrading, technically appropriate, economically viable and socially acceptable" (FAO, 1993).

Scarcity of suitable soil and water resources places major constraints on further agricultural development in many countries throughout the world including the Mediterranean region. Therefore, as the demand for land and water continues to rise, it is imperative that these limited resources be used efficiently for agricultural and other purposes.

2.2. Agriculture and land use

The term "land use" is more comprehensive than the term "soil use". Land, commonly, stands for a section of the earth's surface, with all the physical, chemical and biological features that influence the use of the resource. It refers to soil, spatial variability of landscape, climate, hydrology, vegetation and fauna, and also includes improvements in land management, such as drainage schemes, terraces and other agrobiological and mechanical measures. The term "land use" encompasses not only land use for agricultural and forestry purposes, but also land use for settlements, industrial sites, roads and so on (De Wrachien *et al.*, 2002).

Land use and distribution of agricultural land in the Mediterranean basin are illustrated in Figure 1. As shown in Table 1, there are major differences in land use patterns from one country to another and between north and south of the Mediterranean.

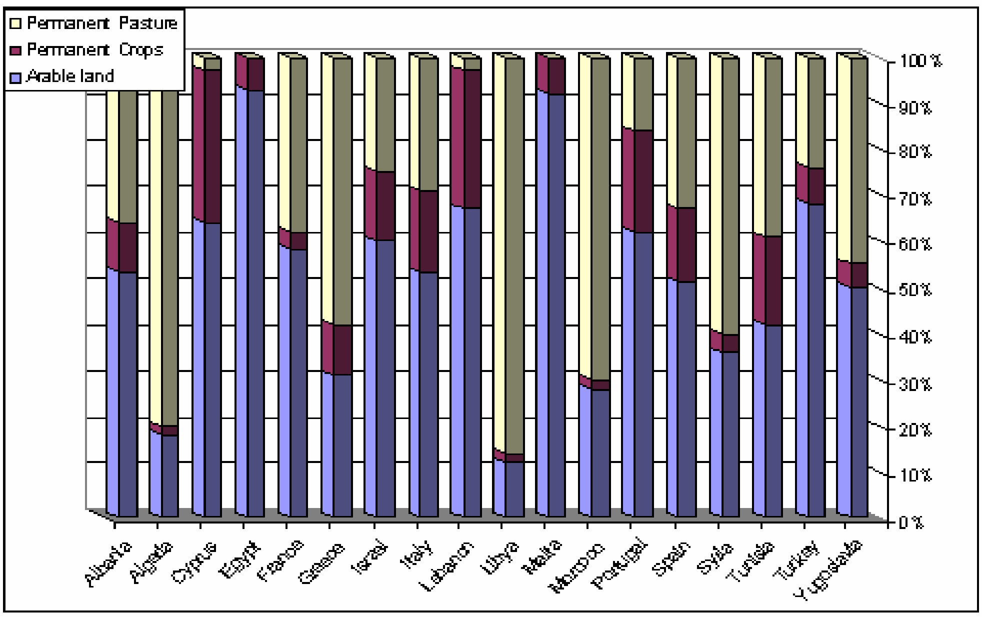

Figure 1. Distribution of agricultural land in the Mediterranean countries (After FAO, 1993)

Table 1. Land use as percentage of cultivated area in the Mediterranean. (After Hamdy and Lacirignola, 1997)

Region	Annual crops %	Permanent crops %	Permanent pastures %
North	57.55	10.90	30.89
South	38.60	6.40	55.0
East	56.50	20.50	22.75
Average	50.88	12.60	36.22

2.3. Land degradation and desertification

Because of the current climate patterns and intensification of human activities Mediterranean countries are already faced with a real threat of land degradation and desertification and there is no doubt that the present enhanced greenhouse effect will only exacerbate this threat in the short term. The main causes of these processes can be summarized as follows (Chisci, 1993):

- change of agricultural systems towards specialized – mechanized hill farming;
- modification of morpho – structural and infrastructural features of the cultural landscape concerned;
- abandoned, previously cultivated fields and/or farms and their man-made structural and infrastructural elements;
- increase in forest and pasture fires.

Until the early seventies, the problem of land degradation due to erosion was considered of minor importance for most of the countries of the Mediterranean region (Chisci and Morgan, 1986), where traditional agricultural systems had proven effective in keeping those processes under control. Consequently, low priority was given to research programs and projects on soil erosion and conservation while higher priority being assigned, among others, to the impact of farm machinery on soil structure and the role of organic matter in the soil.

In the eighties and early nineties, global warming and the impact of the agricultural systems introduced in the sloping lands of the Mediterranean environment in the previous decades were identified as the main culprits of soil erosion and land degradation. Accelerated runoff and erosion, previously unreported, began to be observed in cultivated sloping areas. The unprecedented pressure to increase crop productivity at lower costs, made possible by the technological revolution in agricultural management, had led to soil erosion in the agricultural ecosystem, due to hydrological impact, resulting in severe deterioration in soil fertility and degradation of the landscape.

After having thoroughly examined the problem, the scientific community concluded that a more detailed evaluation of the situation in the different Mediterranean environments was needed. Furthermore, it was recognized that research activities were too fragmentary to be able to cope with the demand for sound soil conservation measures. Another recommendation that emerged was the use of pilot areas for a quantitative assessment of accelerated erosion and of the effects of new conservation measures in the water erosion prone areas of the Mediterranean. It was also suggested that projects be allowed more flexibility, so that programs could be modified during implementation, to benefit from experience gained and lessons learned.

2.4. Agricultural and water use

In the Mediterranean region nearly 70% of the available water resources are allocated to agriculture. (Hamdy and Lacirignola, 1997). In the arid and semi-arid countries of the region agricultural water use accounts for as much as 80% of the water consumed, decreasing to 50% of the total available resources in the Northern countries (Figure 2).

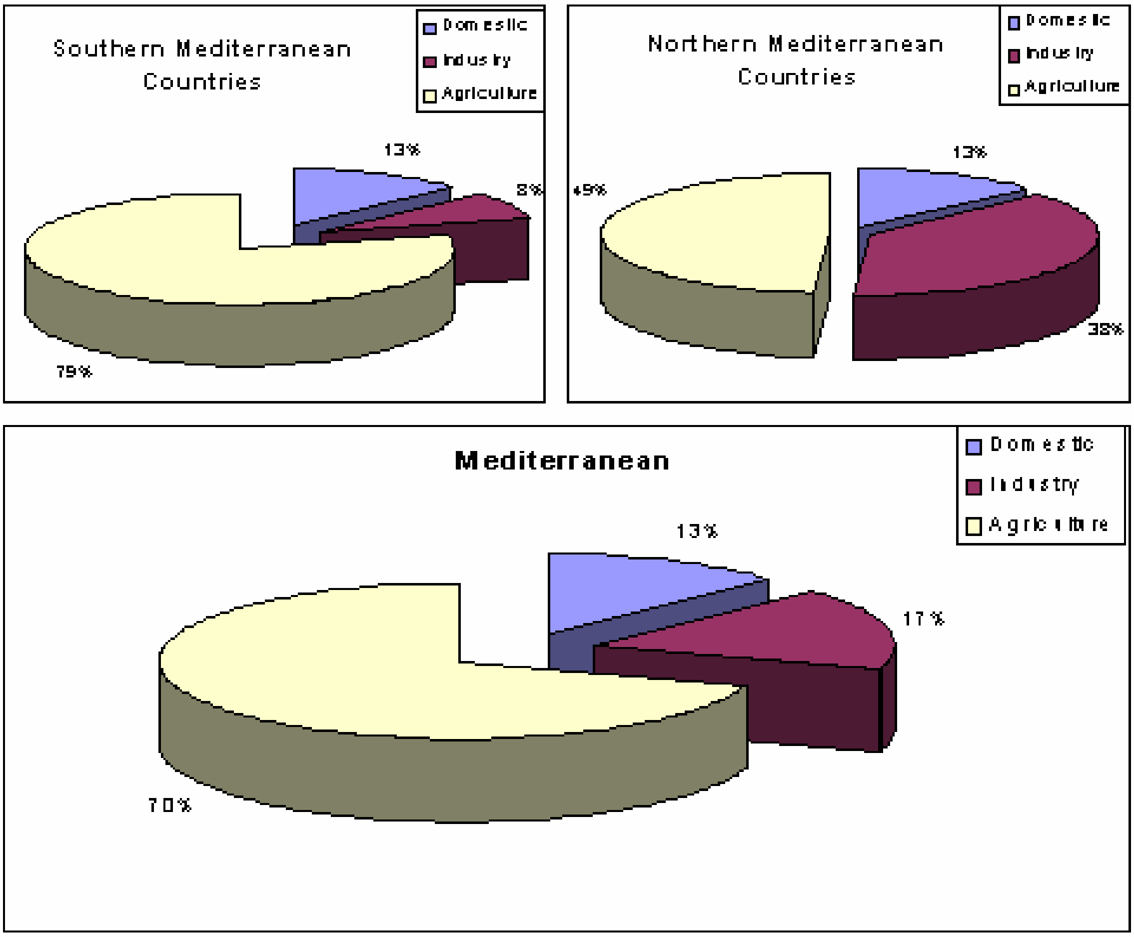

Figure 2. Water use per sector in the Mediterranean (Hamdy and Lacirignola, 1977)

Diminishing water resources in the eastern and southern Mediterranean are expected to be one of the main factors limiting agricultural development, particularly in the 2000 – 2025 period. The water needed for irrigation is even scarcer than the land itself and land suitable for irrigation is becoming harder to find. At present, the irrigated areas account for more than 16 million hectares.

Despite the high priority and massive resources invested, the performance of large public irrigation systems has fallen short of expectations in both the developing and developed countries of the Mediterranean. Crop yield and efficiency in water use are typically less than originally projected and less than reasonably achieved. In addition, the mismanaged irrigation project schemes lead to the deterioration of some of the best and most productive soils. Salinity now seriously affects productivity in the majority of the southern Mediterranean countries as well as in the coastal zones. Salt affected soils in the region amount to nearly 15% of the irrigated lands.

Given the increased costs of new irrigation developments, together with the scarcity of land and water resources, future emphasis will be more on making efficient use of water for irrigation and less on indiscriminate expansion of the irrigated area.

Over the next twenty five years, substantial amounts of fresh water supplies will be diverted from agriculture to industry and households in the region. Irrigated agriculture will face two challenges: water scarcity and dwindling financial resources. Despite these challenges, irrigated agriculture is expected to provide 70 to 75 percent of the additional food grain requirements to the developing countries of the region. This will not be possible without developing effective methodologies and systems for assessing and improving the performance of irrigated agriculture. Such systems have to evaluate the contribution and impact of an irrigation scheme in terms of production, self-reliance, employment, poverty alleviation, financial viability, farmers' profitability and environmental sustainability.

3. CLIMATE AND CLIMATIC CHANGE

3.1. The Greenhouse effect

Over the past centuries, the Earth's climate has been changing due to a number of natural processes, such as gradual variation in solar radiation, meteorite impacts and, more importantly, sudden volcanic eruptions in which solid matter, aerosols and gases are ejected into the atmosphere. Ecosystems have adapted continuously to these natural changes in climate, and flora and fauna have evolved in response to the gradual modifications to their physical surroundings, or have become extinct.

Humanbeings have also been affected by and have adapted to changes in local climate, which, in general terms, have occurred very slowly. Over the past century, however, human activities have begun to affect the global climate. These effects are due not only to population growth, but also to the introduction of technologies developed to improve the standard of living. Human-induced changes have taken place much more rapidly than natural changes. The scale of current climate forcing is unprecedented and can be attributed to greenhouse gas emissions, deforestation, urbanization, and changing land use and agricultural practices. The increase in greenhouse gas emissions into the atmosphere is responsible for the increased air temperature, and this, in turn, induces changes in the different components making up the hydrological cycle such as evapotranspiration rate, intensity and frequency of precipitation, river flows, soil moisture and groundwater recharge. Mankind will certainly respond to these changing conditions by taking adaptive measures such as changing patterns in land use. However, it is difficult to predict what adaptive measures will be chosen, and their socio-economic consequences (Dam, 1999).

In terms of global patterns the following considerations can be drawn from analysis of the hydrologic and meteorological time series available:

- Average global temperature rose by 0.6 °C during the 20th century.
- 1990's was the warmest decade and 1998 the warmest year since 1861.
- The extent of snow cover has decreased by 10% since the late 1960's.
- Average global sea level rose between 0.1 and 0.2 meters during the 20th century.
- Precipitation increased by 0.5 to 1% per decade in the 20th century over the mid and high latitudes of the northern hemisphere and by between 0.2 and 0.3% per decade over the tropics (10°N to 10°S).
- Precipitation decreased over much of the northern sub-tropical (10°N to 30°N) land areas during the 20th century by about 0.3% per decade.
- The frequency of heavy rain events increased by 2 to 4% in the mid and high latitudes of the northern hemisphere in the second half of the 20th century. This could be the result of changes in atmospheric moisture, thunderstorm activity, large-scale storm activity, etc.
- Over the 20th century land areas experiencing severe drought and wetness have increased.
- Some regions of Africa and Asia recorded an increase in the frequency and intensity of drought in the last decade.
- CO_2 concentration has increased by 31% since 1750.
- 75% of CO_2 emissions is produced by fossil fuel burning, the remaining 25% by land use change especially deforestation.
- Methane CH_4 has increased by 151% since 1750 and continues to increase. Fossil fuel burning, livestock, rice cultivation and landfills are responsible for emissions.
- Nitrous Oxide (N_2O) has increased by 17% since 1750 and continues to increase. This gas is produced by agriculture, soils, cattle feed lots and the chemical industry.
- Stratospheric Ozone (O_3) layer has been depleting since 1979.

3.2. 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.

3.3. 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. Scenarios are "internally-consistent pictures of a plausible future climate" (Wigley *et al.*, 1986). 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 plethora of literature on this topic has been recently summarized by the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1992).

The scenarios of the second group have been widely utilized to reconstruct seasonal conditions of the change in temperature, precipitation and potential evapotranspiration 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. They can also represent some of the important large scale transfer of heat and moisture attributable to ocean. GCMs depict the climate using a three dimensional grid over the globe, typically having a horizontal resolution of between 250 and 500km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. Until recently, the standard approach has been to run the model with a nominal "pre-industrial" atmospheric CO_2 concentration (the control run) and then to rerun the model with doubled (or sometimes quadrupled) CO_2 (the perturbed run).This approach is known as "the equilibrium response prediction". It is only in recent years that the effects of atmospheric aerosols (derived from fossil fuel combustion and biomass burning), in combination with greenhouse gas forcing, have been recognised and included in GCM experiments. However, current results are not sufficiently reliable yet.

3.4. 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; 2003). 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 (Figure 3). 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 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.

Figures 4 and 5 give the change in annual values of temperature and rainfall respectively, compared to the baseline period 1961-‘90, according to the HadCM3 model using IS95a forcing scenario. By examining present climate patterns and future trends over the region, Scientists have been able to investigate the relationship between global warming and drought and assess the impacts on water availability and irrigation requirements (Alcamo *et al.*, 2000; Döll, 2002).

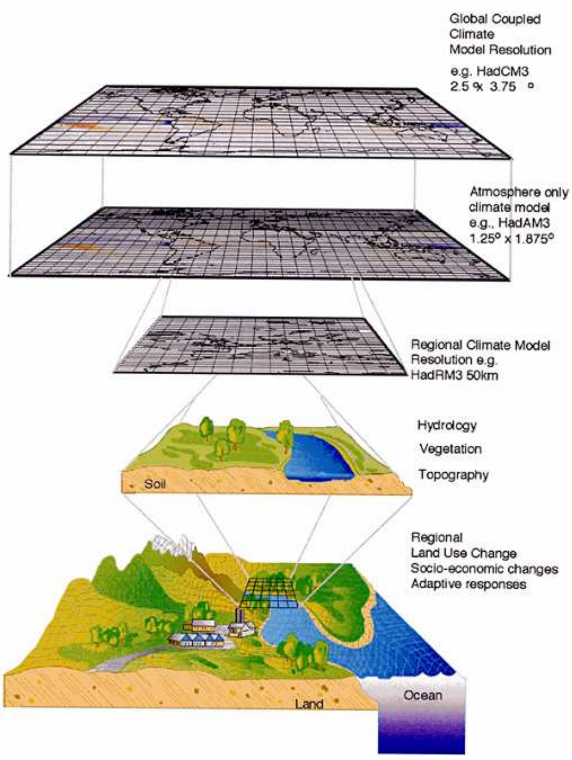

Figure 3. Conceptual structure of Had CM3 (Courtesy of the Hadley Centre, UK)

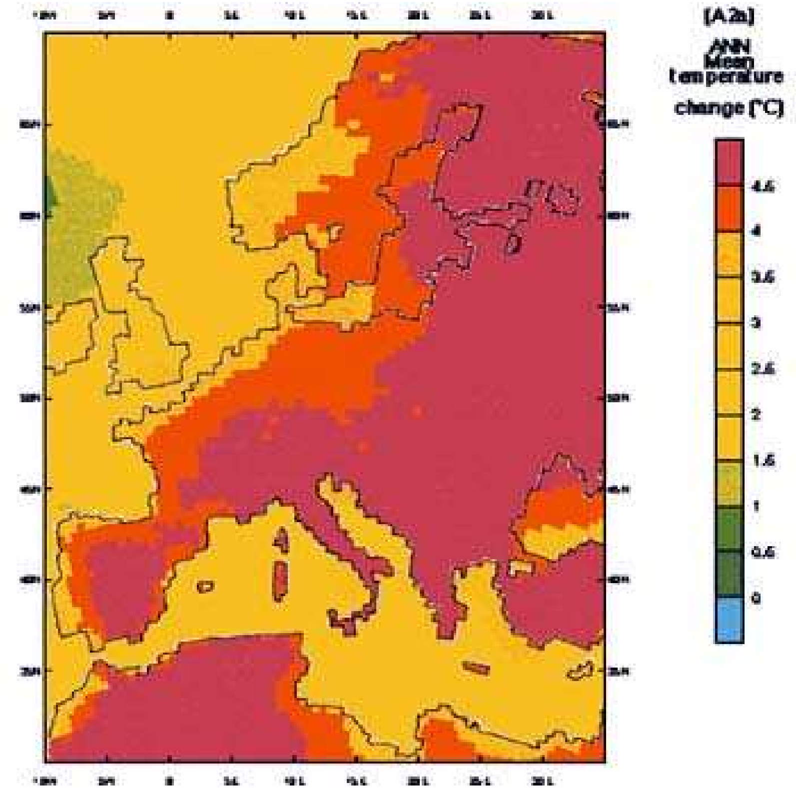

Figure 4. Changes in temperature (°C) for the year 2050, relative to the average annual values of the baseline period 1961-90, according to the Had CM3 model using IS95a forcing scenario. (Courtesy of the Hadley Centre, UK)

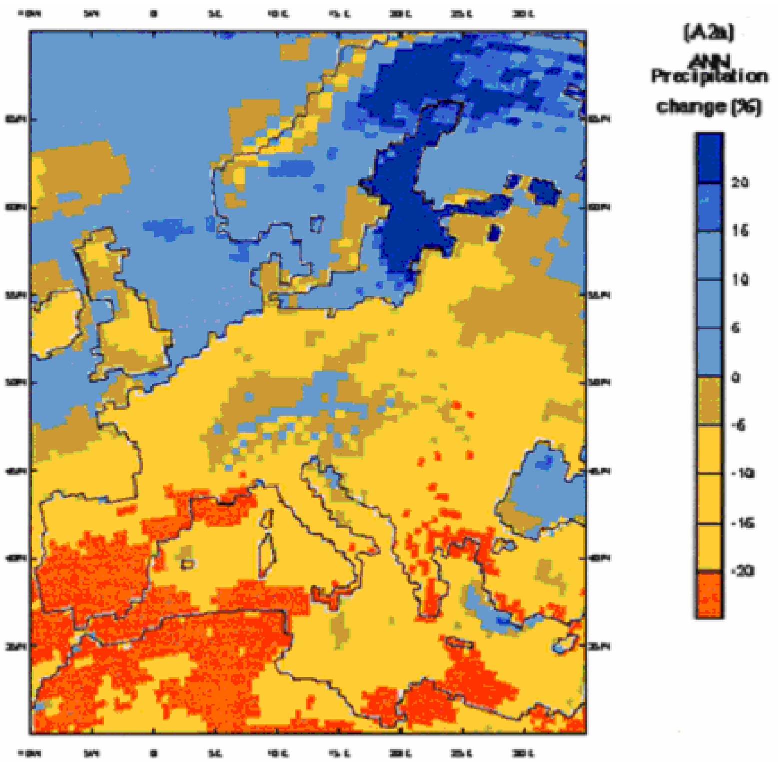

Figure 5. Changes in precipitation (%) for the year 2050, relative to the average annual values of the baseline period 1961-90, according to the Had CM3 model using IS95a forcing scenario. (Courtesy of the Hadley Centre, UK)

3.5. Drought

Drought is a complex phenomenon. It is important to define it clearly to avoid misunderstandings and different interpretations. In the first place, it is necessary to distinguish between dryness and drought. Though both terms describe the condition of serious water scarcity in a region, they are by no means synonymous: dryness has a much broader meaning, not specific to the different environmental components, while the term drought includes its effect on living organisms. Drought is generally viewed as a sustained, regionally extensive occurrence of below average natural water availability, either in the form of precipitation, river runoff or groundwater, while dryness applies to those persistently dry regions where, even in normal circumstances, water is in short supply. Drought adversely affects the economy by diminishing, or even destroying, agricultural production, livestock, energy generation, and domestic and industrial water supply. Drought conditions may vary significantly over time and space, depending on the spatial and temporal irregularity of rainfall distribution and on the heterogeneity of the hydrologic response of the river basins affected. The severity of drought generally depends on climatic and hydrologic regimes as well as on water use. Various Authors have attempted to formulate simple statements that can encapsulate the concept of drought. A straightforward definition of drought is a period during which streamflows are inadequate to supply established uses under a given management system (Dracup *et al*., 1980). The United States Weather Bureau defines drought as a lack of rainfall so great and long continued as to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and for the operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes" (Dracup *et al*., 1980). Kepinska *et al*., (1997) describe drought as a situation whereby water requirements for any use (especially agricultural) exceed that supplied by all possible natural resources of a given region. In agriculture drought is described in terms of reduced yields resulting from insufficient soil moisture as the permanent and acute water shortage of a given plant in a given agricultural and/or forest area, which reduces its life cycle (Vermes, 1998).

Drought can essentially be divided into three successive stages: atmospheric, soil and hydrologic drought, the latter comprising both ground- and surface water streamflow (Byczkowski *et al*., 2001). The first stage (atmospheric drought) is generally caused by prolonged lack of precipitation resulting from persistent high-pressure (anticyclone) circulation. A decrease in rainfall by as much as 80% of mean values in a specific region may lead to atmospheric drought. Lack of precipitation combined with high temperature and increased evaporation leads to the next stage: soil drought. Soil drought implies the depletion of soil moisture in the aeration zone. Fairly deep sandy soils and other soil types with a shallow cultivable top layer are more drought-prone than clayey and loamy soils with a relatively greater water holding capacity. The effects of soil drought are particularly detrimental when it occurs at critical stages of plant growth and development, for example during peak water requirements. It should be stressed, however, that the whole growing season can be regarded as critical, as the plants need to constantly take up readily available water into the active photosphere in order to ensure optimum or high yields. A further decrease in precipitation leads to the last stage, hydrologic drought. This stage is triggered by a period of groundwater low flow resulting in the depletion of groundwater storage in the saturated zone. This process is accompanied by a decrease in groundwater levels and reduced stream flow. Further lack of rainfall leads to the last stage of hydrologic drought, the so-called surface water low-flow period.

To assess the degree of severity of a given period of drought a qualitative appraisal is not sufficient as a quantitative parameter or index must also be determined to represent the intensity of the event. Several indices are used to describe the characteristics of drought and its detrimental effects on both the environment and living organisms (Beran *et al*., 1985; Vermes, 1998).

Whatever the cause, drought poses a major threat to social and economic life and leads to the degradation of natural resources. Not only does it reduce the production of crops (crop yield), the quality of grass and fodder, essential for maintaining animal production, but it also jeopardizes the constant supply of good quality water.

4. 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.

4.1. 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). There have been very few studies of changes in hydrological regimes and river flows in the Mediterranean countries due to the global warming, although considerably more work has been done on desertification problems (De Wrachien *et al*., 2002 a, b). Minikou and Kouvopolous (1991) studied the changes in runoff volumes in three basins in mountainous central Greece, using a monthly water balance model calibrated to each site and arbitrary change scenarios. Some of the results are shown in Table 2. Arnell (1999) analyzed the effect of climate change on hydrological regimes in Europe. This study attempted to place the regional hydrological consequences of climate predictions in a more global context.

Table 2. Percentage changes in annual and seasonal runoff, in Greece, with a 2°C increase in temperature (After Minikou and Kouvopoulos, 1991)

	Precipitation down 10%			Precipitation up 10%		
Catchment	Annual	Winter	Summer	Annual	Winter	Summer
Mesohora	-14	-19	-9	15	17	10
Sykia	-14	-18	-10	15	16	11
Pyli	-12	-13	-11	12	14	11

More recently, state-of-the-art GCMs climate forecast models 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).

All predicted transient climate response to changing greenhouse gas concentrations, and incorporated modern land surface parameterizations. Model-predicted monthly average precipitation and temperature changes were downscaled to the river basin level using model increments (transient minus control) to adjust for GCM bias. The transient emission scenarios differ slightly from one model to another, partly because they represent greenhouse gas chemistry differently. The different emission scenarios used are:

- 1% annual increase in equivalent $CO_2$and sulphate aerosol according to the IS92a scenario;
- equivalent $CO_2$and sulphate aerosol according to IS92a;
- several greenhouse gases (including CO_2) and sulphate aerosol according to IS92a.

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%. Figure 6 shows the projected changes in mean annual runoff (mm yr^{-1}) by the year 2050, relative to the values of the baseline period 1961-‘90, according to the Had-CM3 model using IS95a forcing scenario *(IPCC*, 2001***)***.

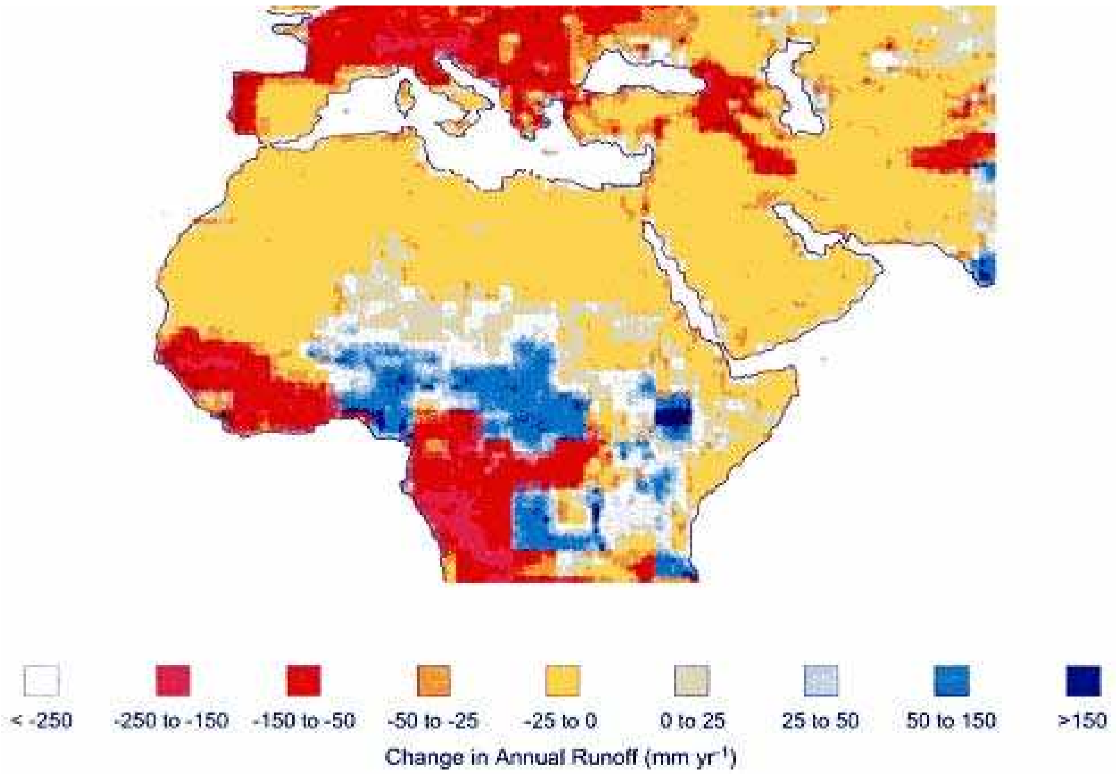

Figure 6. Changes in runoff by the year 2050, relative to the average annual values of the baseline period 1961-‘90, according to the Had CM3 model using IS95a forcing scenario (Adapted from IPCC, 2001)

On the whole, scenarios based on GCMs forecasts do not provide sufficiently reliable information for the assessment of the hydrological consequences of climate change at the scale of the

Mediterranean region. Therefore, reliable quantitative conclusions on possible changes in hydrological regimes cannot be drawn, but it is reasonable to assume that, at the scale of river basins (small and medium-sized basins in particular), global warming will have a greater impacts on extremes events (floods and droughts) than on annual and seasonal values. To this end, technological innovation, institutional adaptation and improved water management could help to mitigate many of the negative consequences of global warming.

4.2. Climate change and irrigation requirements

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 economic factors. Modern agriculture has progressed by weakening the downside risk of these factors through irrigation, the use of pesticides and fertilizers, the substitution of human labour with energy intensive devices, and the manipulation of genetic resources. A major concern in the understanding of the impacts of climate change is the extent to which world agriculture will be affected. Thus, in the long term, climate change is an additional problem that agriculture has to face in meeting global and national food requirements. This recognition has prompted recent advances in the coupling of global vegetation and climate models.

In the last decade, global vegetation models 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). The latter employed the raster-based Global Irrigation Model (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 evapotranspiration 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.

Figure 7a provides, for the Mediterranean region, a map of IRnet per unit irrigated area for the baseline climate, while Figures 7b and 7c present the percent changes for the 2020s time horizon as computed for the MPI-ECHAM4 (7b) and Had-CM3 (**7c**) climate scenarios (Döll, 2002).

The maps show that irrigation requirements (mm/yr) increase in most irrigated areas in the north (Figures 7b, 7c), 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, modelling 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.

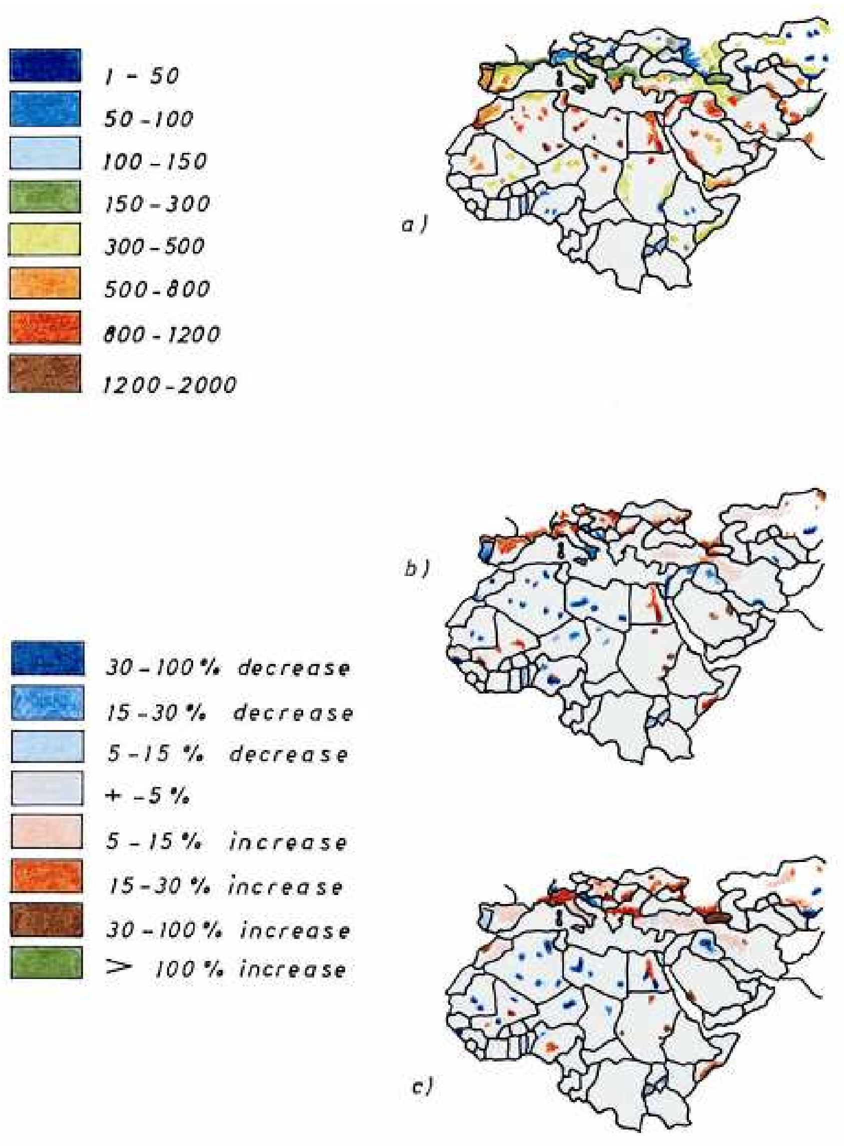

Figure 7. (a) Net irrigation requirement IRnet per unit irrigated area under baseline climate (1961-1990) [mm/yr]. (b) Change of IRnet between baseline climatic condition and the 2020s, due to climate change as computed by ECHAM4. (c) Like (b), but due to climate change as computed by HadCM3. Only those cells are shown in which IRnet per unit cell area was more than 1 mm/yr (baseline climate, 1995 irrigated areas) (Adapted from Döll, 2002)

4.3. Climate change and irrigation systems

The response of water systems to climatic forcing is frequently non-linear. This is due to the existence of critical thresholds, of different types, within the systems such as the threshold between liquid and solid precipitation or between rainfall and the stream flow generation process. Understanding these thresholds is important in terms of understanding and predicting the impact of climate change on a system, and also in terms of assessing critical points ("dangerous levels of change") within the system's response (Arnell, 2000).

Figure 8 illustrates the sequence of stages between "climate change" and "impact" in the water sector (where "impact" is loosely defined as a consequence for users of the water environment). The effect of a change in climate on the system depends on the physical and managerial characteristics of the system and on its current climate. In general, the more stressed the system, the more prone it will be to a change in climate regime. Finally, the impacts on users will depend not only on the climate change and on the nature of the water management procedures but also on how the managers of the system respond and adapt to both short-time crises and long-term trends in water resources. The "response" of the water sector is, therefore, potentially very complicated, and is characterized by non-linearities and critical thresholds.

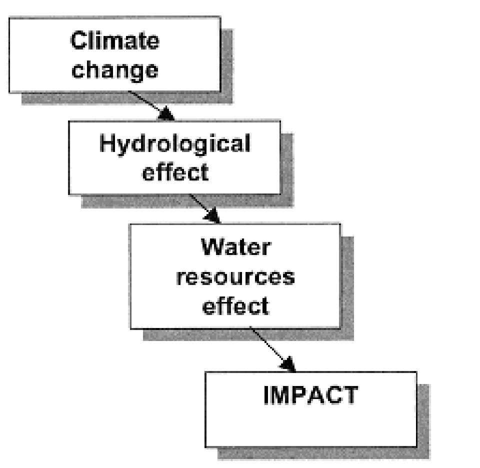

Figure 8. The transition of climate change to impact in the water sector (After Arnell, 2000)

An important critical threshold in irrigation system management is the amount of water demanded from a system. If available supply falls below this threshold, then the system fails. In practice, managers can follow two approaches to prevent system failure. The first is to try to ensure that the supply system never reaches the threshold, by introducing new sources or operating systems differently (the supply-side approach). The second is to try to move the threshold, by encouraging water use efficiency and pricing control (the demand-side approach).

Generally, most of the critical thresholds in water management systems reflect design standards that are defined not in absolute threshold terms, but in terms of the risk of threshold being exceeded. Climate change will alter the risk of design standards being exceeded, and the threshold therefore becomes the tolerable change in risk. In practice, changes in risk are difficult to define because they are affected by different uncertainties.

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). An initial question is whether, based on GCM results or other analyses, there is reason to expect that a region's climate is likely to change significantly during the life of a system. If significant climate change is thought to be likely, the next question is whether there is a basis for forming an expectation about the likelihood and nature of the change and its impacts on the infrastructures.

The suitability and robustness of an infrastructure can be assessed either by running “what if” scenarios that incorporate alternative climates or through synthetic hydrology by translating apparent trends into enhanced persistence. In the absence of an improved basis for forming expectations as to the magnitude, timing and direction of shifts in an irrigated area’s climate and hydrology, it may be difficult to evaluate the suitability of further investments in irrigation development, based on the prospects of climate change.

When there are grounds for formulating reasonable expectations about the likelihood of climate changes, the relevance of these changes will depend on the nature of the project under consideration. Climate changes that are likely to occur several decades from now will have little relevance for decisions involving infrastructure development or incremental expansion of existing facilities’ capacity. Under these circumstances planners and designers should evaluate the options under one or more climate change scenario to determine the impacts on the project’s net benefits. If the climate significantly alters the net benefits, the costs of proceeding with a decision assuming no change can be estimated. If these costs are significant, a decision tree can be constructed for evaluating the alternatives under two or more climate scenarios (Hobbs *et al*., 1997). Delaying an expensive and irreversible project may be a competitive option, especially in view of the prospect that the delay will result in a better understanding as to how the climate is likely to change and impact the effectiveness and performance of the infrastructure.

Aside from the climate change issue, the high costs of and limited opportunities for developing new large scale projects, have led to a shift away from the traditional, fairly inflexible planning principles and design criteria for meeting changing water needs and coping with hydrological variability and uncertainty. Efficient, flexible works designed for current climatic trends would be expected to perform efficiently under different environmental conditions. Thus, institutional flexibility that might complement or substitute infrastructure investments is likely to play an important role in irrigation development under the prospect of global climatic change. 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.

The planning and design process needs to be sufficiently flexible to incorporate consideration of and responses to many possible climate impacts. Introducing the potential impacts of and appropriate responses to climate change in planning and design of irrigation systems can be both expensive and time consuming. The main factors that might influence the worth of incorporating climate change into the analysis are the level of planning (local, national, international), the reliability of GCMs, the hydrologic conditions, and the time horizon of the plan or life of the project. The development of a comprehensive multi-objective decision-making approach that integrates and appropriately considers all these issues, within the project selection process, warrants further research on:

- the processes governing global and regional climates and climate-hydrology interrelations;
- the impacts of increased atmospheric CO_2 on vegetation and runoff;
- the effect of climate variables, such as temperature and precipitation, on water demand for irrigated agriculture.

5. 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 factors through irrigation, the use of pesticides and fertilizers, the substitution of human labour 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 intake. 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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