RURAL DEVELOPMENT AND FOOD SECURITY UNDER CLIMATE VARIABILITY

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***Abstract**: Most of the world's irrigation systems 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 climatic conditions would not change in the future. This will not be so in the years to come due to the global warming and greenhouse effect. Therefore, engineers and decision-makers need to systematically review planning principles, design criteria, operating rules, contingency plans and management policies for new infrastructures.*

In relation of these issues and based on available information, the report gives an overview of current and future (time horizon 2025) irrigation development around the world. Moreover, the paper analyses the results of the most recent and advanced General Circulation Models for assessing the hydrological impacts of climate variability on crop requirements, water availability, food security and the planning and design process of irrigation systems. Finally, a five-step planning and design procedure is proposed able to integrate, within the development process, the hydrological consequences of climate change.

***Keywords:** Climate change, agricultural development, food security*

INTRODUCTION

Agriculture will have to meet the future challenges posed by food security by increasing production while conserving natural resources. The conservation of natural resources is important because of the dependence of agriculture on these resources. 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. This process implies long-term perspective for planning and integrated policies for implementation.

In the past, the increased demand for food has been satisfied by the expansion of agricultural land. Today, the availability of new land for cultivation and additional water resources is limited. Moreover the more or less uncontrolled increase of agricultural production over the last few decades, in both the industrialized and developing countries, has pushed agricultural production to and in many cases, over the edge of sustainability. This means that the traditional methods for increasing production are facing a new challenge; reconciling agricultural development and the conservation of natural resources.

In this context, the prospects of increasing the gross cultivated area, in both the developed and developing countries, are limited by the dwindling number of economically attractive sites for new large-scale irrigation and drainage projects. Therefore, any increase in agricultural production will necessarily rely largely on a more accurate estimation of crop water requirements on the one hand, and on major improvements in the operation, management and performance of existing irrigation and drainage systems, on the other.

The failings of present systems and the inability to sustainably exploit surface and ground water resources can be attributed essentially to poor planning, design, systems management and development.

With a population that is expected to grow from 6 billion today to at least 8 billion by the year 2025, bold measures are essential if the problems of irrigation systems and shortage of food are to be avoided.

Concerning agricultural development, most of the world's 270 million ha of irrigated land and 130 million ha of rainfed land with drainage facilities were developed on a step-by-step basis over the centuries. In many of the systems structures have aged or are deteriorating. Added to this, the systems have to withstand the pressures of changing needs, demands and social and economic evolution. Consequently, the infrastructure in most irrigated and drained areas needs to be renewed or even replaced and thus redesigned and rebuilt, in order to achieve improved sustainable production. This process depends on a number of common and well-coordinated factors, such as new and advanced technology, environmental protection, institutional strengthening, economic and financial assessment, research thrust and human resource development. Most of these factors are well known and linked to uncertainties associated with climate change, world market prices and international trade. These uncertainties call for continued attention and suitable action on many fronts, if productivity and flexibility in agricultural systems are to be improved.

All the above factors and constraints compel decision-makers to review the strengths and weaknesses of current trends in irrigation and drainage and rethink technology, institutional and financial patterns, research thrust and manpower policy so that service levels and system efficiency can be improved in a sustainable manner.

IRRIGATION DEVELOPMENT AND THE GLOBAL FOOD CHALLENGE

To solve the above problems massive investments have been made over the last few decades by governments and individuals and a concerned effort by the international Community. The challenge was to provide enough food for 2 billion more people, while increasing domestic and industrial water demand. Different scenarios have been developed to explore a number of issues, such as the expansion of irrigated agriculture, massive increases in food production from rainfed lands, water productivity trends and public acceptance of genetically modified crops. Opinions differ among the experts as to some of the above issues. However, there is abroad consensus that irrigation can contribute substantially to increasing food production.

Nowadays, the global food production is realized at a cultivated area of about 1.5 billion ha, which represents 12% of the total land area (Schultz and De Wrachien, 2002). At about 1.1 billion ha agricultural exploitation takes place without a water management system. From this area 45% of the food production is being obtained. At present irrigation covers 270 million ha, i.e. 18% of the world's arable land. In Table 1 some characteristic figures per continent, are given for the different water management practices (Schultz, 2002). On the whole, irrigation is responsible for 40% of the output and employs about 30% of population spread over rural areas. It uses about 70% of waters withdrawn from global river systems. About 60% of such waters are used consumptively, the rest returning to the river systems. Drainage of rainfed crops covers about 130 million ha, i.e. 9% of the world's arable land. In about 60 million ha of the irrigated lands there is a drainage system, as well. From the 130 million ha of rainfed drained land about 15% of the crop output is obtained.

Table 1. Role of water management in agricultural cultivation practices in the world regions (after Schultz, 2002)

Continent	Total area in 10^6 ha	Arable land in 10^6 ha	Total population in million	Water management practice in 10^6 ha		
				No system	Drainage *)	Irrigation **)
Asia	2,745	531	3,508	303	49	179
America	3,771	370	757	266	65	40
Europe	2,202	295	703	219	49	27
Africa	1,820	157	598	142	4	11
Oceania	803	56	23	51	2	3
Total	11,341	1,409	5,588	982	168	259
World	13,387	1,512	5,978	1,051	190	271

*) In total about 130 * 10^6 ha rainfed and 60 * 10^6 ha drainage of irrigated areas

**) Irrigation may include drainage as well

Developments in Irrigation

In the last forty years irrigation has been a major source of growth of the food and fiber supply for a global population that more than doubled, rising from 3.0 billion to over 6 billion people. Global irrigated area grew by around 2% a year in the 1960s and 1970s, slowing to closer 1% in the 1980s, and even lower in the 1990s. Irrigated area grew from 150 to 260 million ha between 1965 and 1995, and is now increasing at a very slow rate because of a considerable slowdown in new investments combined with loss of irrigated areas due to salinization and urban encroachment in countries such as China and Pakistan. The regional distribution of these irrigated areas is given in Table 2 (Petit, 2001).

Table 2. Evolution of irrigated area in the world regions (after Petit, 2001)

Region	Irrigated area Thousand ha (1965)	Irrigated area Thousand ha (1995)	Growth during 1965-1995	Irrigated Area (percent of world area)
Asia	102695	180658	76	69
Central and North America	19474	30219	55	12
Europe	13768	24944	81	10
Africa	7722	112242	59	5
South America	4911	9696	97	4
Pacific	1329	2751	107	1
World	**149923**	**260576**	**74**	**100**

Notwithstanding these achievements, nowadays the largest agricultural area (1.1 billion ha) is still without any water management system(Table 1). In this context it is expected that 90% of the increase in food production will have to come from existing cultivated land and only 10% from new land reclamations. In the rainfed areas without a water management system some improvements can be made by water harvesting and watershed management. There is, however, no way that the cultivated area without a water management system can contribute significantly to the require increased in food production. Due to this, the share of irrigated and drained areas in food production will have to increase. This can be achieved either by installing irrigation or drainage facilities in the areas without a system or by improvement and modernization of existing systems. The International Commission on Irrigation and Drainage (ICID) estimates that within the next 25 years, this process may result in a shift to the contribution to the total food production in the direction of 30% for the areas without a water management system, 50% for the areas with an irrigation system and 20% for the rainfed areas with a drainage system (Schultz, 2002). It has to be stressed that these percentages refer to two times the present food production. Such development, however, appears unlikely today. Irrigation investments have slowed down considerably and many projects suffer from major shortcomings due to the poor performance of large irrigation schemes and management of water resources. These factors define what are, perhaps, the greatest challenges facing agriculture today. Given the critical role which the use of water resources in agriculture must play to ensure food security, it is absolutely necessary to improve the performance of irrigated agriculture, namely to increase its productivity, to enhance its contribution to both developed and developing countries and to limit and mitigate its negative impacts on the environment.

The Global Food Challenge

Continuing growth in world population generates the need for continued increases in food production. To meet this increasing demand several actions are required. Globally, the core challenge must be to improve the productivity of water. Where land is limiting, yields for unit area must also be raised. These measures lead to two fundamental development directions (van Hofwegen and Svendsen, 2000):

- increasing the field frontier in those areas where present levels of production are close to the potential;
- closing the yield gap where considerable production gains can be achieved with current technology.

On the basis of the above assumptions, three models of food and irrigation water demand have been developed by non governmental organizations for the time horizon 2025 (Plusquellec, 2002).

- According to the International Water Management Institute (IWMI),the worldwide net irrigated area would have to increase by 52 million ha or 22% and gross (harvested) irrigated areas by 29% to meet the required nutritional levels. Within this scenario, irrigated cereal yields are projected to grow by 40% between 1995 and 2025.
- The Food Agriculture Organization (FAO) model assumes that traditional irrigation efficiency will increase from 43 to 50%. The net irrigated area in developing countries would have to increase by 45 million ha and the total harvested area by 34%. An additional 12% in water use for irrigation would be required. The FAO model is based on the hypothesis that 2.5% of existing irrigation systems are rehabilitated or substituted by new ones every year.
- Under the International Food Policy Research Institute (IFPRI) base scenario, water demand for irrigation would have to increase by only 9.5%. The IFPRI model also examines the effect of lower investments for infrastructure improvement, lower groundwater pumping and lower growth rates in reservoir storage.

These three models foresee that present irrigated agriculture would have to increase by 15-22%. Moreover, water withdrawals for irrigation are also expected to increase at unprecedented rates, which is a major challenge, taking into account that the environmental community sees it imperative that water withdrawals for agriculture should be reduced, having great expectations for the potential created by biotechnology.

Although the scenarios differ considerably, it is generally agreed that the world is entering the twenty-first century on the brink of a new food crisis that is as critical though for more complex that the famine it faced in the 1960s. Therefore, some analysts believe that what is needed is a new and Greener Revolution to once again increase productivity and boost production. But the challenges are for more complex than simply producing more food, because global conditions have change since the Green Revolution Years.

Forty years ago, extensive use of fertilizers and the expansion of irrigation, together with high yield food crops, were the critical factors in preventing global famine. The actual decline in yield increases may be an indication that these instruments have reached their effective limits. Most analysts believe that future increases in food supply will come mainly from improved production (more crop per drop) since the natural resource base will not support either significant expansion of farm lands or more extensive irrigation. One, and maybe the most important option for enhancing the productivity of irrigated agriculture is to improve the water distribution service to individual or groups of farmers.

CLIMATE CHANGE AND IRRIGATION REQUIREMENTS

Agriculture is a human activity that is intimately linked to climate. It is well known that the broad patterns of agricultural development over long time scales can be explained by a confluence 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 labor 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. The issue is particularly important for developing countries since agriculture is the occupation of close to 60% of the population and contributes over 30% of the Gross Domestic Product (GDP)(Kandlikar et al., 2000) Although developed countries may be better equipped to cope with disruption in climate, large changes in this factor will make it difficult for the agricultural sector of these countries to produce food they way they currently do. 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 spurred recent advances in the coupling of global vegetation and climate models.

In the last decade, have been developed global vegetation models 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 General Circulation Models (GCMs) and applied to both paleoclimatic and future scenarios (Doherty et al., 2000, Levis 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. Adam 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 were developed by Seckler et al. (1997) and Alcamo et al. (2000). Alcamo et al. employed the raster-based Global Irrigation Model (GIM) of Döll and Siebert (2001), with a spatial resolution of 0.5° by 0.5°. This model represents one of the most advanced tool nowadays available to explore 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 that were 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 (MPI-ECHAM4), Germany (Röckner et al., 1996)
- the Hadley Centre for Climate Prediction and Research (HCCPR-CM3), UK (Gordon et al., 1999).
- 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).

With regard to the above climatic conditions the GIM computed both the net and gross irrigation water requirements in all 0.5° by 0.5° raster cells with irrigated areas. "Gross irrigation requirement" is the total amount of water that must be applied by irrigation such that evapotraspiration may occur at the potential rate and optimal crop productivity may be achieved. Only part of the applied 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 north of 40°N, by up to 30%, which is mainly due to decreased precipitation, in particular during the summer. South of this latitude, the pattern becomes complex. For most of the irrigated areas of the arid northern part of Africa and the Middle East, IRnet decreases. In Egypt, a decrease of about 50% in the southern part is accompanied by an increase of about 50% in the central part. The decrease depends on the fact that in GIM temperature and precipitation determine the best cropping pattern for an irrigated area. So, when climatic characteristics exceed fixed critical values the cropping pattern shifts from more crops to only one crop per year and vice versa. In central India, baseline IRnet values of 250-350mm are expected to more than double by the 2020s. In large part of China the impact of climate change is negligible (less than 5%), with decreases in northern China, as precipitation is assumed to increase. When the cell-specific net irrigation requirements are summed up over the world regions, increases and decreases of the cell values caused by climate change almost average out, increasing by 3.3% in the 2020s and by 5.5% in the 2070s from the 1092 km^3/y for the baseline climate (Table 3). The simulations also show that on areas equipped for irrigation in 1995 IRnet is likely to increase on 66% of these areas by the 2020s and on 62% by the 2070s.

Table 3. Impact of climate change on computed irrigation requirements IRnet of world regions (after Döll, , 2002)
Irrigated areas of 1995, under 1961-1990 average observed climate ("baseline"), and scaled with MPI-ECHAM4 or HCCPR-CM3 climate change scenarios for 2020-2029 ("2020s") and 2070-2090 ("2070s").

	Irrigated area 1995, 1000 km^2	Cropping intensity	Long-term average IR_{net}, km^3/yr				
			Baseline	2020s		2070s	
				ECHAM4	HadCM3	ECHAM4	HadCM3
Canada	7.1	1.0	2.4	2.9	2.7	3.3	2.9
U.S.A.	235.6	1.0	112.0	120.6	117.9	123.0	117.9
Central America	80.2	1.0	17.5	17.0	17.6	18.1	19.7
South America	98.3	1.0	26.6	27.1	27.5	28.2	29.1
Northern Africa	59.4	1.5	66.4	62.7	65.3	56.0	57.7
Western Africa	8.3	1.0	2.5	2.2	2.4	2.4	2.6
Eastern Africa	35.8	1.0	12.3	13.1	12.2	14.5	14.3
Southern Africa	18.6	1.0	7.1	7.0	7.4	6.4	7.2
OECD Europe	118.0	1.0	52.4	55.8	55.2	56.5	57.8
Eastern Europe	49.4	1.0	16.7	18.4	19.0	19.7	22.1
Former U.S.S.R.	218.7	0.8	104.6	106.6	112.1	104.4	108.7
Middle East	185.3	1.0	144.7	138.7	142.4	126.5	137.8
South Asia	734.6	1.3	366.4	389.8	400.4	410.7	422.0
East Asia	492.5	1.5	123.8	126.0	126.6	131.3	127.1
Southeast Asia	154.4	1.2	17.1	20.3	18.8	30.4	28.6
Oceania	26.1	1.5	17.7	17.8	17.6	18.2	19.7
Japan	27.0	1.5	1.3	1.3	1.8	1.4	1.5
World	**2549.1**		**1091.5**	**1127.5**	**1147.0**	**1151.0**	**1176.8**

CLIMATE CHANGE AND WATER AVAILABILITY

In order to assess the problem of water scarcity, the appropriate averaging units are not world regions but river basins.

Climate predictions from four state of-the-art General Circulation Models were used to assess the hydrologic sensitivity to climate change of nine large, continental river basins (Nijssen et al., 2001). The river basins (Table 4) were selected on the basis of the desire to represent a range of geographic and climatic conditions. Four models have been used:

- the Hadley Centre for Climate Prediction and Research (HCCPR-CM2), UK (Johns et al., 1997);
- the Hadley Centre for Climate Prediction and Research (HCCPR-CM3), UK (Gordon et al., 2000);
- the Max Planck Institute for Meteorology (MPI-ECHAM4), Germany (Röckner et al., 1996);
- the Department of Energy (DOE-PCM3), USA (Washington et al., 2000);

Table 4. Selected river basins (after Nijssen et al., 2001)

River basin	Gauge location	Predominant climatic zones	Area (km^2) upstream of gauge [a]
Amazon	Obidos, Brazil	Tropical	4,618,746
Amur	Komsomolsk, Russia	Arctic Mid latitude – rainy	1,730,000
Mackenzie	Norman Wells, Canada	Arctic	1,570,000
Mekong	Pakse, Laos	Tropical	545,000
Mississippi	Vicksburg, U.S.A.	Mid latitude – rainy	2,964,254
Severnaya Dvina	Ust – Pinega, Russia	Arctic	348,000
Xi	Wuzhou, China	Mid latitude – rainy	329,705
Yellow	Huayuankou, China	Arid – cold Mid latitude – rainy	730,036
Yenisei	Igarka, Russia	Arctic	2,440,000

All predicted transient climate response to changing greenhouse gas concentrations and incorporated modern land surface parameterizations. The transient emission scenarios differ slightly between the models, partly because they represent greenhouse gas chemistry differently. The different emission scenarios used are:

- 1% annual increase in equivalent CO2 and sulphate aerosols according to the IPCC IS92a scenario;
- equivalent CO2 and sulphate aerosols according to IS92a;
- several greenhouse gases (including CO2) and sulphate aerosols according to IS92a.

The IS92a scenario is one of the emission scenarios specified by IPCC and gives a doubling of equivalent CO_2 after about 95 years (IPCC, 1996). A 1% annual increase in equivalent CO_2 (doubling in 70 years) results in a 20% higher radiative foreing for a given future time horizon compared to the IS92a scenario.

Changes in basin-wide mean annual temperature and precipitation were computed for three decades in the transient climate model runs (2025, 2045 and 2095) and hydrologic model simulations were performed for decades centered on 2025 and 2045.

The main conclusions are herewith summarized.

- All models predict a warming for all nine basins, but the amount of warming varies widely between the models, especially with the increased time horizon. The greatest warming is predicted to occur during the winter months in the highest latitudes. Precipitation generally increases for the northern basins (Mackenzie, Severnaya Dvina and Yenisei), but the signal is mixed for basins in the mid-latitudes and tropics, although on average slight precipitation increases are predicted.
- The largest changes in hydrological cycle are predicted for the snow-dominated basins of mid to higher latitudes, as a result of the greater amount of warming that is predicted for these regions. The presence or absence of snow fundamentally changes the water balance, due to the fact that water stored as snow during the winter does not become available for runoff or evapotranspiration until the following spring's melt period.
- Globally, the hydrological response predicted for most of the basins in response to the GCMs predictions is a reduction in annual streamflow in the tropical and mid-latitudes. In contrast, high-latitude basins tend to show an increase in annual runoff, because most of the predicted increase in precipitation occurs during the winter, when the available energy is insufficient for an increase in evaporation. Instead, water is stored as snow and contributes in streamflow during the following melt period.

PLANNING AND DESIGN OF IRRIGATION SYSTEMS UNDER CLIMATE CHANGE

The response of water systems to climatic forcing in 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).

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's 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 et al., 2003 a,b,c,d). An initial questions 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 to 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 subsequent 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 identified as a significant planning issue (first step), the second step in the process would include a forecast of 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 in 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 mighty 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, 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 CO2 on vegetation and runoff;
- the effect of climate variables, such as temperature and precipitation, on water demand for irrigated agriculture.

CONCLUDING REMARKS

- Agriculture will have to meet the future challenges posed by food security by increasing production while conserving natural resources.
- In the past, the increased demand for food has been satisfied by the expansion of agricultural land. Today, the availability of new land for cultivation and additional water is limited. In this context, the prospects of increasing the gross cultivated area, in both the developed and developing countries, are limited by the dwindling number of economically attractive sites for new large-scale irrigation projects. Therefore, any increase in agricultural production will necessarily rely largely on a more accurate estimation of crop water requirements on the one hand, and on major improvements in the operation, management and performance of existing irrigation system, on the other.
- With a population that is expected to grow from 6 billion today to at least 8 billion by the year 2025, bold measures are essential if the problems of irrigation systems and shortage of food are to be avoided.
- Different scenarios have been developed to explore a number of issues, such as the expansion of irrigated agriculture, massive increases in food production from rainfed lands and water productivity trends. Opinions differ among experts as to some of the above issues. However, there is broad consensus that irrigation can contribute substantially to increasing food production in the years to come.
- Most of the world's irrigation systems 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 climatic conditions would not change. This will not be so in the future, due to the global warming and greenhouse effect. Therefore, engineers and decision-makers 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 cope with. The challenge is to identify short-term strategies to face 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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