Impacts of Global Warming on Irrigation and Drainage Development: Perspectives Challenges and Solutions

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Introduction

Irrigated agriculture is expected to play a major role in reaching the broader development objectives of achieving food security and improvements in the quality of life, while conserving the environment, in both the developed and developing countries. Especially as we are faced with the prospect of global population growth from almost 6 billion today to at least 8 billion by 2025 [1].

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

Concerning agricultural development, most of the world is 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 [2].

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 [3].

Irrigation and Drainage Systems Development

Basis for the water management requirements is the world's population, its growth and its standard of living. The world's population in the year 2000 and prognoses of the population growth are shown in Figure 1 [4]. With respect to water management related to

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agricultural production there are broadly speaking three agro-climatic zones, being: temperate humid zone, arid and semi-arid zone and humid tropical zone. In addition, in principle, four types of cultivation practices may be distinguished, being:

- Rainfed cultivation, without or with a drainage system;
- Irrigated cultivation, without or with a drainage system.

Dependent on the local conditions different types of water management with different levels of service will be appropriate. At about 1,100 million ha agricultural exploitation takes place without a water management system. However, in a certain part of these areas methods like water harvesting or soil treatment may be applied. From these areas, 45% of crop output is being obtained. Presently irrigation covers more than 270 million ha and is responsible for 40% of crop output. It uses about 70% of waters withdrawn from global river systems. Drainage of rainfed crops covers about 130 million ha and contributes to about 15% of crop output. In about 60 million ha of the irrigated lands there is a drainage system as well [4].

Based on the forecasts for population growth and the improvement in the standard of living it is expected that food production will have to be doubled in the next 25 years. In addition, 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, either in the highlands, or in the lowlands. There is no way that the cultivated area without a water management system can contribute significantly to the required increase 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 and drainage systems in the areas without a system, improvement, or modernization of existing irrigation and drainage systems, installation of irrigation systems in the rainfed-drained areas, or installation of drainage systems in irrigated areas. A rough estimate may be that over the next 25 years this 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.

2.1 Development in irrigation

Over the last forty years, the irrigation has been a major contributor to the growth of food and fiber supply for a global population that has more than doubled, from 3 to over 6 billion people. Global irrigated area increased by around 2% a year in the 1960s and 1970s, slowing down to around 1% in the 1980s, and lower still in the 1990s. Between 1965 and 1995 the world’s irrigated land grew from 150 to 260 million ha. Nowadays it is increasing at a very slow rate because of the significant slowdown in new investments, combined with the loss of irrigated areas due to salinization and urban encroachment.

Not with standing these achievements, today the majority of agricultural land (1.1 billion ha) still has no water management system. 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 conversion from other uses. In the rainfed areas with no water management systems, some improvements can be achieved with water harvesting and watershed management. However, in no way can the cultivated area with no water management contribute significantly to the required increase in food production. For this reason, the share of irrigated areas in food production will have to increase. This can be achieved either by installing irrigation facilities in the areas without a system or by improving and modernizing existing systems. The International Commission on Irrigation and Drainage (ICID) estimates that within the next 25 years, this process may result in a shift of the contribution to the total food production to around 30% for the areas with no water management system, 50% for the areas with an irrigation system and 20% for the rainfed areas with a drainage system [5, 6]. It has to be realized that these percentages refer to two times the present day food production. In addition it has to be realized that it will be extremely difficult to achieve this in an environmentally sustainable way, especially in the emerging developing countries [7, 8].

Sustainable development can be viewed as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological innovation and adaptation, along with institutional changes, are all in harmony and enhance both the current and future potential, to meet growing human needs and aspirations [9].

All the above factors and constraints compel decision makers to review the strengths and weaknesses of current trends in irrigation 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 [10].
To develop this process in a well-planned and controlled way the following aspects need to be adequately addressed:

- Technology;
- Institutional and financial aspects;
- Research thrust;
- Human resources and networking.

This will require an interdisciplinary, multispectral approach, using a system-engineering methodology, to recognize the necessary interrelationships. The nodes of the network will be organizations, institutions and agencies, as well as professional, academic, commercial and industrial bodies.

The aim is to create a permanent structure able to:

- Speed up the process of collection, selection and exchange of information, avoiding duplication and overlap;
- Build up synergies among the partners;
- Interact with other frameworks;
- Seek financial support to reinforce local activities of particular interest;
- Provide an international forum for debating irrigation and drainage problems and finding sound and environmentally sustainable solutions.

2.2. Development in Drainage and Land Reclamation

Drainage and land reclamation are crucial instruments for achieving sustainable development of both irrigated and rainfed agriculture throughout the world.

Figure 1 shows the expansion of the world’s cultivated, irrigated and drained areas since the beginning of the nineteenth century [11]. Out of a total cultivated area of around 1,500 million ha, 1,100 million ha are agriculturally exploited without a water management system. However, methods such as water harvesting or soil treatment may be applied in some parts. These areas produce 45% of crop output. Irrigated land currently occupies more than 270 million ha and is responsible for 40% of crop output. Irrigation consumes about 70% of water withdrawn from the world’s river systems. About 130 million ha of rainfed areas are equipped with drainage facilities and contribute to around 15% of crop output. Roughly 60 million ha of irrigated land are also provided with drainage systems [12]. Some key figures for the 10 countries with the largest drained areas are given in Table 1.

Concerning drainage developments, on the basis of the above figures and recent available databases, the situation in the world’s cropland can be summed up in Table 2.

The currently drained area of 190 million ha has been developed over a period of roughly two centuries. The current rate of drainage development is unknown but estimated to be in the order of 0.5 – 1.0 million ha a year (including upgrading and rehabilitation). Considering that the continuing agricultural expansion will increase the need for improved and affordable drainage, for the 2025 time horizon the following projection can be made [13].

Figure 1: World Population and Growth in Least Developed Countries, Emerging Developing Countries and Developed Countries [4]

Figure 2: Expansion of World’s Cultivated Area With no Water Management System and Under Irrigation and Currently Drained Land [10]
3. Climate Change Scenarios

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. Climate change is defined as “the difference between long-term mean values of a climate parameter, where the mean is taken over a specific interval of time, usually a number of decades [14].

Human beings 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 [15, 16].

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

<table>
<thead>
<tr>
<th>Country</th>
<th>Population (x106)</th>
<th>% of population in agriculture</th>
<th>Total area (106 ha)</th>
<th>Arable land (106 ha)</th>
<th>Drained area (106 ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>168</td>
<td>19</td>
<td>851</td>
<td>66</td>
<td>8</td>
</tr>
<tr>
<td>Canada</td>
<td>31</td>
<td>3</td>
<td>997</td>
<td>46</td>
<td>10</td>
</tr>
<tr>
<td>China</td>
<td>1267</td>
<td>68</td>
<td>960</td>
<td>96</td>
<td>29</td>
</tr>
<tr>
<td>Germany</td>
<td>82</td>
<td>3</td>
<td>36</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>India</td>
<td>998</td>
<td>61</td>
<td>329</td>
<td>170</td>
<td>13</td>
</tr>
<tr>
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<td>209</td>
<td>50</td>
<td>190</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Japan</td>
<td>127</td>
<td>4</td>
<td>38</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
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<td>48</td>
<td>80</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>Poland</td>
<td>39</td>
<td>23</td>
<td>32</td>
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<td>4</td>
</tr>
<tr>
<td>USA</td>
<td>276</td>
<td>2</td>
<td>936</td>
<td>188</td>
<td>47</td>
</tr>
<tr>
<td>Total</td>
<td>3349</td>
<td></td>
<td>4449</td>
<td>650</td>
<td>142</td>
</tr>
</tbody>
</table>

| World     | 6000              |                               | 13000              | 1512                | 190                  |

Table 1: Indicative Key Figures for the 10 Countries with the Largest Drained Area

Table 2: State of Drainage Development of the World’s Cropland [12]
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” [17]. These scenarios can be classified into three groups:

1. Hypothetical scenarios;

2. Climate scenarios based on General Circulation Models (GCMs);

3. Scenarios based on reconstruction of warm periods in the past (paleo-climatic reconstruction).

The plethora of literature on this topic has been recently summarized by the Intergovernmental Panel on Climate Change.

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 next century. GCMs are complex three-dimensional computer-based models of the atmospheric circulation, which provide details of changes in regional climates for any part of the Earth. Until recently, the standard approach has been to run the model with a nominal “pre-industrial” atmospheric carbon dioxide (CO2) concentration (the control run) and then to rerun the model with doubled (or sometimes quadrupled) CO2 (the perturbed run). This approach is known as “the equilibrium response prediction”. The more recent and advanced GCMs are, nowadays, able to take into account the gradual increase in the CO2 concentration through the perturbed run.

The climate models must incorporate a description of the atmospheric circulation and composition, oceanic circulation, hydrological cycle and other phenomena.

To look at past and future changes in temperature these models need to take into account:

• Anthropogenic emissions of greenhouse gases and aerosols;

• External sources of climate variability such as volcanoes and solar variability;

• Internal feedback processes of increasing greenhouse gases, such as cloud-albedo, ice-albedo and water vapor feedbacks.

Climate predictions from four state-of-the-art GCMs were used to assess the hydrologic sensitivity to climate change of nine large, continental river basins [18]. The river basins 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;

• The Hadley Centre for Climate Prediction and Research (HCCPR-CM3), UK;

• The Max Planck Institute for Meteorology (MPI-ECHAM4), Germany;

• The Department of Energy (DOE-PCM3), USA.

All predicted transient climate response to changing greenhouse gas concentrations and incorporated modern land surface parameterizations. The transient emission scenarios differ slightly from one model to another, partly because they represent greenhouse gas chemistry differently.

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 [19].

The main conclusions are summarized below.

• All models predict a warming for all nine basins, but the amount of warming varies widely between the models, especially for the longer time horizon. The greatest warming is predicted to occur during the winter months in the highest latitudes. Precipitation generally increases for the northern basins, but the signal is mixed for basins in the mid-latitudes and tropics, although on average slight precipitation increases are predicted [20].

• 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 [21].

• Globally, the hydrological response predicted for most of the basins in response to the GCMs predictions is a reduction in annual stream flow 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 to stream flow during the subsequent melt period.

• GCMs trying to predict the changes in temperature over past 140 years cannot match the observations by using only natural events, such as volcanic eruptions, solar variability and others. The last 50 years can only be explained if increasing levels of greenhouse gases and aerosols due to human activities are included.

4. Planning and Design of Irrigation and Drainage Systems Under Climate Change

Uncertainties as to how the climate will change and how irrigation and drainage 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 [22]. 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 [23].

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.

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 is irrigated or drained 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, the time horizon of the plan or life of the project[24, 25].

5. Strategic Action Program

The above described themes and principles tackle the root cause of the major problems encountered in irrigation and drainage system development. To be effective, they have to be translated into actions through the formulation of programs that take into account the actual conditions of the environment where they are expected to be implemented. These programs should include:

• The adoption of a comprehensive approach that considers land and water use and management and the environment in an integrated manner;

• The promotion of regional co-operation to ensure that the concerns of all parties are translated into sound decisions;

• The recognition of the relationships between different land uses and availability of water resources (quantity and quality);

• The encouragement of broad based participation, including governments, professional and research institutions and non-governmental organizations;

• The endorsement of phased programs of action at the national and local levels.
This regional approach makes up and outlines the body of a Strategic Action Program, a crucial procedure for implementing priority actions at both national and local levels. The objectives of the Strategic Action Plan are to [26]:

- Evaluate trends;
- Assess causes and implications;
- Review of optimal interventions with their legal, economic and financial implications;
- Provide a cost estimate for investments;
- Establish a framework for monitoring and evaluation;
- Identify priority actions to address key issues.

Priority selection should follow the criteria listed below:

- Ensure optimization of interventions, in order to concentrate resources on significant problems;
- Pay due attention to both technical and non-technical aspects (human resources development, legal and institutional aspects, environmental impacts);
- Avoid duplication and overlap;
- Emphasize adaptive and cost effective solutions through adaptation and/or improvement of existing technology to specific tasks;
- Select topics for investigation and research that are likely to achieve the greatest benefit, considering return on investment, response time, probability of success and impact on agricultural production.

This integrated approach is expected to produce significant benefits in environmental and economic terms, a more sustainable use of land and water resources in irrigated agriculture and higher yields and incomes.

6. Concluding Remarks

Despite the enormous advances in our ability to understand, interpret and ultimately manage the natural world we have reached the 21st century in awesome ignorance of what is likely to unfold in terms of both the natural changes and the human activities that affect the environment and the responses of the Earth to those stimuli. One certain fact is that the planet will be subjected to pressures hitherto unprecedented in its recent evolutionary history.

The “tomorrow’s world” will not simply be an inflated version of the “today’s world”, with more people, more energy consumption, more industry, rather it will be qualitatively different from today in at least three important respects.

First, new technology will transform the relationship between man and the natural world. An example is the gradual transition from agriculture that is heavily dependent on chemicals to one that is essentially biologically intensive through the application of biotechnologies. Consequently, the release of bio-engineered organisms is likely to pose new kinds of risks if the development and use of such organisms are not carefully controlled.

Second, society will be moving beyond the era of localized environmental problems. What were once local incidents of natural resource impairment shared throughout a common watershed or basin, now involve many neighboring countries. What were once acute, short-lived episodes of reversible damage now affect many generations. What were once straightforward questions of conservation versus development now reflect more complex linkages.

The third major change refers to climate variations. 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).

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 the best course for a project is 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 and drainage project selection, requires further research of the processes governing climate changes, the impacts of increased atmospheric carbon dioxide on vegetation and runoff, the effect of climate variables on water demand for irrigation and the impacts of climate on infrastructure performance.

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