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Water Productivity Research in the Context of CGIAR

For Information and Comments

This working draft paper "Water Productivity Research in the Context of CGIAR" was prepared by Jacob Kijne for SCOPAS as a source of information to facilitate informed discussion of the draft paper "Water and the CGIAR" (SDR/TAC:IAR/01/23A) at TAC 81 under Agenda Item 8. The Water Productivity paper should be read in conjunction with the paper on Water and the CGIAR. TAC Members are invited to provide comments on both draft papers.

TAC SECRETARIAT

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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Water productivity in the Context of the CGIAR[1]

Summary

The objective of the discussion paper is twofold: to describe the opportunities for and constraints in improving the productivity of water in agriculture, and to assess the role of the CGIAR in enhancing crop yields per unit of water through interdisciplinary research studies.

After a brief introduction to the paper in chapter 1, chapter 2 discusses various ways of expressing water use efficiency and water productivity. Different disciplines have developed their own parameters for expressing water use efficiency or water productivity. To outsiders and in interdisciplinary contacts the use of the different terms needs to be carefully explained. The relationships between yield and evapotranspiration are discussed in some detail. The dependence of yield on evapotranspiration is the cornerstone for improved water use in agriculture. Evaporative losses from crops are the only real losses from the system. Other so-called losses, such as deep percolation, runoff and evapotranspiration from non-beneficial crops could – at least in theory – be reduced or recouped for use elsewhere.

At the plant and crop level, plant breeding (both traditionally and through molecular biological methods) has contributed to higher yields per unit of water applied, and will continue to do so, e.g. by incorporating genes for drought and salinity tolerance. Various improved field-level agronomic practices are discussed, including their potential impact on the environment.

At the water management level, several methods to improve the performance of irrigation system have been identified. Their possible implications for human health are discussed. Finally there are opportunities for enhancing water productivity through economic incentives, policy changes and institutional arrangements.

Chapter 3 provides an overview of the international organizations active in global water issues. They range from NGO's and UN organizations to universities and private sector organizations. Opportunities for collaboration of the CGIAR and these organizations and institutions are discussed.

Chapter 4 carries on by analysing current water-related research in the CGIAR, with sections on plant breeding, soil and water conservation methods, system and basin level studies, and economics and political measures. CGIAR research priorities and strategies for water aspects of NMR research are discussed and an attempt is made to compare the trend in water research for the CGIAR with research efforts in other international organizations. It is pointed out that although many CGIAR centers are involved in one or more aspects of water productivity research, there remain gaps in water-related research that could be addressed by CGIAR centers.

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[1] Prepared by Jacob Kijne (consultant) as a background paper for TAC and SCOPAS discussions on Water and the CGIAR document (SDR/TAC:IAR/01/23A).

Future water-related research in the CGIAR is the topic of the next chapter. The discussion focuses on the CGIAR aims of poverty reduction and sustainability of the environment in the context of greater competition for water worldwide. An overview of research challenges in water productivity includes a discussion of the variability of basic data, globalization, groundwater depletion, economic considerations and global warming. CGIAR's comparative advantage with respect to inter-disciplinary water productivity research is emphasized. As an appendix to chapter 5, a document is attached that describes the IWMI initiative for a worldwide Dialogue on water, food, and the environment.

The paper also includes a list of references and an Annex, which provides an assessment of IWMI's strategic plans based on the recent EPMR, IWMI's latest annual report and Strategic Plan for 2000-2005.

1. Introduction

In 'Food Secure World for All: Toward a new Vision and Strategy for the CGIAR' (2000a), TAC has listed two important principles with respect to water management research. They are worth repeating here as introduction to this discussion paper. They are:
1) *The CGIAR should concentrate on Natural Resources Management (NRM) research that contributes to productivity enhancement and sustainability of natural resources for production of crop, livestock, forest and fish outputs that have impacts on poverty reduction and food security, giving appropriate consideration for intergenerational equity of benefits.*

This principle should be a necessary condition for undertaking NRM research in the CGIAR System. It derives from the fact that priority should be given to research directly related to the mission and goals of the System. Effective management of the natural environment is an activity pursued by many organizations for many different and legitimate purposes, including global climate change, wildlife management, ecosystem health and use for recreational purposes. Given the competence and large numbers of alternative suppliers, the CGIAR should pursue only those activities that are targeting sustainable productivity improvements. In some cases, such as in fisheries or forestry, this may well translate into protection of the resource base as a key factor governing sustainable production.

(2) *The CGIAR should give much greater attention to research to resolve water issues.*

Irrigation currently uses more water than all other sectors and agriculture faces competing demands for water from the urban sector. Unless properly managed, lack of access to fresh water may well emerge as the key constraint to global food production. Resolving water conflicts could become the single most important resource-management issue in the future, There are inter-sectoral water management issues (competing use of water for agriculture, drinking, industrial uses, environmental uses including fisheries) as well as issues within and between countries. The resolution of these issues of competing demands for water use may be assisted by well-focussed research to improve the efficiency of water use in agriculture.

These principles set the stage on which water-related research in the CGIAR will be judged. In order to do so, our present understanding of the limits and opportunities for enhancing water productivity in agriculture will first be assessed and present water-related research in the CGIAR evaluated. Enhancing water productivity has been identified as one of two pillars for future water development (e.g., Cosgrove and Rijsberman, 2000). The other pillar is the development of additional water resources, which is perceived to be far more difficult than increasing water productivity, especially in agriculture. The argument of – as it has been called – "more crop per drop" is that recycling still holds potential for saving water. It has been argued that gains are also possible by providing more reliable supplies, e.g., through precision technology and the introduction of on-demand delivery of irrigation supplies. Supplemental irrigation with low-cost precision technology is expected to offer a means for poor farmers to produce more crop with less water.

The first aim of the paper then is to understand whether these opportunities exist. If there is doubt about their existence, the paper aims to identify what additional studies need to be carried out to ascertain under what conditions improvements in water productivity in agriculture are possible. A second aim of the paper, therefore, is to propose a number of priority topics for water management research in CG IAR and discuss how these research topics can be implemented in the near future.

2. Improving Water Productivity: Opportunities and Constraints

2.1 Water Use Efficiency or Water Productivity? A Matter of Definitions

The term water use efficiency (WUE) is commonly used to measure how water is used in agriculture. Unfortunately, the use of this term leads to a great deal of confusion. Efficiency is a measure of the output obtainable from a given input. In irrigation and water management, typically the output (yield) is related to crop consumptive use and the input is the water diverted to meet crop consumptive demands. Letey (1993) and Keller and Keller (1995), among others, have pointed out that much of the water diverted to meet the crop consumptive demands is not converted to vapor through evapotranspiration. Water 'lost' through runoff or seepage and percolation remains available for use if captured and applied elsewhere. Although the quantity of water that seeps from the root zone to the groundwater is not lost from the system, it does result in additional costs of pumping water from the ground. Furthermore, contamination with saline groundwater makes the water that seeped away less useful for further use; desalinization of such waters would be an additional expense.

Two definitions of WUE, yield per unit of water evapotranspired and yield per unit of water applied, have been used extensively and continue to be used in this way. The latter often without clearly specifying whether the amount applied was the flow to a field, a farm or to some larger irrigation unit, thus adding to the confusion. Irrigation engineers commonly prefer some measure of the amount of water applied rather than evapotranspiration in the denominator of WUE for the simple reason that one can more easily measure amounts of water in canals and watercourses. However, focusing on water applied as irrigation water ignores other sources of water that contribute to crop production. The most obvious one is rainfall, which is easily measured, but the same is true for the much more difficult to measure capillary rise from a shallow watertable. Misleadingly high figures of WUE of irrigation water are obtained when irrigation is supplemental to significant amounts of rain during the growing season, which is not included in the calculation of WUE. Those WUE values are not comparable to the WUE values of irrigation water obtained in semi-arid lands without rainfall during the growing season (Oweis etal, 1999).

Using evapotranspiration in the denominator of WUE can solve this problem. However, the question then arises whether transpiration wouldn't be the better parameter to use rather than evapotranspiration. Evaporation from moist soil between the plants is not essential for plant growth and can easily (but not necessarily cheaply) be reduced by the application of gravel and organic mulches. Purists, such as Monteith (1993), have pointed out that transpired water is lost rather than used. Only a small fraction of the water taken up by roots is used for metabolic processes and when plants 'use' less water because transpiration is restricted by high humidity, they grow faster (in other words, the efficiency of water use is greater). In that sense, water evaporated from moist soil contributes somewhat to the efficiency of water use by increasing the humidity.

When irrigation engineers use the term "irrigation efficiency", they refer to the water required to grow a crop (i.e., evapotranspiration, percolation and seepage, leaching for salinity control, and land preparation) divided by the water delivered. This is the measure most commonly used when people speak of irrigation systems or countries with irrigation efficiencies of only 40%. The inverse of this "irrigation efficiency" is the "relative water supply", as a performance indicator of irrigation systems. Relative water supply values, say between 1 and 1.5 are achieved when water is scarce under conditions of good water management and control in the system.

Economists consider parameters such as yield per unit of water applied or used, or yield per unit land as indices of partial productivity since the denominator takes into account only one resource. They may prefer to use net value of output per unit of water applied. Which parameter should go in the denominator, irrigation or irrigation and rain, depends on whether the aim is to optimize the use of irrigation water or all sources of water in a more holistic approach. Because farmers usually do not consider externalities (third party effects), or pay only part of the real cost of their water, the value of the output over supplied water ratio differs depending on whether it is considered from the farmers' point of view and for the society as a whole. The use of water by different users under varying circumstances may result in different optimal values of the economic water productivity (i.e. ratio of net value of output over supplied water).

Net farm income is arguably the correct measure of economic costs if inputs to agriculture, such as labor have alternative uses and if changes in production due to water supply and quality regulations have only a minimal effect on commodity prices. When changes in production do affect prices, the change in net consumer expenditure (consumer surplus) should be added to the change in economic welfare (Sunding et al., 1997). Gross farm income captures how the changes in water availability affect the market value of agricultural products. However, gross farm income may overstate economic impact on farmers if inputs that are used in conjunction with water in agricultural production may be used for production in other sectors of the economy. Apart from net and gross farm income, a third measure of economic activity and profitability is the national product. Reductions in agricultural income and the income from labor and other agricultural inputs have a multiplier effect. A fall in the level of economic activity in agriculture, as represented by a fall in sales, reverberates throughout the general economy.

Another important economic impact measure is how water scarcity affects employment in agriculture. Employment effects of water policies, both on farm and in non-farm sectors, can be measured in terms of lost person-years. The number of lost person-years depends on whether the economy is growing and the unemployment rate is low, so that it is easier for farm workers and others losing agricultural jobs to be absorbed by other sectors of the economy.

There are obviously various valid ways in which water productivity can be expressed. The concept of "more crop per drop", propagated by IWMI in recent years, requires a clear definition of what it is we are talking about. 'Crop" could refer to the marketable value or the total biomass produced, and "water" could mean evapotranspiration to one, and the net sum of all applied water, including rainfall, net change in soil water content and capillary rise, to another. Because of confusion with respect to the WUE term, increasingly "water productivity" is used to denote crop yield over evapotranspiration. We will follow this usage in the paper, recognizing the validity of continuous use of other terms, including WUE, provided the terms in numerator and denominator are clearly defined. Howell (2001) in a recent review discusses in more detail all aspects of the term water use efficiency as commonly used in the literature.

2.2 Yield-Evapotranspiration Relationships

The relationship between yield and evapotranspiration (ET) has been the subject of a number of excellent reviews (see, for example Hanks, 1984, Howell, Cuenta and Solomon, 1990, Dinar and Zilberman, 1991, Hanks and Ritchie, 1991, Letey 1993, Howell, 1990). Based on work by de Wit (1958), which in turn followed from studies by Briggs and Shantz (1913), it is generally accepted that relative yield (actual over maximum yield) is linearly related to relative transpiration (actual over maximum transpiration). Data reported in the 1980s by Hanks and his coworkers at Utah State University demonstrated that the relationship between yield and ET was identical whether high salinity or limited water availability caused water stress leading to reduced ET. However, not all field data support this equality, probably due to salt-induced poor soil-physical conditions, which have a negative effect on crop growth in addition to the osmotic effects of salts in soil water (e.g. Kijne et al., 1988).

Experimental evidence reported by Letey (1993) supports a linear relationship between yield and ET for forages or total dry matter production of non-forages. A linear relationship between the marketable part of the crop and ET has been reported for several non-forage crops, such as corn, wheat, sugarbeet and potatoes. Some crops, particularly row crops, have a linear relationship between yield and ET that extrapolates to a finite value of ET at zero production. Some small amount of ET is required to achieve any production for these crops, primarily because of evaporation. Letey (1993) demonstrates that under these conditions, highest yield per unit of water evapotranspired is obtained by irrigating to achieve the maximum ET based on crop and climatic conditions. Relations between some crops, e.g. cotton lint, and ET are curvilinear, which implies that yield per unit of water evapotranspired is maximal at an ET level considerably below maximum. This approach to assessing the most efficient water use when growing crops with curvilinear relations between yield and ET is valid as long as land resources are not limiting and costly. Irrigation practices that reduce yields require higher land area to achieve the same total production.

Irrigation water salinity and irrigation uniformity significantly affect production and in a similar way. For a given level of applied water, yields decrease with an increase in salinity of irrigation water and they also decrease when the uniformity of water application decreases. This also leads to curvilinear relations between yield and ET, and optimal yields per unit of water evapotranspired are achieved at less than the maximal yield level corresponding to maximal ET.

Usually, in definitions of WUE or water productivity, it is assumed that the crop itself uses all water evapotranspired. However, this is a matter of scale. The assumption is more likely to be correct for a farmer's field, but at the scale of a canal command area undoubtedly some vegetation along canal banks and roads will benefit from the irrigation water. For this reason, Solomon and Burt (1999), distinguish between beneficial, non-beneficial and reasonable water use. Non- productive but beneficial use includes deep percolation of water from the root zone to maintain salt balance of the topsoil, evapotranspiration form wind breaks and cover crops, and also the water used in wetting of seedbeds to enhance germination. These distinctions have proved valuable when considering water balances on different scales to assess the effect of water transfers away from irrigated agriculture.

2.3 Measuring Evapotranspiration

Evapotranspiration is not easily measured. The driving force for transpiration is the difference between the saturation vapor pressure at the temperature of leaf tissue and the vapor pressure of external air. When the leaf and air temperature are the same, this pressure difference is equal to saturation vapor pressure deficit. When the foliage of a crop has developed to the point where ground cover is virtually complete, the rate of transpiration depends mainly on weather (saturation pressure deficit and wind velocity) and on the so-called canopy conductance as used in the Penman-Monteith equation. There are indirect methods for the measurement of transpiration, such as the heat pulse technique tested by Yunusa et al. (2000), who found reasonable agreement between measured and calculated values of transpiration for irrigated grapevines in glasshouses. Evapotranspiration, of course, is made up of transpiration and evaporation. Independent measurement of soil evaporation is difficult. Weather and the wetness of the surface soil govern evaporation from soil under a growing crop, and it also varies with the degree of ground cover. Considerable progress has been made with the measurement of evapotranspiration for a crop with incomplete groundcover, but in practice this remains a complicated issue.

The normal approach is not to measure ET or its components, but to estimate it using the FAO procedure that quantifies ET of crops (also known as their consumptive use of water) by multiplying a reference ET with an empirical crop coefficient. The reference ET represents the non-stressed ET based on weather data taken from a uniformly covered grassed weather station. Allen et al. (1998) describe recent advantages in this procedure which include the development of the so-called FAO-56 dual crop coefficient. Allen (2000) uses this method in a study in which various ways of calculating ET for an irrigated area in Turkey were compared. Perhaps the most telling phrase in the paper is that before comparison, the predictions of actual ET by the FAO-56 procedure were reduced by 15% to account for the less than pristine crop establishment, growth and water management in the area. In general, the various predictions of actual ET, reported in the literature, are found to be within 20% of each other.

Considering the inherent uncertainty in ET estimates, confidence limits of the estimated values should be presented if possible (see Clemmens and Burt, 1997). Unfortunately in many modeling studies, including those used to link possible food shortages with water scarcity, did not explicitly consider the effect of uncertainty in the yield-evapotranspiration relationship arising from uncertainty in the evapotranspiration parameter. For modeling studies, in case standard deviations of ET estimates cannot be calculated because of lack of data, one should attempt to assess the consequences of an assumed uncertainty in ET on the outcome of the study.

2.4 Plant and Crop Level

2.4.1 Enhancing Water Productivity by Plant Breeding

Plant breeding over the last century has indirectly increased water productivity because yields have increased with no additional water consumption. Improved varieties have come from conventional breeding programs where selection has been for yield per unit of land. Most of the increases have been due to improvements in the harvest index (the ratio of marketable product to total biomass), that some have argued may now be approaching its theoretical limit in many of our major crops. The development of an appropriate phenology by genetic modification so that the duration of the vegetative and reproductive periods are matched as well as possible with the expected water supply, or with the absence of crop hazards, is usually responsible for the most significant improvements in yield stability. Planting, flowering and maturation dates are important in matching the period of maximum crop growth with the time when saturation vapor pressure deficit is low, and may be genetically modified. One way to genetically improve water productivity is to modify canopy development to reduce evaporation from the soil surface. Hence much work has been done on the selection for large leaf area during the vegetative period to increase early vigor. Recently reported system analysis studies of crop growth (Sinclair and Muchow, 2001) confirmed the importance of leaf size, seed growth rate, and depth of water extraction on water productivity.

Biotechnology is considered to have great potential for the development of drought- or salt-tolerant crops (see, for example, the article by M.A. Altieri in the March 30, 2000 issue of the San Francisco Chronicle, referred to in the Report of the NGO Committee, CGIAR MTM meeting, Dresden). At present, many researchers, including in CGIAR centers, are trying to find practical solutions to realize this great potential of biotechnology, e.g., by trying to transfer traits for virus resistance, greater nutritional value and salt tolerance into food crops. The expectation is that techniques in molecular biology will be useful in regulating some of the conservative characteristics in cultivated species that influence water productivity. For example, it may be that some irrigated crops are too conservative in that they readily shed leaves, flowers and fruiting bodies as soon as water deficits develop. The genetic regulation of cyclokinin production may result in less conservative responses to drought and to greater yields. However, it could also be argued that conventional breeding could more easily and effectively alter these processes. For example, in tomatoes genes for growth under saline conditions are present in wild relatives of tomato. Genetic modification to incorporate these genes in cultivated varieties is therefore not necessary. Cross breeding of wild and cultivated varieties has produced good tomato varieties that grow well under saline conditions (Voorrips, 2000). Nevertheless, molecular biology is likely to make a significant contribution to the genetic improvement in water productivity by the provision of new tools, in the form of molecular markers, or tags, for traits plant breeders wish to select.

2.4.2 Sensitive Stages and Crop Water Production Functions

There are two approaches to estimating crop-water production functions. The first one is to develop these functions from theoretical and empirical models of the several components of the process by which crops take up water. Parameters characterizing this process are either measured directly or estimated. The other approach is to estimate production functions by statistical analyses of the correlation between yield and production factors (evaporative demand, water application, soil salinity, fertility, and other variables). Much research has been done on the synthesis of crop-water production functions.

Several researchers have developed expressions that incorporate the different sensitivities of crops to water stress during the various growth stages. The reason for this interest in sensitive stages lies in the desire to apply irrigation water in water-short conditions when the application of water has most effect on yield. Initially, this growth stage was taken into account as follows:

$$Y/Ymax = \Sigma\ (ET/ETmax)^{\lambda}$$

where ETmax is the maximum seasonal evapotranspiration corresponding to the maximum yield; ET is the actual seasonal ET corresponding to actual yield; the summation is over all growth stages and λ is the sensitivity index of the particular growth stage. Later, Jensen (1968) developed an alternative formulation which has the product over successive growth stages rather than the summation, to account for the residual effect of a water shortage in an earlier growth stage. To give an extreme example, complete failure because of drought during the first growth stage cannot be corrected by adequate water supply later in the season. This interstage dependence is also known from conditioning of a plant for water stress during early growth stages. For example, the reduction in plant size by early stress appears to harden a maize crop so that a deficit following the pollination period has less effect on the yield. The well-known Doorenbos and Kassam (1979) equation

$$(1-Y/Ym) = ky(1 - ET/ETm)$$

is widely used to estimate relative crop yield from relative evapotranspiration with variable ky, the yield response function, for different parts of the growing season. The usefulness of this type of relationships between yield and evapotranspiration depends crucially on the accuracy of the sensitivity index λ or yield response function ky, whose values appear to be to some extent site specific (Vaux and Pruitt, 1983; Ghahraman and Sepaskhak, 1997). Much research continues to be done on water-yield relations and sensitive growth stages, often as part of studies on the effect of deficit irrigation, to be discussed in a later section.

2.4.3 Yield-Water-Salinity Relationships

The response of crop yield to soil salinity, mainly in the absence of water stress, has been studied extensively. (e.g. Maas and Hoffman, 1977, and Letey et al. 1990). Data from yield-water and yield-soil salinity relations have been combined with models relating saline water application to soil salinity to construct water-salinity-production functions that relate crop yield to the volume and salt content of applied irrigation water. To some extent these relations are simplifications of a more complicated reality since yield is related to average soil salinity in the root zone and over time, to the salinity and the volume of applied irrigation water and to the volume of drainage water. These parameters are interdependent through the process of leaching. Leaching to maintain an acceptable salt balance in the root zone is often considered by non-specialists as wasteful, especially as irrigation engineers and scientists appear to be in doubt about the required leaching rates and the efficiency of the leaching practice. For example, the extent to which so-called bypass or preferential flow through the soil profile influences the efficiency of leaching slats from the root zone is largely unknown. Because of the high cost and complexity, only a few field experiments have been done that were specifically designed to investigate relationships between amount and quality of irrigation water and the resulting yields, soil salinity and drainage volume and quality.

As was alluded to before, salinity and non-uniformity in irrigation water application appear to have much the same effect on the yield-water response function: the response surface becomes skewed and flattened. Hence larger amounts of irrigation water are required to produce yields that are equal to those obtained with non-saline irrigation water and uniformly applied irrigation water. Perhaps one may conclude that yields tend to be lower in actual field situations, where spatial variability is a factor, than predicted by models that do not take variability (sufficiently) into account. In general, models seem to predict yields obtained with saline irrigation water reasonably well, but only up to a level of salinity of 3.5 dS/m (e.g. Dinar et al., 1991).

Likewise, the threshold relations of salt tolerance of crops, developed by Maas (1990) appear not to hold for actual field situations. Yield reduction has been found to occur at lower values of soil salinity than predicted by the salt tolerance data of Maas and co-workers (e.g., see Hussain et al., 1995). Salt tolerance is also dependent on growth stage. Maize (corn) seedlings were found to be much more sensitive to salt than older maize plants and seedling growth more sensitive than seedling emergence (Maas et al., 1983). Salt tolerance is obviously not completely predictable as it is also influenced by differences between cultivars, evaporative demand (e.g. temperature and humidity), soil conditions and cultural practices, and hence differences between measured and predicted values are expected. A serious limitation of virtually all water-salinity production functions is that the adverse effect of saline irrigation water, especially of sodic water, on soil physical conditions (i.e., reduced infiltration rate, lower hydraulic conductivity, crusting of soil surface and hardpans) is not accounted for.

2.5 Field Level: Agronomic Practices

2.5.1 Interaction of Water and Nutrients

Inadequate crop nutrition of irrigated crops has a negative effect on water productivity through reductions in leaf area, dry matter, and the quantity and quality of the economic yield. When nitrogen limits crop yield, higher rates of applied N increase water productivity, perhaps by as much as 40% (Rhoades, 1984). In general, fertilizer applications can result in improved root development and soil water extraction from deeper soil layers resulting in higher yields per unit of water evapotranspired, especially under conditions of complete soil cover. The interdependence of rainfall and nutrition in rainfed agriculture is complicated. Apparently in some rainfed situations, fertilizers reduce economic yield by permitting rapid early-season crop development and accelerated depletion of soil water reserves during or before drought-sensitive growth stages. Monitoring of site-specific water and nutrition status is required to establish the appropriate amounts of fertilizers for the specific soil water retention and rainfall conditions. General statements, such as that in sub-Saharan Africa N application is only economical in areas with at least 900 mm annual precipitation, cannot be made with confidence. Actual crop water requirements and hence water productivity depend primarily on rainfall variability and modality in Sub-Saharan Africa with its bi-modal rainfall pattern.

2.5.2 Environment and Water Issues

The environmental consequences of intensive irrigated agriculture are well documented. For example, farmers in USA, Australia and Western Europe now face constraints on their nutrient management because of the impact on the environment of their fertilizer applications. Nitrogen is a potential pollutant as well as an essential plant nutrient and fertilizer use is one of the contributing factors to elevated NO_3 concentrations in groundwater. Deep percolation of water below the root zone following irrigation transports N and other fertilizer residues to the groundwater.

Water quality, both in surface waters and in aquifers, is often adversely affected by irrigation. Experimentally quantifying the combined effects of irrigation amount, water salinity and N management on yield and chemical leaching is expensive, and various models have been developed to predict these effects. The greatest utility of these models is probably to account for complicated feedback mechanisms between the plant and the soil-water-chemical system. For example, salinity reduces plant growth, which leads to lower evapotranspiration, which leads to more leaching and the removal of more salt and also N and pesticide from the root zone. In turn, reduced N causes reduced plant growth, reduced evapotranspiration, more leaching and even less N in the root zone. Presumably, this process continues until some sustainable, low-yield level has been attained. When the environmental situation requires reducing NO_3 movement to the groundwater, the tendency has been to focus policy on the amount of N application to achieve this goal. Based on model studies, however, irrigation management has been identified as being of equal or greater importance than N application in reducing N leaching. This has been supported by field observations of NO_3-N in drainage effluent from many farms in California (Pang and Letey,1998). The main shortcoming of the models is that no denitrification is assumed. They therefore over-predict the amount of N available for plant growth or for leaching under conditions conducive to denitrification.

Apart from its effect on water quality, also the amount of water available for sustaining environmental health is affected by irrigated agriculture. In many countries, agriculture and natural ecosystems are in a stiff competition for the scarce water resource. Probably in the recent past it was agriculture that was allowed to have water at the expense of the environment. As a consequence, wet lands fell dry and biodiversity was reduced. The relation between agriculture and the environment, however, is gradually changing in favor of the environment. Hence the importance of concerted efforts to increase the productivity of water in irrigated agriculture.

2.5.3 Cultural Practices and Water Productivity

A number of cultural effects on water productivity have been noted in the literature. Cultivar selection (with its specific growing season length, harvest index, and disease resistance) and planting date, seeding rate, raised beds, row spacing, row orientation, intensity of tillage, mulches and residue management can directly affect crop yields. For example, it is well known that the productivity of water of crops grown during the winter is higher than of those grown during the summer when the evaporative demand is higher. Obviously, moving planting dates and growing seasons to periods of low evaporative demand increases the productivity of water.

These various cultural and agronomic practices are effective in increasing water productivity through effects on crop radiation interception, the partitioning of rainfall or irrigation between infiltration and runoff, the partitioning of evapotranspiration between evaporation and transpiration, and the harvest index (Howell et al., 1990). Alternate-row irrigation, minimizing pre-planting and land preparation irrigation applications, and reducing the period between irrigation for land preparation and the transplanting of rice seedlings can cut down on water losses through evaporation and deep percolation. Land preparation is very water demanding, for example, up to 1500 mm on otherwise suitable heavy-textured soils that crack while drying following harvest of the previous crop (Tuong et al. (1996). As mentioned before, water savings at field or farm level don't necessarily translate into savings at system or basin level. This depends on whether the water flows to a sink, e.g. percolates to saline groundwater or flows into the sea, or can be captured and reused again before it flows to the sink.

Direct seeding of rice can probably reduce such water losses, but the evidence is not conclusive yet (see Guerra et al., 1998). However, it has been said that direct-seeded rice crops have more disease, insect and weed problems and thus would require new pest and weed management strategies, including the use of herbicides and pest-resistant cultivars (Timsina and Connor, 2001). Intermittent irrigation of rice, which allows the soil surface to dry out between irrigations instead of growing the rice in standing water, will also increase water productivity in rice cultivation. It has the added potential advantage of controlling malaria and Japanese encephalitis (Van der Hoek, et al., 2001).

Considerable uncertainty exists under actual field situations in the values of soil and management parameters, such as field capacity, wilting point and sowing data, which are essential input data for modeling studies. Soil water retention parameters (water content at saturation, field capacity and permanent wilting point) were found to be the most sensitive to errors of estimate (Bouman, 1994). For example, to obtain an accuracy of about 10% in predicted yield in average weather years, water content at field capacity and saturation should be known with 0.01 (volume fraction) accuracy, and at wilting point with 0.02 accuracy. The uncertainty in the simulated yield was large: there was 90% probability that simulated yields were between 0.6 and 1.95 times the simulated standard yield in average years. In general, accurate yield prediction will be conditional on the availability of accurate soil and management parameters.

2.6 Water Management Level

2.6.1 Improvements in Performance of Irrigation Systems

According to one estimate, an equivalent of at least $250 billion in current prices has already been spent to create irrigation capacity in developing countries alone (Bhatia and Falkenmark, 1992). Public irrigation investments have become an enormous burden on government budgets because cost recovery has fallen short of even modest targets. In many countries, including India and Pakistan, irrigation receipts were less than the costs of operation and maintenance. Annual irrigation subsidies are estimated to be of the order of over $500 million in Pakistan and more than twice as much in India (Bhatia and Falkenmark, ibid.).

Without proper techniques for monitoring physical performance of irrigation systems, it is impossible to assess the potential benefits that may accrue from further investments to improve them. Identifying and evaluating indicators for irrigation performance has started only in recent years, and the use of such indicators is unfortunately not yet widespread. Molden and Gates (1990) have introduced performance parameters for adequacy, efficiency, dependability and equity of water delivery, which are time or space averaged values of temporal or spatial coefficients of variation. Sam-Amaoh and Gowing (2001) have developed a methodology for assessing irrigation performance in the absence of water delivery data. The method uses farmers' assessments of the effectiveness of water delivery in the system and analyses the information using fuzzy set theory.

Irrigation methods vary in their water application efficiencies (i.e., the ratio of the amount of water delivered to the root zone and the total amount applied to the soil) and hence in the attainable water productivity values. Sprinkler and drip irrigation methods have the potential to deliver amounts of water more closely to what is desired than surface irrigation methods do. But the surface irrigation methods, ranging from wild flooding to furrow irrigation, are the most widely used in developing countries. Various electronic control systems exist to improve the water application efficiency in furrow irrigation, for example by reducing furrow inflow before the water reaches the end of the furrow, and by controlling the cut-off times. A more sophisticated method monitors the rate of water advance during the first set of irrigations of a field. Based on these data the infiltration rate is determined and used to set the flow rates for subsequent irrigations of the field (Latimer and Reddell, 1990). This system has the potential to improve furrow irrigation management but its use in developing countries is probably non-existent.

Another system, also of limited applicability to date in developing countries, is the low-energy precision application (LEPA) which irrigates alternate furrows only. It has been claimed that LEPA is superior to sprinkler and traditional furrow irrigation in terms of application efficiency, water productivity, and energy saving potential

2.6.2 Deficit irrigation

Deliberately managing crop water applications to create a prescribed water deficit, which results in a small yield reduction that is less than the concomitant reduction in evapotranspiration, is usually called deficit irrigation. The potential benefits of deficit irrigation arise from enhanced water productivity and lower production costs if one or more irrigations can be eliminated. The most extensive use of deficit irrigation in the USA is in the Texas High Plains. *De facto* deficit irrigation occurred on a wide scale in India and Pakistan, where the original planners had designed the systems for low cropping intensities and low water allowances. Nowadays the situation in some parts of the Indian Subcontinent is more complicated with larger amounts of water available at the farm gate, and widespread conjunctive use of canal water and groundwater. For deficit irrigation to be successful, farmers need to know the deficit that can be allowed at each of the growth stages, the level of water stress that already exists in the root zone, and – most importantly – have control over the timing and amount of irrigations. Recently, an optimization model for deficit irrigation systems has been developed and applied to an irrigation system in Spain (Reca, et al., 2001). The authors claim that with a water market, irrigation supplies can be reduced to as low as 20 to 40% of current applications if the cropping system excludes water demanding crops, such as corn and sugarbeet, and low profit crops (yield per unit of water), such as melon and potatoes. Unfortunately, the model has not been tested in the field.

Perry and Narayanamurthy (1998), amongst others, have pointed out that deficit irrigation carries considerable risk for the farmers when water supplies are uncertain, as is the case with rainfall and unreliable irrigation supplies. Where water availability falls below a certain level, the value of the crop can fall to zero – either because the crop dies, or because the product is of such low quality as to be unmarketable. There is a theoretical trade-off between under-irrigation and uncertainty. If the amount of water that will be received is precisely known, the farmer can aim for the point that maximizes returns to available resources. If there is no water shortage, the farmer will maximize returns per unit of land by applying enough water to maximize net value of production per unit land. If water is scarce, the farmer will reduce his irrigation as appropriate to maximize returns to water. All of this assuming the farmer has control over timing and amount of irrigations.

Flexible water delivery gives the farmer greater control over amount, frequency of availability and duration of irrigation supplies This is usually the case with sprinkler and drip irrigation, and with pumped groundwater, if the farmer owns the pump. A totally flexible delivery system for surface irrigation in large irrigation systems is very expensive because of the required over-capacity in the conveyance system. Hence the different levels of water delivery flexibility found for instance in California. In California's San Joaquin Valley, changing from the existing fixed rotational delivery system to a more flexible on-demand system would allow irrigation supplies to be reduced by 35% (Lamacq and Wallender, 1994). However, because of frequent errors in the existing rotational delivery, errors were also introduced into the recommended simulated delivery schedule, which resulted in much smaller benefits of the suggested delivery schedule. This is in agreement with Perry's (2001) observation, also from modeling studies, that fixed schedules perform within 3% of flexible schedules. Well executed, fixed irrigation schedules for typical field crops in India perform as well as sophisticated and responsive irrigation systems, which are far more expensive to install and more difficult to manage.

Irrigation engineers and others have argued for the introduction of demand-driven delivery systems. Demand-driven in the Indian sub-continent is perhaps a misnomer. The area to be irrigated is calculated and sanctioned in relation to known (or expected) variability of supplies. The farmer can only 'demand' water when the canals in his area are running, and then only in a reasonable pattern of timing and flow rate. By contrast, in supply systems, typically with several thousand hectares as the management unit, the schedule of canal operation is defined in relation to the predominant cropping pattern, and the canal schedules are broadly adjusted in light of rainfall and its impact on farm level demands (Perry, 1993). In some parts of China, although the main system is supply driven, farmers do have control over timing and amount of water at the farm gate because the water is stored in small farm ponds.

For conditions in New South Wales, Australia, with much higher rainfall during the growing season of wheat than in India, it was found that weather variability between years would cause the number of irrigations to vary from 2 to 7. Mistiming of irrigations in either a fixed schedule based on mean climatic data or a demand system where farmers order their irrigations before they know whether rain will occur or not, would lead to an inefficient use of water (Mason and Smith, 1981; Smith et al., 1985). The determination of suitable irrigation regimes is even more complex in the presence of a naturally fluctuating water table. In the Tarai region of India, the groundwater contribution to evaporation can vary by about 20% between wet years and dry years (Mishra, et al., 1995).

2.6.3 Health And Water Issues

Since its inception, irrigated agriculture has been beneficial to mankind by providing more and better food. However, the negative effects on human health have also been apparent for a long time in the prevalence of water-borne diseases. The relation between water management practices in paddy cultivation and the incidence of malaria, schistosomiasis and Japanese encephalitis was alluded to in section 2.5.3 above. Intermittent irrigation can help reduce the incidence of these diseases.

The availability of irrigation water has led to non-agricultural water use in irrigation systems, especially by poor people without other sources of drinking and household water. Depending on the quality of the water this may be beneficial or not. An important but hitherto rather neglected area of research is to test whether the operation of irrigation systems can be changed to achieve greater health benefits without negative impacts on agricultural performance. The use of untreated wastewater to irrigate crops, for instance in peri-urban agriculture, carries with it largely unknown health risks. Drainage water quality varies greatly depending on its source. Generally, industrial wastewater is likely to be more hazardous than agricultural drainage water. However, there are exceptions, e.g. where agricultural drainage water contains toxic levels of such chemicals as arsenic or selenium. Increased water scarcity will probably lead to more use of wastewater for irrigation. Site-specific testing of water quality is needed, but is unlikely to happen in the near future in many developing countries.

2.7 Effect of Institutions and Policies on Water Productivity

Improved water productivity may achieve several goals such as increasing agricultural production and allowing economic growth in rural areas. However, it may be asked whether investments in other parts of the infrastructure are not more likely to achieve these goals than investments in irrigation. For example, the steady decline in poverty in India from the mid-sixties to the early eighties was strongly associated with agricultural growth, particularly the Green Revolution, which coincided with massive investments in agriculture and rural infrastructure (Fan, et al., 1999). In IFPRI's analysis of impact of various types of investments on growth and agricultural productivity, the impact of additional irrigation investments came third after rural roads, and agricultural research and extension. Additional government spending on irrigation had a significant impact on productivity growth, but no discernible impact on poverty reduction. While spending on irrigation and also on power have been essential elements in the past for sustaining agricultural growth, the levels of irrigation may now be such that it may be more important to maintain the systems than to increase them further (Fan et al., 1999). IFRI's studies have also indicated that the marginal returns to several infra-structural investments in India are now higher in many rainfed areas. They also have a potentially greater impact on reducing rural poverty (Bhalla et al, 1999).

It is difficult to account for all additional potential benefits of irrigation, such as health benefits resulting from better nutrition and greater rural employment, when weighing the pros and cons of new investments in irrigation against the benefits of other investments. In the past, benefits were often exaggerated in order to get an acceptable rate of return on the investment to ensure that the construction of additional irrigation systems would be implemented (Jones, 1995). Many of the irrigation benefits are site-specific and no generalizations can be made.

Specific water related policy issues include the need to have secure water rights in terms of water quantity and its quality, appropriate water pricing, and laws pertaining to water user associations. A legally secure water right is needed in potential conflict situations between water users when (part of) a water right is transferred, e.g. from agricultural to urban regions in a regulated water market, to enhance economic water productivity. The concept of water rights, however, is considered completely alien in rural areas of many developing countries. Water pricing is equally controversial. When water is a scarce good, it becomes part of good management practices to measure flows and price the water. The suggested price level probably depends foremost on whether one sees water as an economic good or also recognizes its social value.

Do pricing mechanisms have a role in encouraging more efficient water and energy use? Studies by IWMI and other, e.g. in Iran, Pakistan and India, have shown that the charge for water required to substantially affect demand would be about 10 times the charge required to cover operation and maintenance costs. A charge sufficient to cover these costs will have minimal effect on the demand for water (Perry, 2001). Introducing volumetric charges for irrigation water is difficult and involves considerable expense for the installation of measuring structures and for fraud prevention, especially in areas with many small farms, such as found in the Indian sub-continent.

Laws pertaining to water user associations deal with devolution of water rights from centralized bureaucratic agencies to farmers and water user associations. Devolution has a number of advantages, one of which is the empowerment of the user by requiring user consent to any reallocation of water, and compensation for any water transferred.

Hassam et al. (2000) illustrated the trade-off between economic efficiency and food self-sufficiency by an example from Sudan. They found that cotton yields per ha currently achieved by farmers in the Gezira generate economic returns that are sufficient to import about 50% more wheat than can be domestically produced on the same area. Cotton also has larger employment benefits than wheat. Expanding irrigated wheat production in the Gezira for food self-sufficiency at the expense of cotton would therefore compromise economic efficiency. The introduction of more effective policy measures for the adoption of improved wheat technologies to close the gap between potential and current yield levels could change the balance between the relative benefits of cotton and wheat production. A rise in the world market price of wheat would have the same effect. This study supports Allan's (2000) argument in favor of the import of 'virtual water' in the Middle East instead of attempts to achieve food self-sufficiency in the region. As Pingali and Shaw (2001) have pointed out, policies designed for achieving food self-sufficiency tend to undervalue goods and the products of resources (e.g. land and labor) that can be traded internationally.

It has been calculated that in the 1980s, 10% more yield per unit land gave rise to 4% more jobs in agriculture; now 10% more yield results in only 1% more jobs in agriculture (Michael Lipton, Crawford Lecture, 28 October 1999, CGIAR, Washington DC). Hence, yields have to grow much faster for employment opportunities to increase in the rural areas of developing countries and for more people to be able to purchase their food. This highlights the importance of economic growth that results in more jobs in urban and rural areas alike. The issue of employment in agriculture is complicated. Many young people in rural areas, for example in the Indian sub-continent, seem to be under- or un-employed, while at the same time there appears to be a labor shortage. For example, often farmers apply excessive depths of irrigation water to make sure all the high spots in the field are covered, rather than spend the labor to level the field. In other words, water is substituted for labor. This may make economic sense only as long as water is not scarce.

There is considerable uncertainty in farmers' behavior. Some farmers will tend to accept risk in anticipation of greater profit, while others will tend to avoid risk even when there is a potential for high profit. In terms of food security, achieving a long-term average lower yield, while keeping the associated risks lower, may be preferable to a somewhat higher long-term yield with higher risks. Th is especially true for developing countries with lower buffering capacity in terms of food or money for lower yields in a less productive year.

2.8 Conclusions

At least four areas of uncertainty affecting water productivity have been identified in this paper. First, there is uncertainty in the estimation and measurement of evapotranspiration. There is also uncertainty in models relating crop yields and the amount and quality of applied water. Thirdly, there is considerable discrepancy between yield prediction from models with a limited number of variables and the actual yields obtained in farmers' fields. And finally, there is uncertainty in farmers' behavior vis-à-vis choices that involve risk taking, especially when they are faced with less water than they were used to.

Soil matric stress (because the soil is dry), osmotic stress (because of high salt content in soil), non-uniformity of water application, and spatial variability of crop stand, soil characteristics, fertilizer application, probably all happen at the same time in farmers' fields. These fields, consequently, exhibit different yield-growth factor relationships than occur under controlled experimental conditions, resulting in reduced growth and lower water productivity. Monitoring these various factors in farmers' field is probably the only way to improve our ability to predict actual yields. This type of field experiments is expensive.

Models can help in understanding the complexity of interacting factors affecting yield, but they have to be verified under actual field conditions.

Deficit irrigation, which in theory may lead to higher water productivity, carries considerable risks for farmers if they have insufficient control over their water supply. Conditions for success of deficit irrigation were found to include flexibility in amount and timing of water delivery and farmers' control over water delivery. Improvements in water delivery schedules to ensure high water productivity are not easy and come at a cost. Unfortunately, benefits and costs of deficit irrigation and of various other cultural practices that could lead to higher water productivity are usually not assessed. Therefore, we don't know why these improved technologies and other agronomic and cultural practices have not been adopted or at least not on a wide scale. Further work on the conditions for success of the introduction of water productivity enhancing measures, including water pricing and water markets should include economic analyses. Much of the work, including the field experiments mentioned in the previous paragraph, could be done by or in collaboration with national agricultural research centers. Obviously, this type of applied research remains immensely important.

As some of the examples in this chapter make clear, research focus in developing countries and in the western world have moved in different directions. In the latter, the focus of research in water management has shifted to include environmental problems (other than salinity). Sophisticated models, for example developed in California for water, nutrient and salt balances in irrigated lands, have at present only limited application in developing countries. This is not only a matter of availability of data but it also results from far less political and societal attention in most developing countries for the negative impact of agriculture on the environment. This is bound to change over time as for instance illustrated by the existence of environmental action groups with respect to dam building.

Enhancement of scientific knowledge on the pressing issues in water productivity in agriculture, with specific reference to the problems in developing countries, should therefore be an important research area for CG centers in collaboration with NARS, as will be discussed in a later chapter.

A fundamental question that was raised in this chapter concerns the economic utility of further investments in irrigation development other than operation and maintenance of existing systems. It is recognized that there are vast differences in this respect among developing countries, and IFPRI's conclusions for India can not be assumed to be valid for other countries without further studies. But it certainly points to an important research area. From this review it is not immediately apparent whether greater gains in water productivity in agriculture are to be expected from improvements in irrigation (e.g. better system performance, re-use of drainage water, etc.) or from genetic improvements in our common food crops.

3 Current World Situation on Water: International Organizations and Cooperation

There are many international organizations mandated to work on some aspects of water. There are at least four categories: international NGO's and UN institutes, international research institutions, university departments whose studies are of international importance, and private sector organizations.

3.1 NGO's and UN Institutes

The Global Water Partnership (GWP) and the World Water Council (WWC) belong in the first category. They were started some five years ago with the specific aim of bringing the various users of water together. GWP is an association covering all uses of water and focuses on integrated water resource management (IWRM). In its first few years GWP developed the concept of IWRM as a holistic, interdisciplinary way of studying and managing water management at a river basin lev el, which includes economic and environmental issues in the use of water resources. GWP initiated several discussions between different water users. The organization played a major role in the preparations for the Second World Water Forum, held in March 2000 in The Hague, the Netherlands, for which GWP wrote a document entitled Towards Water Security: A Framework for Action. One of the objectives of this plan was to get activities going in several parts of the world. GWP has now evolved into a network of regional partnerships. GWP is not a research organization but supports the synthesis of knowledge as well as capacity building. GWP assists in developing awareness on critical water issues, but the World Water Council was set up with the explicit aim of developing awareness on water issues. Every three years a World Water Forum is convened every three years by WWC. At the second of such meetings, in The Hague, the World Water Vision was presented which was prepared under the guidance of the WWC.

FAO's Water Resources Development and Management Services (AGLW) has as its mission to promote efficient use and conservation of water resources to achieve food security and sustainable agriculture and rural development. One of the key programs is the dissemination of statistics on irrigated agriculture through the AQUASTAT program (e.g., the recently produced Atlas on Water Resources and Irrigation in Africa, on CD-ROM). Others are the preparation of state-of-the-art papers on technical subjects, staging technical consultations on water management topics, and organizing training seminars and country reviews. The aim of AGLW's Water and Sustainable Development Program is to implement the promotion of sustainable agriculture through the application of the principles of integrated rural water management in agriculture, aquaculture and agroforestry. This program doesn't seem to be as active now as it was in the early 90's. FAO-AGLW is an active partner of IWMI as will be explained below.

Other international organizations, which are IWMI's partners in the Dialogue[2] on Water, Food, and the Environment to be launched at the Stockholm Water Symposium in August 2001, are the International Commission on Irrigation and Drainage (ICID, a world-wide organization of practitioners in irrigation and drainage), World Conservation Union (IUCN), United Nations Environment Program (UNEP), and the World Health Organization (WHO).

3.2 International Research Organizations

One of the other, non-CGIAR, international research organizations is the International Program for Technology Research in Irrigation and Drainage (IPTRID). It is based at FAO

[2] The Dialogue will be discussed in Chapter 5, as it is part of future water-related research and development in the CGIAR. All IWMI's partners in this Dialogue are listed there.

and was set up by the World Bank to promote research in irrigation and drainage in the public sector. It is not a research organization itself, but was supported by and collaborated with several research organizations. It has undergone a recent (2001) review and was found to require substantial change. It is envisaged that it will link more closely than in the past with advanced research organizations. IPTRID is expected to form a network of institutions to coordinate some of the irrigation and drainage research. Its impact so far on irrigation and drainage research worldwide has been small.

Recently the International Center for Biosaline Agriculture, (ICBA) has started its work in Dubai with support from the Islamic Development Bank. Its research and development focus includes irrigation with brackish water, propagation and management of halophytes for optimum production, and plant genetic resource characterization, evaluation, documentation and data management. The institute will initially address the problems in the member countries of the Gulf Cooperation Council, and later on scale up to deal with similar problems in other arid and semi-arid countries, especially in the Mediterranean region. ICARDA and CSA have signed a Memorandum of Understanding with ICBA.

Others included in this category are national institutions with an international mandate. These include the International Institute for Land Reclamation and Drainage (ILRI) in Wageningen, the Netherlands, which aims to assist applied research institutions in developing countries to obtain, to translate, and to apply development-related international knowledge for more sustainable use of land and water. Another, also located in the Netherlands, is International Institute for Infrastructural, Hydraulic, and Environmental Engineering (IHE) in Delft. Its objective is to be an international platform where the transfer of knowledge is taking place to all parts of the developing world. Two institutes are located in Great Britain: the Institute of Irrigation and Development Studies (IIDS) in Southampton, which aims to be a center of excellence for teaching in water-related engineering for rural and urban communities in less developed countries. The other is HR Wallingford Overseas Development Unit (ODU) with its mission to be a viable expert group capable of assisting poorer countries in improving the productivity of their investments in water resources through innovative solutions and problem solving capabilities.

Of equal or perhaps even greater importance are national research institutes in developing countries, such as the Soil Salinity Research Institute in Karnal, India, the National Water Research Center in Egypt, and the Pakistan Agricultural Research Council of Pakistan, to name but a few.

None of these lists are exhaustive but they serve as illustrations of institutions that so far have been much involved in the development and dissemination of synthesized knowledge in the field of water resources for agriculture.

3.3 University Departments

Many universities in the USA, Europe and Australia have departments involved in research and teaching of issues of considerable significance for the improvement of water productivity in agriculture. Some of this work was mentioned in Chapter 2. Several universities have entire departments with an international, water-related focus. At other universities there are just one or a few staff members with international experience (e.g., as former staff members of CGIAR centers) who continue to do research studies of relevance for water problems in developing countries.

In the USA, two universities come to mind where there is a designated institute for water-related work: the International Irrigation Center at Utah State University, Logan, Utah. This Institute is linked with the Department of Biological and Irrigation Engineering, which (under different names) has a long history of relevant irrigation and drainage studies. The other is Cornell International Institute for Food, Agriculture and Development, at Cornell University, Ithaca, NY. The latter institute has a broader mandate than IIC at Logan, Utah, but it also has a long history of research and development of water-related issues. Institutes at other US universities may be less well known than these two, but several other (e.g., the Leopold Center for Sustainable Agriculture at Iowa State University, Ames, Iowa) are also involved in development studies, including water related research. The Berkeley, Davis and Riverside Campus of the University of California have also done much water-related research, but in recent years the emphasis has shifted from field studies to model studies, many of which address environmental problems associated with US agriculture, which are not yet relevant for developing countries.

3.4 Private Sector Organizations

Engineering consultancy firms in western and developing countries continue to be active in the construction, maintenance and rehabilitation of irrigation and drainage systems in developing countries. As best they are involved in the application of synthesized knowledge, perhaps generated at their own organizations or developed at recognized research institutions. At worst, their work still shows the same shortcomings and imperfections that have characterized much irrigation construction and rehabilitation work over the last fifty years. Organizations, such as GWP and others mentioned above stimulate the dissemination of research findings that are relevant to the work of the engineering firms.

One of the members of GWP is the Water Association Worldwide (WAW), which itself is a network of associations of private sector firms from many countries. Member organizations of the WAW are American Water Resources Association, American Water Works Association, Associacion Interamericana de Ingenieria Saitaria y Ambiental, Australian Water Association, Environmental and Water Resources Institute of the American Society of Civil Engineers, Charter Institute of Water and Environmental Management, European Water Association, International Water Association, New Zealand Water and Wastes Association, and Water Environment Federation. The private sector organizations brought together in WAW appear to be mainly from western countries and Latin America. Perhaps no such umbrella organizations exist in Asia and Africa, which would make it more difficult to involve local engineering firms in a dialogue on policy matters or disseminate to them recently acquired knowledge on best practices for improving water productivity in agriculture.

3.5 Conclusions

Opportunities for collaboration between CGIAR and international organizations on water productivity issues exist at various levels. In terms of research, strategic and applied, the most likely candidates are other international and national research organizations, not only in the western world but increasingly also in developing countries, most of which were not mentioned by name. Other potential research collaborators include university departments and individual researchers with relevant experience and interests.

On policy matters and awareness building collaboration can be channeled through organizations such as GWP and WWC which reach many different water users in a wide range of countries. An example of the latter is IWMI's initiative on the Dialogue on Water, Food, and the Environment to be discussed in more detail elsewhere in the paper.

Collaboration with the private sector on research issues is always complicated by the fact that many engineering firms cannot make their research findings available as an international public good. On policy matters, under the umbrella of GWP and WWC, collaboration with the private sector may be more fruitful.

4. Water-Related Research in the CGIAR: Past Experiences and Present Situation

4.1 Introduction

The research studies in the field of water productivity that are currently being undertaken by CGIAR centers can be categorized in four groups. These are plant breeding for greater tolerance for drought conditions and salinity; studies on soil and water conservation measures at field and farm level; water management studies at system and basin level; and studies on the economics and policies that are expected to enhance water productivity in agriculture. These categories will be used in the following overview, which is the result of a desk study of the most recent annual reports of the centers, some medium term plans, and various TAC documents that will be referred to in the text. In section 4.6 we will assess current research activities in view of the CGIAR priorities and strategies for water aspects of research in natural resource management (NRM).

4.2 Plant Breeding Research

All commodity centers are involved in crop genetic improvement programs, both though conventional plant breeding and molecular biology. CIMMYT, for example, in a paper on "reducing plants' thirst at molecular level" describes plant breeding to increase tolerance of maize for drought and nitrogen stress. Centers are working together on developing technologies in molecular biology that appear to be promising in this respect. The 1999 Strategic Planning Workshop on Molecular Approaches for the Genetic Improvement of Cereals in Water-limited Environments has given a boost to this inter-center exchange of information. It appears that in maize, rice, wheat, sorghum and millet the same genome regions are linked to an important component of drought tolerance, the duration of the anthesis-silking interval. The approach of identifying molecular markers is expected to speed up the selection process. As in the development of high quality protein maize, the biochemical work may prove to be indispensable in studies on disease and pest control, which probably is now the focus of attention of most CGIAR molecular biology research, but also for drought and salt tolerance studies. CIMMYT and IRRI are collaborating in a maize-rice functional genomics project, which seeks to discover the key genes responsible for drought tolerance and to produce molecular tools that will enhance breeding for the requisite traits.

Meanwhile conventional breeding programs continue unabated. WARDA, for example, reports on studies aiming at widening the genetic base of the West African rice germplasm by successfully introgressing useful genes from indigenous rice varieties into *Oryza sativa* to produce progenies with higher tolerance for and resistance to major yield-limiting stresses in West Africa. CIMMYT has developed experimental varieties of wheat for marginal rainfed environments that were derived from wild varieties and yield up to 2 T/ha where other material is dying from drought. They also report on experimental wheat varieties for irrigated conditions that produce well with only two irrigations instead of the usual four or five. ICARDA continues to develop germplasm for improved drought tolerant barley, durum wheat, and food and feed legumes in collaboration with its partners for North Africa and West Asia. Collaboration in these studies with national partners is mentioned by most centers. For example, IRRI mentions the contributions from Chinese partners who through conventional breeding had developed good high-yielding varieties of upland (non-irrigated) rice that do well despite lack of water.

4.3 Soil and Water Conservation Measures.

Conservation tillage and bed planting systems in rainfed wheat production have led to water savings of 30 to 40% according to studies reported by CIMMYT. The adoption of these technologies in some Latin American countries apparently increases 10 fold each year.

IRRI reported results of research on water management for rice fields. Variations in management included maintaining soil saturation after 40 days of growth, or just before the plants flower. A second one involved reducing the water level from a depth of five cm to soil saturation just a week after transplanting. The third variation was a more complex system of abandoning standing water altogether and irrigating the field every four days to keep the soil saturated throughout the growth of the crop. Reducing water levels limited percolation losses from the field, but also led to yield reduction of up to ten percent. If the soil was allowed to dry out to less than saturation, yield losses were greater still.

ICRISAT has studied means of preventing the large run-off losses often associated with the short intense burst of rain in semi-arid countries. Inexpensive, small earthen dams were found to be effective in reducing gully erosion and forming seasonal reservoirs that recharge depleted wells and extend the cropping season through supplemental irrigation. Land-forming appropriate for small farmers included various treatments such as the formation of bunds, staggered trenches, silt traps, tied ridges, ridge/furrow combinations, contour planting, grassed waterways, vegetative barriers, and dug-out ponds. All of these help to conserve water and cause it to infiltrate into the soil where crops can use it. Water that is not taken up by the crop raises the water table and also the water level in wells for drinking water.

Minimum or no-till relay cropping keeps the soil protected during high intensity rains and shades the soil thus keeping the surface temperatures low and providing better growth conditions for soil-fertility-enhancing organisms. ICRISAT's studies at the Patancheru research station have quantified the potential of these techniques when applied in an integrated fashion. Evaporation and percolation losses were reduced from 45% to 19% of total rainfall, and runoff losses from 25% to 14%. Soil losses from erosion declined by 75% and sorghum yields increased more than threefold to 4 T/ha. Soybean yields and those of other leguminous food crops were more than doubled. It is now being attempted to repeat those successes in community watersheds in Ethiopia, Thailand, Vietnam and elsewhere in India.

In the Rice-Wheat Consortium (RWC), IRRI, CIMMYT and the NARS of India, Pakistan, Bangladesh and Nepal are working together. RWC's aim is to help sustain the productivity of the rice-wheat rotational production system of the Indus-Gangetic Plain. It has four areas of attention: tillage and crop establishment, integrated nutrient management, integrated water management and system ecology/integrated pest management. One of RWC's achievements has been its awareness that factor productivity in the rice-wheat production areas was falling. It recently reported on the successful adoption of zero tillage in Haryana, India.

Studies on supplementary irrigation conducted by ICARDA have shown that water used in supplementary irrigation, i.e. small amounts of irrigation supplementing rainfall that by itself would not suffice for crop production, is far more efficient than irrigation applied without considering rainfall. ICARDA is also involved in soil water management studies that aim to increase the amount of rainwater stored in the root zone by reducing runoff.

ICARDA is one of the co-convenors of the Optimizing Soil Water Use Consortium, a constituent part of the System-wide Soil, Water, and Nutrient Management Program. The Consortium's aim is to develop sustainable and profitable agricultural production in dry areas based on the optimal use of available water. ICARDA and ICRISAT together with NARS and extension services work in 12 countries in West Asia and Africa. Another collaborative effort is the collaborative research program for sustainable agricultural development in Central Asia and the Caucasus in which nine CG centers participate (CIMMYT, CIP, ICARDA, ICRISAT, IFPRI, IRRI, IPGRI, ISNAR and IWMI).

It has been estimated that the potential beneficial results from some rather simple changes in land management, such as reduced tillage methods, could annually 'save' as much as 5 billion m^3 irrigation water and 0.5 billion liter diesel fuel and also reduce pesticide use significantly (Sanchez, 2001). The diesel fuel savings alone would represent an annual reduction of 1.3 million tons of carbon emissions (the principal contributor to global warming). These savings may turn out to be overestimated because the so-called saved water is likely to be used on additional land, perhaps downstream in the basin, or pumped up from the groundwater for other users or for agriculture elsewhere. Nevertheless, these land management changes are beneficial and it is worthwhile to introduce them as widely as possible through participatory approaches with the farmers involved.

4.4 System and Basin-Level Research

In recent years, IWMI has issued several reports on water management at the level of irrigation systems and river basins. Two results of these studies are of importance in the context of this paper. The first one is the distinction between irrigation efficiency and water productivity, mentioned in chapter 2 of this paper, where it was explained that irrigation water not consumed by the plants in evapotranspiration can be – and often is – used again downstream. Hence low values of the traditional irrigation efficiency at field or farm level do not necessarily imply wasteful use of water at system or basin level. However, we should keep in mind also that water management in many irrigation systems can and should be improved.

The other important result is the development of irrigation performance parameters that make it possible to rank irrigation systems according to a set of parameters. These include indicators of irrigated agricultural output, i.e. production per unit area and per unit of water diverted from the source or actually consumed by the crop. The standardized gross value of production is one of the indicators that were developed to compare irrigation performance across irrigation systems. To eliminate the effect of local prices, equivalent yields are calculated based on local prices of the crops grown, compared to the local price of the predominant, locally grown, internationally traded base crop. This equivalent production is then valued at world prices. Relative water supply, i.e. total water supply, including rainfall and capillary rise, over crop demand, and relative irrigation supply, i.e. irrigation supply over irrigation demand, are also used as irrigation performance parameters.

IWMI reported data for the productivity of water in more than 40 irrigation systems worldwide, which demonstrate a 10-fold difference in the gross value of output per unit of water consumed by evapotranspiration. Some of this difference is due to the price of grain versus high valued crops, and certainly not all agriculture can be devoted to high valued crops. But even among grain producing areas, the differences are large, demonstrating a potential for improved water productivity. In areas where water has become scarce, such as in China, IWMI and partners have indeed monitored significant increases in water productivity.

ICRISAT in its Medium Term Plan for 2000-2002 identifies as one of many areas of attention the study of options for more efficient management of watersheds and catchments and to quantify interactions of natural resource endowments on crop performance and water productivity. IWMI and ICRISAT have signed a Memorandum of Understanding with several objections, one of which is to do joined research on watershed management.

4.5 Economics and Policies

Two key research questions in this area are: What are the best ways of allocating scarce water to the many users that need it? and How can we stimulate that agricultural technologies be used and/or adopted for use?

IFPRI's studies aim to improve our understanding of how different ways of allocating water affect economic productivity, poverty and the environment and to suggest fair and efficient mechanisms for allocating and using water. An example of these studies is one of a river basin in Chili that showed that a system of trading water rights could direct water to higher valued uses. It could also encourage farmers to use irrigation to produce high value crops for both domestic and overseas markets, which need not reduce agricultural income significantly. It was found that the farmers could also increase their income by selling their unused rights to industries and cities during periods of little or no water demand.

Many centers follow up on the introduction of technologies by assessing whether the target groups have adopted them. Systematic studies of how to stimulate farmers to adopt new technologies do not appear in the annual reports which probably indicates that they are not high on the centers' agendas. By developing new technologies in a participatory manner together with the target group, one tends to assume that adoption will follow.

4.6 CGIAR Research Priorities and Strategies for Water Aspects of NMR Research

Since the mid-1980s CGIAR has emphasized the importance of productivity- increasing but at the same time resource-conserving technologies and has allocated an increasing portion of its financial resources to furthering their development and use. TAC has reported extensively on natural resources and sustainable practices. Much of this focused on land, water and biodiversity, but was more recently expanded to include fisheries and forests.

TAC, as was mentioned in the introductory chapter of this paper, has recently restated the underlying principles of NRM research specifically with respect to water issues as productivity-enhancing and resources-sustaining. TAC (1995) expressed that NMR research should also take into account the off-site impacts of on-site practices, such as, for example, silted reservoirs, degraded water, and threats to human and environmental health. One consequence of this point of view is the need for a watershed-based, integrated approach to NRM research, especially for work on soil and water management. This approach should also include the study of private and social benefits and costs and the design of institutional mechanisms for compensatory actions at the watershed level.

It is interesting to note that several of the centers have reported that their NRM research takes place in an integrated manner. For example, ICRISAT follows an integrated approach in transforming watershed, for which they coined the phrase "turning the grey areas green". WARDA reported on research on crop and natural resource management (C&NRM) in the upland systems, which showed the potential of the use of leguminous cover crops and the benefits of rock-phosphate on poor upland soils. Other elements were the planting of inter-specific rice varieties, which combine strong competition with weeds and are acid-soils adaptive. Water control and access to markets are also seen as essential elements of the integrated approach. WARDA developed an integrated crop management (ICM) package that was introduced and evaluated with a large group of farmers, in which the farmers' practice was compared with the ICM practice. WARDA emphasizes the importance of complete farmers' adoption of the ICM package, because with partial adoption the potential yield of the plots is no longer as high as with the full package.

A conclusion in TAC (1997, page xiii), however, is that within the Integrated NRM (INRM) framework there is a need for additional focus on specific subject matter. Water is seen as one of those areas of focus that need much greater emphasis within an INRM framework. TAC considers water-related issues, including waterborne diseases, to be some of the key ones that will face agriculture, forestry and fisheries even more pressingly in the future. The System-wide Water Management Program (SWIM) for which IWMI is the convening center was at the time expected to give at least part of this required focus. The Soil, Water, Nutrient Management (SWNM) program had a more narrow water focus, i.e. the soil-water relations.

The TAC (1997, page xv) document also called for research to look at why there is a lack of application of known technologies. Why are the research-generated information and water-saving measures not widely used?

Four priority activities were listed (TAC, 1997, page xvi):

- Make an identifiable contribution to poverty alleviation and environmental protection and enhancement
- Be results-oriented and utilization focused (demand-driven with high probability of use)
- Make optimum use of existing information and fill knowledge gaps
- Build on the CGIAR's international advantage.

The link of NMR with poverty alleviation, central to CGIAR's mission, involves links with a complex process of economic growth, development of food and water security, protection of the environment and natural resources, and in most case, changes in the distribution of benefits from economic development to favor the poor (TAC, 1997, page 8).

Notably, in the priorities listed for soil and water research in TAC (1997, page 19), improved water productivity is not mentioned as an overarching one. The topics, briefly summarized, are:

- In terms of links between productivity-enhancing and resource-conserving: better management of water and nutrient supplies, prevention of soil and water degradation, management of soil fertility.
- In terms of spatial and landscape linkages: the devolution of management to local groups, impacts of agriculture on downstream water supplies; erosion control.
- In terms of links between research and adoption: reasons for limited use of existing information, how to get more effective implementation of existing knowledge.
- In terns of temporal links: measurement of rate of change of natural resources and the impact of such changes on food and water security.

Additional related specific research topics are listed in TAC (1996, page 46). They include studies on soil organic matter, soil biological relations, methods of combating and predicting erosion, managing water (see below), better models for water and solute movement in the soil, management of soil nutrient fertility, movement and reaction of nutrients, modeling in general, measurement of the status and trends of natural resources, local government and decentralization, and increasing crop and other enterprise productivity in a sustainable way. Indeed a very broad spectrum, but written more from the perspective of the study of soils than of water.

The research topic on water management for greater efficiency refers especially to rainfed agriculture.

The first priority activity listed in TAC (1997, page xvi, see above) linked poverty alleviation and environment protection. Protection of the environment is a complicated matter, as was lucidly explained in TAC (2000b). Its authors argue convincingly that a given biophysical change can result in values that run along a continuum from negative to neutral to positive. The example presented refers to a hypothetical technology resulting from CGIAR research that may affect stream flow downstream from where it was applied. The ultimate impact of that change on people could be negative if it contributes to the magnitude or frequency of flooding, or exacerbates the problems of drought. The impact would be neutral if adequate flow occurs with or without the innovation, and positive if the change contributes to water flow continuing longer into the dry season. Such environmental impacts are quite site-specific and difficult to predict. Actually, CGIAR's productivity research could affect downstream water supplies both ways. In rainfed agriculture water-conserving practices or an increase in the area upstream planted with water demanding crops would reduce water availability downstream. Alternatively, the development of drought-resistant or less water-demanding varieties for the upstream area could release more water for downstream users.

The basic points made in the paper are that (i) most CGIAR innovations eventually will result in changes in the environment or in the biophysical conditions; (ii) the changes have to be linked to impacts on people, i.e. be given in economic and/or social terms; and (iii) it is in the context of changes over time that issues of sustainability become important. Often impacts are not all negative or all positive. For example, irrigated agriculture has positive impacts because of the resulting increase in food security, but negative ones because of salinization and drawdown of the groundwater level. Another example is land and water degradation induced by crop intensification in Asian rice mono-culture systems as well as in the rice-wheat systems of India and Pakistan. It is difficult to express these various opposite impacts in quantifiable terms. The authors of TAC (2000b) argue that the great majority of research by CG centers can be said to be either neutral or positive to the quality of the environment. The exception is the contamination of soil and water through the increased use of agro-chemicals. There are, however, also the obvious tradeoffs in productivity and poverty alleviation that must be evaluated.

4.7 Trends in water research for the CGIAR relative to other international organizations

Comparing current research efforts on water issues in CG centers and the rather lofty priorities and strategies as formulated by TAC in this respect, a gap appears between what is being done and what is needed for CGIAR to contribute substantially to solutions to the most pressing water issues. One obvious reason for the discrepancy is that a clear focus on water productivity, i.e. productivity per unit water used by the crop, is new. Earlier work dealt with the more familiar topic of soil-water. Understanding of the urgency of such a clear focus on water productivity is also relatively new, and not only in the CGIAR. Other organizations, such as FAO, have also only recently recognized water productivity as a high priority area. International institutions involved in the organization of the World Water Forum meetings have been very helpful in communicating the potential hazards of continuing using water as if it were an unlimited resource.

One consequence of water-related research in the CG IAR being relatively new is that it is fragmented and lacks a clear focus. The concept of water productivity is not yet pervasive to most CGIAR research on water. It may be crucial to the study at hand, but so long as water productivity is not seen as the central issue, the research has few links with other water-related research. The categories used in sections 4.2 – 4.5 to describe current CG research activities related to water indicate the different approaches and different disciplines involved in these studies.

As was described in some detail in Chapter 3, there are no international research institutions exclusively dealing with water-related issues across the entire range of water uses, including drinking water supplies, industry, agriculture and environment. Fragmentation in research efforts is therefore unavoidable. But CGIAR's focus on water within agriculture, its interdisciplinary approach to research, and its international reach, should all help to make its water-related research less fragmented than it is now.

Studies on the implementation of soil and water conservation measures, as described in section 4.3 above, are applied research. It is recognized both that these studies are much needed and that they border on development and extension. The integrated crop management approach, as for example found in WARDA's research program in the Sahel, encompasses many aspects of the crop production system. This type of work was at one time known as farming systems approach. It could be asked whether CG centers have a clear comparative advantage here. Over time, more and more of this work is being done by NARS and other partners of the centers. Guidance and collaboration by CG centers, especially with respect to research design and data analysis and interpretation may still be needed.

On the other hand, it can be argued that a major shortcoming of much past agricultural research has been the focus on one or a few factors as a means to improve production. It is now recognized that improving only a few growth factors while neglecting other crop management factors will not lead to optimal yields. CGIAR, therefore, firmly believes that lasting improvements in production can only come if the whole production system is taken into account. The emphasis on integrated NRM research is therefore correct. As was illustrated in chapter 2 of this paper, water productivity research has many aspects. How this dilemma of the need for simultaneous focus and a holistic approach in research could be bridged in future CGIAR research will be addressed in the next chapter. Meanwhile, it may be of some comfort to realize that other research organizations also struggle with this dilemma of focus and integration.

5. Water-related Research in the CGIAR: A Vision for the Future

5.1 Introduction

Several scenarios for the future were presented at the Second World Water Conference in The Hague, March 2000. One of these described what could happen when past trends in water use were allowed to continue in a business as usual manner. Another painted a slightly more hopeful scenario, by assuming certain changes would take place. Such scenarios are excellent tools to draw attention to problems, which are by some perceived as very urgent and are completely ignored by others. In this case, the issues are increasing water scarcity and hence fiercer competition for water that is likely to reduce available flows for agriculture with a negative impact on agricultural production and food security. The downside of such scenarios is that one can easily fit the existing data to suit the wished for outcome. Data sets have considerable margin of error, contradict each other and are incomplete. A small change in the data analysis, in the underlying assumptions or the interpretation of trends can change the outcome considerably. The challenge for CGIAR is not to think in trends that could possibly be derived from the recent past, but to think of ways to change the course of events by innovative research.

5.2 Water, Poverty and the Environment

Crop production, especially in Asia, increased rapidly in the 1960s and '70s as a result of the Green Revolution. Large investments in irrigation contributed in no small measure to this growth in production. This increase in irrigated agriculture has been beneficial to farmers, and the rural and urban poor, but it has also led to environmental damage, such as degraded land and water supplies. Many small farmers and poor people however continue to face water scarcity. Without water they can not satisfy their basic needs for food and sustainable livelihoods.

In the mid 1980's the trend in crop production changed. For example, in Asia the annual compound growth rate in the area under rice was 0.6% from 1984-1996. For the same period rice yield per unit land increased by 1.2% per year *versus* 2.5% in the eight years prior to 1984. The figures for total production were an increase of 1.5% per year after 1984 and 3.2% in the eight years before 1984. In East Asia (Japan, North and South Korea) the area under rice decreased from 1984-1996 by 0.9%, yield by 0.6% and production by 1.4%. The greatest increase in production during this period (4%) occurred in Southeast Asia (Cambodia, Laos, Myanmar and Vietnam) (Dawe et al. 1999).

By and large, the agriculture community continues to see growth of irrigation as an imperative to achieving the goals of poverty alleviation and food security. According to one scenario with fairly optimistic assumptions on productivity growth and efficiency, IWMI estimated that 29% more irrigated land would be required by the year 2025 to meet food needs. Because of greater water productivity and higher yielding crops, the increase in water needs for agriculture would be proportionally smaller at 17%. Other reported estimates are of the same order of magnitude.

From an environment point of view and with the objective to sustain and improve environmental quality and biodiversity, there is an equally strong demand to reduce the amount of water for agriculture by at least eight percent. The difference between the 17% increase and 8% decrease is about 625 km^3 of water, which is more than the 500 km^3 expected to be used in 2025 for the domestic water supply worldwide.

The World Water Vision, developed for the Second World Water Forum, attempted to bridge this difference and proposed a target of additional supplies for agriculture of 6% by 2025 (Cosgrove and Rijsberman, 2000). Of course, neither the agriculture nor the environmental community is happy with this compromise. Improving water productivity in agriculture is the key to finding this balance between the need for water in agriculture and for environmental sustainability. And therefore also for achieving the twin goals of food and environmental security.

5.3 Research on Improving Water Productivity

A distinction needs to be made between "problems" and "research needs". Accumulation of facts, filling in gaps, repetitive solving of site-specific problems does not, of itself, constitute research. Problems are defined in discipline-specific terms, which makes it very difficult to prioritize across these self-imposed boundaries between disciplines. Moreover, not all problems have solutions. Instead one should first identify a broad pivotal problem area, such as low productivity of water in rainfed agriculture. Then one examines the relative importance of several issues (e.g. unpredictability of rainfall, low input of other production factors, lack of financial resources, etc.) to isolate the category containing the most potent causes of low water productivity in rainfed agriculture. Multi-disciplinary attention would then be concentrated on that category. An iterative process in which new understanding grows from past learning and past mistakes characterizes research.

The pivotal water-related problem facing rainfed agriculture is the low productivity of rainwater and of irrigated agriculture the low productivity of the water supply diverted from the source (e.g. river, reservoir or groundwater). The first problem translates into the research question on how to increase the portion of rain stored in the root zone. The research question for the second problem is how to improve the water productivity keeping in mind its spatial dimension (i.e. "wasted water" at some location may be re-used elsewhere downstream in the same system or river basin). In some situations both questions are linked: improved water conservation and use in upstream rainfed agriculture causes less water to be available for irrigation downstream in the river basin.

Several possible ways of increasing water productivity have already been identified, such as reducing non-beneficial evaporation, reallocate water to less water-demanding crops. However, as mentioned above, it is necessary to first examine the relative importance of the underlying issues, rather than embark quickly on addressing one or more of these possible solutions to the problem

Innovative thinking about more effective use of water in agricultural production requires bridging the dichotomy between rainfed and irrigated agriculture. As research has shown, supplementary irrigation can make just the difference between crop failure and a worthwhile harvest. There are similarities between rainfed and irrigated agriculture in terms of the measures that can be taken to enhance the proportion of applied water that is effectively stored in the root zone and used for plant growth. For example, simple, low-pressure drip irrigation systems with elevated drums for water storage were found to be very suitable for applying supplementary irrigation to small vegetable plots. These systems have been introduced successfully in several African countries (Ngigi, et al., 2001).

5.4 Overview of Research Challenges in Water Productivity

5.4.1 Variability of basic data

Elsewhere in this paper we have alluded to several of the challenges that are inherent in research on water productivity. One of these is the spatial and temporal variability of the data needed to assess water productivity in crop production systems. IWMI has compared performance parameters of some forty irrigation systems in various parts of the world. Sakthivadivel et al.(1999) reported that these systems exhibited a wide range of values of the gross value of output per unit of water consumed in evapotranspiration (0.05 - 0.62 $/m^3). An equally wide range was found when water productivity was expressed as yield per unit of water. Moreover, the coefficient of variation (standard deviation/mean) of these values for any one system over time is of the order of 40 to 50%[3]. Relative water supplies (i.e., total water supply, including irrigation, rainfall, capillary rise, over crop water demand) of the studied irrigation systems ranged from 1.2 to 4.1, with an equally high coefficient of variation.

[3] Unpublished data by J.W. Kijne (2001)

The range in values of water productivity parameters in different irrigation systems, interesting as it is, gives no indication of the measures that need to be taken to increase water productivity. It is conceivable that the constraints in enhancing water productivity are greater in some systems, which now exhibit low water productivity, than in others that have already relatively high water productivity. The value of a water productivity parameter is the result of many processes working together in some integrated manner to produce crop yields for that particular set of circumstances. One of the greatest challenges, therefore, is to determine the relative importance of the underlying processes and issues. The most critical ones are not necessarily the same everywhere.

5.4.2 Globalization

Competition for water in agriculture occurs at a time when agriculture is also exposed to the effects of globalization of the world economy. Globalization forces farmers to become more commercial and more efficient producers as they are increasingly competing with other producers worldwide. Higher quality products and at lower prices are required to survive on the international market. Lower prices can only be attained when – among other things – irrigation services are better and/or less expensive than many farmers are getting now.

5.4.3 Groundwater depletion

In many semi-arid countries, the availability of irrigation water is adversely affected by groundwater depletion. Many of the most populous countries of the world – China, India, Pakistan, Mexico and nearly all the countries of West Asia and North Africa – have depleted their groundwater resource. There is rapid draw-down of fresh water aquifers (by as much as 1 or 2 m per year), due mainly to the worldwide explosion in the use of well and pumps for irrigation, domestic and industrial supplies. Use of groundwater increased rapidly because it is an attractive source of water: it is not evaporated as surface reservoirs are, and it is available when needed by starting the pump, in contrast to canal water, which is usually only available according to some rigid schedule. The trade-off, however, is that groundwater has concurrently been polluted by downward flow of water from cropped lands containing salts (including sodium salts, which have a bad effect on soil structure), residues of agro-chemicals and fertilizers, and by seepage of waste water from industries and intensive livestock farming.

Where groundwater is too saline for agricultural production, pumps have not been installed resulting in rising groundwater levels due to over-irrigation and seepage from irrigation canals. Much agricultural land has gone out of production as capillary rise from shallow water tables has ruined the soil and poisoned the crops. To reverse this process is difficult and expensive. The total area affected is not precisely known, in part because the land is affected to varying degrees. Some land may be reclaimed and again be cropped for some time. The distinction between salinity-degraded land and land fit for cropping is a fluid one. Hence it is hard to estimate, as has been attempted by CGIAR's Standing Committee on Impact Assessment, how large an area worldwide could have been used for some other purpose if no salinity problem existed.

5.4.4 Economic and institutional considerations

Improving water resource management requires recognizing precisely how the overall water sector is linked to the national economy. Equally important is it to understand how alternative economic policy instruments influence water use across different economic sectors; between local, regional and national levels; and among households, farms and firms. Macro-economic policies not aimed at the water sector can have a strategic impact on resource allocation and aggregate demand in the economy. (FAO, 1996). This is how CGIAR water productivity research fits into a much larger macro-economic picture.

The importance of pricing and other incentives to encourage consumers to adopt efficient water-use practices depends on the relative value of the water. When good quality water is plentiful and cheap, it does not pay to invest in costly monitoring devices and pricing systems. However, because demand is responsive to price, as water becomes scarce, it becomes increasingly worthwhile to carefully measure, monitor and price water use. It has been argued that the transaction cost associated with organizing the large number of farmers to collectively agree on the terms for the trade, is what affects water trading most. Rather than charging water cost to individual farmers, it is best to rely on water users' associations. Trading is also crucially dependent on collective action and on possession of transferable rights to water by the original recipients.

The Global Water Partnership has estimated that investment needs for improvements to irrigation, drainage and the necessary increase in irrigated area are $ 40 billion per year, but much more must be done to obtain realistic figures. This level of investment should improve water productivity and thus earn a good economic return. For comparison, in the UK investment in water services is around $ 5 billion per year; in the USA, the cost of implementing the Clean Water Act have been about $ 32.5 billion per year between 1990 and 1995.

It is expected that capital will, increasingly, come from private capital markets, with the critical government role being that of light transparent benchmarking and regulation (Briscoe, 1999). Others, e.g. within GWP, have argued that public regulation of private operators is inevitably required given the social, developmental and environmental importance of he water resource. To date private sector investment has concentrated on relatively few countries in the Far East and Latin America, and is limited to water supply and sewerage projects. Attracting private sector investments will require the recipient countries to have good water governance – strong regulatory frameworks, sound policies and up-to-date laws – and impartial and consistent law enforcement. Developing guidelines for the establishment of good water governance is an appropriate international strategic research topic.

It has been argued that water short countries, rather than investing in irrigation expansion to continue their food self-sufficiency policy, should preferably be importing food (so-called virtual water import). This may apply particularly to the staples that can be shipped easily and stored for long periods. Many developing countries are however hesitant to accept such a shift in approach because it would make them vulnerable when short of hard currencies, and to possible food embargoes by exporting countries.

5.4.5 Global warming

There are many water-related research issues that must be addressed at the global level, such as global warming, public health, and energy conservation. Research in these fields should address the implications of these phenomena for future water resources use and management.

In its latest Annual Report, CGIAR (2001) focuses on agricultural research and climate change. It is expected that climate change will increase flooding in some regions and exacerbate the frequency and magnitude of droughts in central Asia, northern and southern Africa, the Middle East, the Mediterranean region, and Australia. Obviously, more frequent and longer droughts will have a potentially adverse effect on agricultural production in semi-arid and arid countries. This prediction provides an additional urgency to the study of the enhancement of water productivity. Especially, as crops in the tropics and sub-tropics are assumed to be near their maximum temperature tolerance, even a modest increase in temperature will mean a yield decline. How to adapt agriculture to the anticipated effects of global warming could be the greatest challenge of agricultural research in the next decades.
Agriculture will continue to use more water than any other area of human activity. Unfortunately, the links between land use, crop production, food security, ecosystem protection and water resource management are not well articulated and frequently not understood.

5.5 The role of CGIAR: its Comparative Advantage in Water Productivity Research

In its Vision and Strategy document (TAC, 2000), already referred to in the Introduction of this paper, the CGIAR has expressed that it "will mobilize and bring the best science to bear on productivity and institutional problems that have proven intractable in the past in the context of poverty reduction and prevention".

F. Rijsberman, DG of IWMI, gave substance to this sentiment in an e-mail of 25 April 2001 to the CDC. Here he opined that the CGIAR is well positioned to address the challenge of water in agriculture. "The crop centers combine the expertise to improve drought resistance and water productivity – even though a focus on these multiple traits will mean a relative shift in focus. It will require a considerable paradigm shift to think in terms of yield per unit of water as a major complement to yield per unit of land. Key areas of a major research program on the water and agriculture challenge, to be addressed in a coordinated overall framework, can be grouped as follows:

1. increasing the drought stress tolerance of key irrigated and rainfed food and cash crops through breeding and biotechnology, thereby also adapting agriculture to increased climatic variability due to anthropogenic climate change;
2. similarly increasing the water productivity of key food and cash crops through breeding and biotechnology;
3. improving soil water and soil fertility management to sustainably increase yields in, particularly, rainfed agriculture;
4. improving integrated water resources management at the basin level to increase water productivity and (re-)allocate water resources to a sustainable mix of high value uses, from crops to forestry, to fisheries, the environment and domestic and industrial use and reduce conflicts among users;

5. integrated natural resources management with full involvement of all stakeholders and explicit sustainability and poverty alleviation objectives."

The authors of this paper concur with the opinion that the CGIAR has the opportunity and the comparative advantage to take a leading role in research on enhancing water productivity in agriculture worldwide. In addition to the five key areas of research mentioned by Rijsberman and quoted above, two more, i.e. water quality and institutional arrangements for integrated water resource management, could be added to this list of key research areas in which the CGIAR institutes collectively have a comparative advantage. Water quality plays an extremely important role in the productivity of water and in establishing whether (further) recycling of the water is justified. Uncertainty with respect to water quality exist in terms of the expected yield response to simultaneously imposed under-irrigation and salt stress, as was discussed in chapter 2 of this paper. To resolve this uncertainty multidisciplinary research efforts are needed.

Regarding institutional arrangements, IWMI and its partners have done research on irrigation management transfer, wherein the financial burden for operation and maintenance of the system are devolved to water user organizations. For most countries, presently experimenting with irrigation management transfer, the primary reason to undertake it is to significantly reduce public expenditures for irrigation's recurring costs. There seems to be a consensus that irrigation management transfer programs should involve at least three contingent strategies: improvement of support service delivery, empowerment of farmers, and the irrigation system's long term financial viability. Institutional arrangements for integrated water resource management are probably much more complex than those for farmer-managed irrigation systems, and they have not been the subject of CGIAR research yet.

Throughout this paper, we have emphasized the need for integration in the execution of water productivity research by the CGIAR. Although seven separate issues, five by Rijsberman and two additional ones, have been mentioned here, it is crucial that they be addressed in a coordinated overall framework.

IWMI has recently taken two initiatives to bring CG centers together with others to focus on water productivity in agriculture. The first is the Dialogue and the second a workshop on water productivity in agriculture. The IWMI Dialogue on Water, Food and the Environment was mentioned already in chapter 3, where all the partners in the dialogue were listed. The Dialogue, to be launched at the Stockholm Water Symposium in August 2001, seeks to engage in a cross-sectoral dialogue NARS, NGO's and others on water for food and environmental security. The aim of the Dialogue is to strive for consensus among key stakeholders from the irrigation, environment and rural development communities on the role irrigated agriculture plays and should play in the future. A summary of the paper that describes the Dialogue is enclosed in Annex 1.

The workshop on water productivity will be held in November 2001 at IWMI. It will bring together researchers in the fields of plant breeding, molecular biology, agricultural economy and irrigation from CG centers and some collaborating institutions to explore opportunities for and constraints in improving water productivity in agriculture. It will also consider the type of inter-disciplinary research that is required, i.e. field studies, modeling, etc. One of the objectives of the workshop is to propose joint research programs on water productivity.

The concept of improved water productivity in agriculture does not permeate a significant portion of CGIAR's research yet. For example, other CG centers could have been involved in relevant research in this area than were included in the description of current water-related research in the previous chapter. Examples that come to mind are ICRAF and ILRI. ICRAF mentions the need for planting trees for carbon sequestration but does not appear to be concerned about the trees' need for water (see, for example, Renault et al, 2001). ILRI as the CGIAR's livestock center could play a role in studying the consequences of intensive livestock husbandry for water quality, waste disposal and resource degradation in general, research ILRI does not appear to be conducting now. Opportunities for enlarging CGIAR's focus on water productivity in agriculture certainly exist. Whether these opportunities will be fully grasped and CGIAR's comparative advantage put to good use will depend on the centers' willingness to engage in collaborative research.

5.6 Appendix - Dialogue on Water, Food and Environment: Proposal

Version 3.1 of April 3, 2001, prepared by Chair, on the basis of the discussion of the 2nd draft at the Rome working group meeting.

Summary

The water-food-environment issue can be characterised through three quotes as follows:

"Water resources, and the related ecosystems that provide and sustain them, are under threat from pollution, unsustainable use, land-use changes, climate change and many other forces. The link between these threats and poverty is clear, for it is the poor who are hit first and hardest." Source: Ministerial Declaration, 2nd World Water Forum, The Hague, March 2000

"On the one hand, the fundamental fear of food shortages encourages ever greater use of water resources for agriculture. On the other, there is a need to divert water from irrigated food production to other users and to protect the resource and the ecosystem. Many believe this conflict is one of the most critical problems to be tackled in the early 21st century"
Source: Global Water Partnership, Framework for Action 2000, p58

"We need a Blue Revolution in agriculture that focuses on increasing productivity per unit of water – "more crop per drop". Source: Secretary General Kofi Annan of the United Nations in his report to the Millennium Conference in September 2000

A key issue in the water-food-environment area is the fragmented, sectoral approach at both global and national/local level to issues of food and hunger, poverty and livelihoods, health, and environment. Some organisations and ministries emphasise the accepted goals to drastically reduce poverty and hunger, but pay less attention to health and environmental goals. Others work mostly on the sustainability goals of Agenda 21 and the Conventions on Biodiversity, Desertification, Climate Change and Ramsar, placing less emphasis on food security. Sectoral based agendas focusing on subsets of society's overall goals lead to very different views on how water should be used.

While, in principle, there need not be a conflict among all these objectives, in practice the agriculture and environment communities, particularly, have drastically different views on the way in which water resources should be managed and developed in the coming decades. The agriculture community emphasises the need to maintain food security and reduce hunger and rural poverty for a growing world population and concludes that 15-20% more water will have to be made available for agriculture in the coming 25 years. The environmental community emphasises current damages to ecosystems through overuse and pollution and concludes that an increase in water used by agriculture would be disastrous. There is no agreement on desirable solutions and this leads to stagnation in investments and increasing conflicts over water at the local level.

The lack of agreement on socially desirable solutions affects the poor and vulnerable groups in society, particularly in the South, that are hit first and hardest by growing water insecurity. Health and poverty parameters are affected by this lack of water security.

Development Objective

The development objective of the proposed Dialogue on Water, Food and Environment is to *"**Improve water resources management for agricultural production and environmental security to reduce poverty and hunger and to improve human health**".*

Intermediate Objective

Build bridges between agricultural and environmental communities on water resources issues, by improving the linkages between the sectoral approaches that dominate policymaking and implementation, particularly at national level.

Immediate Objectives

Establish and strengthen a viable dialogue, at primarily national and local levels.
Draw together, maintain and improve the required knowledge base for the Dialogue.
Create a platform for local or basin scale activities that enhance food and environmental security in order to enhance the exchange of experience and the development and identification of best practices.
Raise awareness amongst the relevant actors and stakeholders.

Outputs

1.1 Cross-sectoral dialogues ***at national level*** on socially desirable options to achieve food and environmental security to reduce poverty and hunger and improve health in at least 15-20 countries (workshops, technical reports and public awareness materials).

1.2 Dialogues ***at basin and local level*** on socially desirable options to achieve food and environmental security to reduce poverty and hunger and improve health in at least 5-10 river basins / case study sites (workshops, technical reports and public awareness materials).

2.1 Common definitions on water, food, and environmental security, etc. and common indicators of poverty, hunger, health, environmental quality etc.

2.2 Credible and authoritative information and analyses on water availability, use and requirements for agriculture, environment and associated uses.

2.3 Scenarios at global, national and basin level concerning alternative options to develop and manage water resources for food and environmental security.

2.4 Assessment of impacts on food security, hunger, poverty, livelihoods, health, environmental quality and biodiversity of alternative scenarios.

3.1 Exchange of practical experience at the local level among the practitioners.

3.1 Synthesis of best practice information based on the experience gained in thousands of local action projects. Better actions taken at local scales as a result of this interaction.

3.2 Inputs of local experience into the dialogue processes at national and basin/local level.

4.1 Annual Dialogue meetings of all participants that raise the issue on the global political agenda through press releases, interviews and presentations of Dialogue Ambassadors.
4.2 Presentations at key meetings: Bonn Freshwater Conference, Rio+10, 3rd World Water Forum, ICID Congress in Montreal 2003, meetings of the UN Conventions.

Activities
To this end a ***Dialogue on Water, Food and Environment*** is proposed as a process to be carried out with the following three main blocks of activities (See Figure 1), plus a communication program:

A true cross-sectoral ***dialogue process*** among the stakeholders, primarily at national and local levels, that is open, clear, transparent and inclusive. A large number of national level dialogues or roundtables would form the heart of the dialogue. River basin and local level dialogues would complement these to exchange information and address issues affecting users directly. Special efforts would be made to connect to the local level, where the key challenge is to involve the real water users, the man or woman "at the pump".

An enhanced ***knowledge base*** to feed the dialogue and establish credible and authoritative knowledge accepted by both agricultural and environmental constituencies. The knowledge base would focus on achieving food and environmental security and on impacts of past development as well as on evaluation of options for future development. It would focus on creating and implementing linkages and interactions among ongoing and new key activities that fit the overall framework (but are funded and managed independently).

Networking for local and basin level ***action-oriented projects*** focused on testing and evaluating innovative approaches that enhance sustainable water security for agriculture and the environment. This would essentially be a platform for information exchange – leading to identification of "best practices".

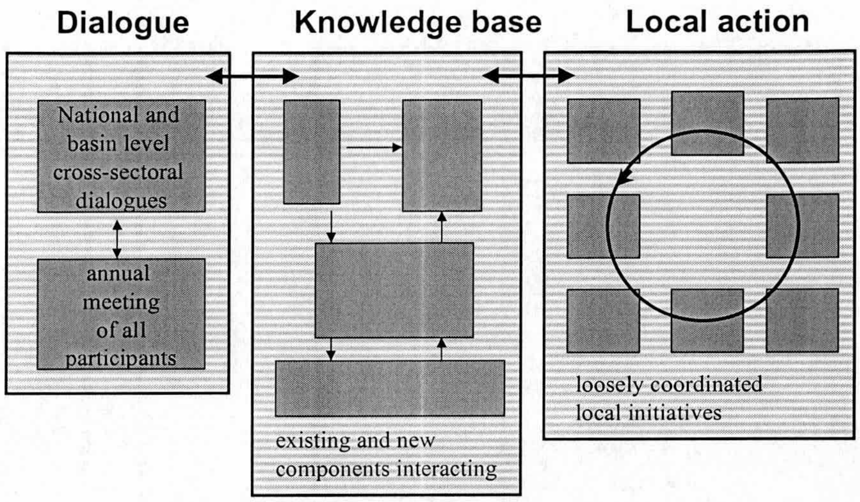

Figure 1. The dialogue process is about creating the links between existing programs, rather than developing new activities: it focuses on the arrows rather than the boxes.

References

Allan, J.A., 2000. *The Middle East Water Question: Hydropolitics and the Global Economy*. I.B.Tauris, Publishers, London, New York

Allen, R.G., 2000. Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *J. of Hydrology* 229:27-41

Allen, R.G., L.S.Pereira, D.Raes, M.Smith, 1998. Crop evapotranspiration: Guidelines for computing crop requirements. *Irrigation and Drainage Paper No. 56* FAO, Rome, Italy. 300pp.

Bhatia, R. and M. Falkenmark, 1992. *Water resource policies and urban poor: innovative approaches and policy imperatives*. Background paper for the working group on "water and sustainable urban development", International Conference on Water and the Environment: Development Issues for the 21st Century.

Bhalla, G.S., P.Hazell, and J.Kerr, 1999. Prospects for India's cereal supply and demand to 2020. 2020 Vision Discussion Paper 29. *Intern. Food Policy Res. Inst.* Washington, DC. USA.

Bouman, B.A.M., 1994. A framework to deal with uncertainty in soil and management parameters in crop yield simulation: a case study for rice. *Agric. Systems* 46:1:17

Briscoe, J., 1999. The financing of hydropower, irrigation and water supply infrastructure in developing countries. *Water Resources Development* 15:459-491.

CGIAR, 2001. *The Challenge of Climate Change: Poor Farmers at Risk.* CGIAR Annual Report 2000. CGIAR Secretariat, The World Bank, Washington DC. USA

CGIAR-TAC, 1995. *Natural Resources Management Research as a factor in priority setting*. Document prepared for International Centers Week 1995. CGIAR Secretariat, The World Bank, Washington DC, USA

CGAR-TAC, 1996. *A Strategic Review of Natural Resources Management Research on Soil and Water*. TAC Secretariat, FAO, Rome, Italy

CGIAR-TAC, 1997. *Priorities and Strategies for Soil and Water Aspects of Natural Resources Management research in the CGIAR.* TAC Secretariat, FAO, Rome, Italy

CGIAR-TAC, 2000a. *Food Secure World for All: Toward a new Vision and Strategy for the CGIAR*. CGIAR Secretariat, The World Bank, Washington DC, USA

CGIAR-TAC, 2000b. *Environmental Impacts of the CGIAR. An initial assessment.* A report from TAC's Standing Panel on Impact Assessment. TAC Secretariat, FAO, Rome, Italy

Clemmens, A.J., C.M. Burt, 1997. Accuracy of irrigation efficiency estimates. *J.Irrigation and Drainage Eng.* 123:443-453

Cosgrove, W.J. and F.R. Rijsberman. 2000. *World Water Vision: Making Water Everybody's Business.* Eartscan Publications, London.

Dawe, D., T.P. Tuong, S.I. Bhunyan and K.L.C. Guerra, 1999. *The outlook for water reseources in the year 2020: challenges for research on water management in rice production.* IRRI, Los Banos Philippines.

Dinar, A., 1993. Economic factors and opportunities as determinants of water use efficiency in agriculture. *Irrigation Sci.* 14:47-52

Dinar, A., J.D.Rhoades, P.Nash, B.L.Waggoner, 1991. Production functions relating crop yield, water quality and quantity, soil salinity and drainage volume. *Agric. Water Management* 19: 51-66

Dinar, A., D. Zilberman, 1991. The economics of resource conservation, pollution reduction technology selection. The case of irrigation water. *Resources and Energy* 13:323-348.

Doorenbos, J. and A. H. Kassam, 1979. *Yield response to water*. FAO. Irrigation and Drainage Paper 33. FAO, Rome, Italy

Fan,S., P.Hazell and S. Thorat, 1999. Linkages between government spending, growth and poverty in rural India. Research Report 10. *Intern. Food Policy Res. Inst.* Washington, DC. USA

FAO, 1996. *Water Development for Food Security*. A background paper for the World Food Summit, FAO AGLW, Rome, Italy

Ghahraman, B, A.R. Sepaskhah, 1997. Use of water deficit sensitivity index for partial irrigation scheduling of wheat and barley. *Irrigation Sci.* 18:11-16.

Global Water Partnership, 2000. *Towards water security: a framework for action.* GWP, Stockholm, Sweden

Guerra, L.C., S.I. Bhuiyan, T.P. Tuong, R.Barker, 1998. Producing more rice with less water from irrigated systems. *Discussion Paper Series No. 29.* IRRI, Manila, Philippines.

Hanks, R.J.,1983. Yield and water-use relationships: An overview. In: *Limitations to efficient water use in crop production.* H.M.Taylor, W.R.Jordan, T.R.Sinclair (Eds) America Society of Agronomy, Madison, WI, p 393+

Hanks, J. and J.T. Ritchie, 1991. *Modeling plant and soil systems*. No 31 in the series Agronomy. American Society of Agronomy. Madison, WI, USA.

Hassam, R.M., H.Fabi, D.Byerlee, 2000. The trade-off between economic efficiency and food self-sufficiency in using Sudan's irrigated land resources. *Food policy* 25:35-54

Hoek, W.van der, R. Sakthivadivel, M. Renshaw, J.B. Silver, M.H. Bvirley, F. Konradsen, 2001.*Alternate wet/dry irrigation in rice cultivation: a practical way to save water and control malaria and Japanese encephalitis?* Research report 47. IWMI. Colombo, Sri Lanka.

Howell, T.A., 1990. Relationships between crop production, transpiration, evapotranspiration and irrigation. In: *Irrigation of Agricultural Crops.* B.A.Steward and D.R.Nielsen (Eds.). Agronomy Series No.30. Madison, Wisconsin: American Society of Agronomy.

Howell, T.A., 2001. Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal* 93:281-289

Howell, T.A., R.H. Cuenca, K.H. Solomon, 1990. Crop yield response. In: *Management of farm irrigation systems.* Pp. 93-122. Hoffman, G.J., T.A. Howell, K.H. Solomon Eds. Amer. Soc. Agric. Eng., St Joseph, MI, USA

Hofwegen, P van, and M. Svendsen,2000. *A Vision of Water for Food and Rural Development.* World Water Forum, World Water Council, The Hague, the Netherlands

Hussain, et al. 1995. Strategic research program: Drainage re-use and economic impacts of salinity in Egypt's irrigation waters. *Working Paper Series No. 8-4.* Ministry of Public Works and Water Resources, Cairo, Egypt.

Jensen, M.E., 1968. Water consumption by agricultural plants. In: *Water deficits in plant growth,* vol. 1, T.T. Kolowski (Ed.) Academic Press, New York, NY, USA

Jones, W.I., 1995. *The World Bank and Irrigation.* OED, World Bank, Washington DC, USA

Keller, A. and J.Keller, 1995. *Effective efficiency: A water use concept for allocating freshwater resources.* Water Resources and Irrigation Division Discussion Paper 22. Winrock International. Arlington, Virginia, USA

Kijne, J.W., S.A. Prathapar, M.C.S. Wopereis, and K.L. Sahrawat, 1988. *How to manage salinity in irrigated lands: a selective review with particular reference to irrigation in developing countries.* SWIM Paper 2. IWMI. Colombo, Sri Lanka

Lamacq,S. and W.W.Wallender, 1994. Soil water model for evaluating water delivery flexibility. *J. Irrigation and Drainage Eng.* 120:756-774.

Latimer, E.A., D.L. Reddell, 1990. Components for an advance rate feedback irrigation system. *Transactions Am. Soc.Agric. Eng.* 33:1162-1170

Letey, J., 1993. Relationship between salinity and efficient water use. *Irrigation Sci.* 14:75-84

Letey, J., K. Knapp, K.H. Solomon, 1990. Crop water production functions under saline conditions, In: *Agricultural Salinity Assessment and Management.* K.K. Tanji (Ed). New York, NY, Am. Soc. Civil Engineers.

Maas, E.V., 1990. Crop salt tolerance. In: *Agricultural salinity assessment and management.* K.K. Tanji (Ed.) American Society of Civil Engineers, New, N.Y., USA

Maas, E.V., G.J.Hoffman, 1977. Crop salt tolerance – current assessment. *ASCE J. Irrigation Drainage Division* 103:115-134

Maas, E.V., G.J.Hoffman, G.D. Chaba, J.A. Poss, M.C. Shannon,1983. Salt sensitivity of corn at various growth stages. *Irrigation Sci.* 4:45-57.

Mason, W.K., R.C.G. Smith, 1981. Irrigation for crops in a sub-humid environment. *Irrigation Sci.* 2:103-111.

Mishra, H.S., T.R. Rathore, V.S. Tomar, 1995. Water use efficiency of irrigated wheat in the Tarai Region of India. *Irrigation Sci.* 16:75-80.

Molden, D.J,T.K. Gates, 1990. Performance measures for evaluation of irrigation-water-delivery systems. *J. Irrigation and Drainage Eng.* 116:804-823

Monteith, J.L., 1993. The exchange of water and carbon by crops in a mediterranean climate. *Irrigation Sci.*14:85-93.

Ngigi, S.N., J.N. Thome, D.W. Waweru, and H.G. Blank, 2001. Low-cost irrigation for poverty reduction: an evaluation of low-head drip irrigation technologies in Kenya. In: *Improving Water and Land Resources Management for Food, Livelihoods and Nature.* Annual Report 2000-2001. IWMI, Colombo, Sri Lanka

Oweis, T., A. Hachem, J.W. Kijne, 1999. *Water harvesting and supplementary irrigation for improved water use efficiency in dry areas.* SWIM Paper No. 7. IWMI, Colombo, Sri Lanka

Pang, X.P., J. Letey, 1998. Development and evaluation of ENVIRO-GRIO, an integrated water, salinity and nitrogen model. *Soil Sci.Soc.Am.J.* 62:1418-1427

Perry, C.J., 1993. *Irrigation in conditions of water shortage: the case of India.* Technical Guideline No.8A. World Bank, New Delhi.

Perry, C.J., 2001a. *Charging for water: the issues and options, with a case study from Iran.* Research Report 52, IWMI, Colombo, Sri Lanka.

Perry,C.J., S.G. Narayanamurthy, 1998. *Farmer response to rationed and uncertain irrigation supplies.* Research Report 24. IWMI, Colombo, Sri Lanka

Pingali, P.L. and M.Shah, 2001. *Rice-Wheat Cropping Systems in the Indo-Gangetic Plains: policy redirections for sustainable resource use.* Paper presented at workshop in New Delhi, India

Reca, J., J.Roldan, M.Alcaide, R.Lopez, and E. Camacho, 2001. Optimisation model for water allocation in deficit irrigation systems. I. Description of the model, and II. Application to the Bembezar irrigation system. *Agricultural Water Management* 48: 103-132

Renault, D., M. Hemakumara and D. Molden, 2001. Impacts of water consumption by perennial vegetation in irrigated areas of the humid tropics. In: *Improving Water and Land Resources Management for Food, Livelihoods and Nature.* Annual Report 2000-2001. IWMI, Colombo, Sri Lanka

Rhoades, F.M., 1984. Nitrogen or water stress: their interrelationships. In: *Nitrogen in crop production.* Pp. 207-317. R.D.Hauck (Ed.). American Society of Agronomy, Madison, WI, USA

Sakthivadivel, R., C. de Fraiture, D.J. Molden, C. Perry, W. Kloezen 1999. *Indicators of land and water productivity in irrigated agriculture.* International Journal of Water Resources Development, 15(1/2):161-179.

Sam-Amoah, L.K., J.W. Gowing, 2001. Assessing the performance of irrigation schemes with minimum data on water deliveries. *Irrigation and Drainage* 50:31-39

Sanchez, P.A., 2001. Agricultural Research and Climate Change: why CGIAR is relevant to the needs of poor framers. In: *The Challenge of Climate Change: poor farmers at risk.* CGIAR Annual Report 2000. CGIAR Secretariat, The World Bank, Washington DC

Sinclair, T.R. and R.C. Muchow, 2001. System analysis of plant traits to increase grain yields on limited water supplies. *Agronomy Journal* 93:263-270

Smith, R.C.G., J.L. Steiner, W.S. Meyer, D. Erskine, 1985. Influence of season to season variability in weather on irrigation scheduling of wheat: a simulation study. *Irrigation Sci.* 6:241-251.

Solomon, K.H., C. Burt, 1999. Irrigation sagacity: a measure of prudent water use. *Irrigation Sci.* 18:135-140

Sunding, D., D. Zilberman, N. MacDougall, R. Howitt, A.Dinar, 1997. Modeling the impact of reducing agricultural water supplies: lessons from California's Bay/Delta problem In: *Decentralization and coordination of water resource management.* D.D. Parker and Y.Tsur, (Eds).. Norwell, MA,USA, Kluwer Academic Publishers. Pp 389-409.

Swaminathan, M.S., 1995. Population, environment and food security. In: *Issues in Agriculture* 7. CGIAR, Washington, DC, USA

Timsina, J., D.J.Connor, 2001. *Review: Productivity and management of rice-wheat cropping systems: issues and challenges.* Field Crop Research 69:93-132.

Tuong, T.P, R.J. Cabangon, M.C.S. Wopereis, 1996. Quantifying flow processes during land soaking of cracked rice soils. *Soil Sci. Soc. Am.J.* 600:872-879

Vaux, H.J., W.O. Pruitt, 1983. Crop-water production functions. *Advances in Irrigation* 2:61-97

Voorrips, R., 2000. Breeding tomatoes to conquer saline soil. In: *Water for Food.* (P.S.Bindraban and C.W.J.Roest, Eds.). Wageningen University and Research Centre, Wageningen, the Netherlands

Wit, C.T. de, 1958. Transpiration and crop yields. *Verslagen Landbouwkundig Onderzoek* 64.6 Instituut voor Biologisch and Scheikundig Onderzoek van Landbouwgewassen, Wageningen, The Netherlands

World Bank, 1993. *World Development Report* 1992. World Bank, Washington DC, USA.

Yunusa, I.A.M., R.R. Walker, B.R. Loveys and D.H. Blackmore, 2000. Determination of transpiration in irrigated grapevines: comparison of the heat-pulse technique with gravimetric and micrometeorological methods. *Irrigation Science* 20:1-8

Annex: Assessment of the Strategic Plans of IWMI based on the recent *EPMR*

1. Priority setting and research focus.

The Second External Programme and Management Review of IWMI (EPMR) expressed the need for improved priority setting to focus the research efforts on the most critical issues within a global water management research framework. The recently published Strategic Plan 2000-2005 provides such priority setting. Five research themes have been identified. These are:

- Integrated Water Management for Agriculture
- Sustainable Smallholder Water and Land Management Systems
- Sustainable Groundwater Management
- Water Resources Institutions and Policies
- Water, Health and Environment.

The first research theme has as its first research activity the generation of new knowledge on irrigation and water resources. The first research question mentioned in this context is 'How can the productivity of water be enhanced through water management interventions'. Clearly, this research theme is the intellectual home for the Water Productivity Research advocated in this Paper.

2. **Strategy formulation**

The Center also quickly followed up on EPMR's suggestion to develop a clearer and more precise formulation of its strategy. The Strategic Plan 2000-2005 provides a precise overview of the new directions the Center wishes to follow under the guidance of the new DG. The strengths, weaknesses, opportunities and threats as seen by the Center are spelled out and a vision is developed. In the Vision it is recognized that IWMI is first and foremost a research institute specializing in integrated water and land resources management.

The research themes are described and for each of them a logical framework has been developed. Realistic milestones for each of the research themes are specified in the logical frameworks. All of this indicates a clear sense of direction and priority setting. The emphasis on water productivity in several of the themes confirms the importance the Center attaches to the enhancement of water productivity in agriculture as an overarching principle of its research.

3. **Effective coordination of water research within the CGIAR**

The EPMR observed that the System-wide Initiative on water Management (SWIM) has become the main tool for collaboration with other CG centers and that this collaboration is mainly of a bilateral nature. Moreover, the EPMR noted that most of IWMI's contributions to SWIM are or could be incorporated in one or more of the Institute's global research programs. TAC expressed the opinion that inter-center collaboration is essential, given the importance that water management has or should have in the research programs of many of the CG centers.

It is important to note that.IWMI has addressed these concerns about SWIM in two ways as mentioned in the previous section, i.e. by initiation of the Dialogue on Water. Food and the Environment, which will have its secretariat at IWMI, and by organizing a system-wide workshop on water productivity research. In both initiatives, IWMI plays the coordinating role commensurate with its role as convening center for SWIM.

4. Growth expectations

The EPMR was surprised that IWMI has not been able to raise the $11 million per year *de facto* recommended by TAC. Although the Panel believed that IWMI could put effectively to good use a higher level of funding, it also expressed doubt that the draft Strategic Plan provided sufficient justification for a $5million increase in the annual budget the Center was seeking.

The newly published Strategic Plan 2000-2005 justifies such an increase in IWMI's annual budget. In fact, it anticipates a budget for 2001 of $12.2 million, for 2002 $14.2 million, for 2003 $15.7, for 2004 $16.5 and for the last year of the plan period, 2005 $17.4 million. The initial jump from the budget for 2000 to the budget for 2001 reflects the fact that IWMI has incorporated the sustainable land use management program of the former International Board for Soil Research and Management (IBSRAM) into its present research themes.

It is realized that the expected growth of IWMI is to take place in a period of increasing competition for research funding. Nevertheless, considering the essential role irrigation is expected to play in future food production and the increasing global awareness of the importance of water resources management in and for agriculture, and given the determination of the new DG, it should not be doubted that considerable growth of IWMI's finances and research scope are feasible.

5. Impact assessment needs

One of EPMR's recommendations is for IWMI to adopt more formal procedures for priority setting and impact assessment. Priority setting was briefly discussed in section 1 above. Impact assessment, according to the Panel, would help in priority setting. The Panel recognized that impact assessment is not easy for a research center such as IWMI, which focuses its research on improving the way in which water is managed in the pursuit of food security and poverty reduction. In spite of these difficulties, the Panel believed that IWMI should endeavor to assess the extent to which its research has had an impact on the food security and poverty alleviation goals of the CGIAR. The Center in its response mentions that IWMI's impacts largely occur through the stimulus of new research ideas and concepts, which lead to changed behavior among policy makers, donors, other scientists, and water managers. It notes that there usually is a long time-lag and a large number of intervening variables between the stimulus and the outcome.

It is too early to assess the extent to which the Center has succeeded in developing a systematic way of assessing the impact of its research. An indication of a start in this direction is found in the logical frameworks in the Strategic Plan 2000-2005, where in several of the research themes measurable impacts are mentioned. For example, in Sustainable Smallholder Water and Land Management Theme, one of the milestones for 2004 is that project impact will be established for the widespread adoption of improved water and land management technologies. Also in the Water, Health and Environment Theme, one of the milestones for 2003 is that the impacts of water-saving irrigation methods on human health will be documented.