Modernization and optimization of irrigation systems to increase water productivity

by

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Abstract

Population increase and the improvement of living standards brought about by development will result in a sharp increase in food demand during the next decades. Most of this increase will be met by the products of irrigated agriculture. At the same time, the water input per unit irrigated area will have to be reduced in response to water scarcity and environmental concerns. Water productivity is projected to increase through gains in crop yield and reductions in irrigation water. In order to meet these projections, irrigation systems will have to be modernized and optimised. Water productivity can be defined in a number of ways, although it always represents the output of a given activity (in economic terms, if possible)

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divided by some expression of water input. Five expressions for this indicator were identified, using different approaches to water input. A hydrological analysis of water productivity poses a number of questions on the choice of the water input expression. In fact, when adopting a basin-wide perspective, irrigation return flows often can not be considered as net water losses. A number of irrigation modernization and optimization measures are discussed in the paper. Particular attention was paid to the improvement of irrigation management, which shows much better economic return than the improvement of the irrigation structures. The hydrological effects of these improvements may be deceiving, since they will be accompanied by larger crop evapotranspiration and even increased cropping intensity. As a consequence, less water will be available for alternative uses.

Key Words: Irrigation Modernization Optimization Water Productivity

Introduction

Today's world population of 6,000 million is expected to reach about 8,100 million by 2030, an increase of 35%. The growing population will result in considerable additional demand of food. Simultaneously, the water demand from non-agricultural sectors will keep growing in both developed and developing countries. A recent FAO analysis (Anonymous, 2003) of 93 developing countries expects agricultural production to increase over the period 1998-2030 by 49 % in rain fed systems and by 81 % in irrigated systems. Therefore, much of the additional food production is expected to come from irrigated land, three quarters of which is located in developing countries. The irrigated area in developing countries in 1998 nearly doubled that of 1962. There are many reasons to believe that such rapid rate of expansion will not continue in the next decades. FAO estimates that the irrigated area in the selected 93 developing countries will only grow by 23 % over the 1998-2030 period. However, the effective harvested irrigated area (considering the increase in cropping intensity) is expected to increase by 34 %.

The question is whether there will be enough freshwater to satisfy the growing needs of agricultural and non-agricultural users. FAO expects that the withdrawal of irrigation water in the 93 countries of its study will grow during the period 1998-2030 by only about 14 %, a small increase compared to the projected increase in the irrigated area. Crop water consumption per unit of area is expected to decrease by 3 %, and gross crop water use by 16 %. FAO explains most of this difference by an expected improvement in irrigation efficiency, that should result in a reduction in the water withdrawals per unit of irrigated area. Another part of this reduction will be due to changes in cropping patterns for some countries, such as China, where a substantial shift from rice (high-water demanding crop) to wheat (low-water demanding crop) is expected.

Underlying these projected figures is a notable increase in water productivity. The International Food Policy Research Institute (IFPRI) recently performed a study focusing on water productivity based on assumptions slightly different to those of FAO (Cai and Rosegrant, 2001). This study concluded that the average water productivity of rice will increase in the period 1995-2025 from 0.39 kg m^{-3} to 0.53 kg m^{-3} in developing countries and from 0.47 kg m^{-3} to 0.57 kg m^{-3} in developed countries. According to IFPRI, the average water productivity of all other cereals during the same period will increase from 0.56 kg m^{-3} to 0.94 kg m^{-3} in developing countries and from 1.00 kg m^{-3} to 1.32 kg m^{-3} in developed countries. Both the increase of crop yield (1 % per year during 1995-2020) and the reduction of gross crop water use through improvements in basin efficiency (from 56 % to 61 %) will contribute to the increase of water productivity projected by IFPRI. The major expected contribution will come from the increase of crop yield. If, due to increasing environmental concern, water withdrawal is reduced with respect to the baseline scenario and higher basin efficiency is attained, then an additional 10 % increase in water productivity is expected. Therefore, the goal to meet the projected water productivity needed to feed the growing population will be challenging breeders, agronomists and irrigation specialists in the upcoming years. The FAO model is based on the assumption that 2.5 % of the existing irrigated area is rehabilitated or substituted by new irrigation systems each year, an activity that would commit a considerable investment in irrigation hardware and technology.

The aim of this paper is to discuss how the modernization and optimization of irrigation systems can contribute to the increase of water productivity in a context of global water scarcity. Attention will be paid to the role of irrigated agriculture in the satisfaction of the growing food demand.

Addressing water scarcity

Modernization and optimization of irrigation systems have often been promoted in public and private agendas as tools to improve irrigation efficiency, producing more agricultural goods with less water input. However, this represents just one approach to the solution of water problems. Allan (1997; 1999) analysed the available alternatives to overcome water scarcity in a given society:

1. **Using more *virtual water***. This alternative consists on importing products requiring large amounts of water in their production. All water-stressed countries already resort to virtual water to some extent. For instance, cereals and wheat flour are commonly imported commodities in dry regions. Middle Eastern and Northern African countries have had a seven fold increase in these imports between 1960 and 1992 (Allan, 1997). Imports by the end of the considered period amounted to 40 Mt, roughly equivalent to 40,000 hm^3 of virtual water. This is an impressive figure, particularly when compared to the estimated 340,000 hm^3 of regional renewable water resources (Abu-Zeid and Hamdy, 2002). In the period 1995-99, the virtual water balance of Australia showed a net export of 146,000 hm^3 of virtual water, while Spain was a net importer, with 83,000 hm^3 (Hoekstra and Hung, 2003).

2. **Improve the *economic efficiency* of water**. Societies reassign water uses to obtain maximum return per unit of water. This alternative comprises changes between groups of water uses (usually from agricultural to industrial and urban uses), and within each group. In the agricultural sector, farmers respond to market rules (among other issues) searching for the highest return per unit land or per unit water, depending on the relative scarcity of both resources.

3. **Improve the *technical efficiency***. The strategy is to perform the same activities, but using less water. Technical efficiency has implications in all water related disciplines, including agronomy and plant breeding. In the irrigation field this is accomplished by increasing irrigation efficiency. In order to obtain this goal, there are two different procedures: improving the water structures, and improving water management.

Considering these three alternatives (which are used simultaneously in most regions of the world) the preferred order is coincident with the order of presentation. However, regional decision makers prefer technical efficiency overall. According to Allan (1999), the reasons for choosing technical efficiency arise from the following facts: a) it is an uncompromising choice; b) it catalyses some economic sectors, such as construction; and c) it does not produce explicit "losers". In fact, all users touched by public investments will obtain some kind of gain, while the rest will remain the same. The compound balance will always be positive (thus avoiding zero-sum games).

These reasons seem important, but in fact all of them are negative and unsupportive of decision makers. However, there must be something positive about choosing technical efficiency. The following is a list of additional (positive) reasons in favour of technical efficiency in the field of irrigation. Most of these reasons are not related to water use, and fall in the categories of rural development and environmental protection, two appreciated externalities of the agricultural sector.

- The modernization of irrigation systems improves living conditions in the rural world. This effort would be a recognition of the "multifunctionality" of agriculture, a concept recently adopted by the European Union. There is more to irrigated agriculture than just the production of food and fibre. Irrigation keeps water linked to the rural areas, and stabilizes rural population in desert areas. It adds to the "communitarian value of water".

This theory is based on the existence of a strong link between water and the cultural values in rural areas.

- Proper technical management improves the environment, since it effectively reduces the salt and nutrient leaching from irrigated areas (Rhoades and Suarez, 1977; Tedeschi et al. 2001; Cavero et al. 2003).

- The modernization of the irrigation systems adds technology to agricultural production: rural employment becomes more attractive and competitive.

This discussion leads to a prominent role of technical efficiency (irrigation modernization and optimization) in overcoming water scarcity. In order to evaluate its effect for a given society, a discussion of water productivity is required.

Concepts of water productivity and scale considerations

Water productivity can be expressed as agricultural production per unit volume of water. The numerator may be expressed in terms of crop yield (kg ha^{-1}). Alternatively, crop yield may be transformed into monetary units (i.e., € ha^{-1}). The latter will be particularly convenient when comparing different crops or different types of water use. A number of options are available to define the volume of water per unit of area (m^3 ha^{-1}) in the denominator. Different water productivity indicators (€ m^{-3}) result from choosing different options:

$$WP_1 = \frac{\text{Production}}{\text{Water Used (rainfall} + \text{diverted)}} \qquad [1]$$

$$WP_2 = \frac{\text{Production}}{\text{Water Diverted}} \quad [2]$$

$$WP_3 = \frac{\text{Production}}{\text{Water Beneficially and Non Beneficially Consumed}} = \frac{\text{Production}}{\text{ICUC} \times \text{Water Diverted}} \quad [3]$$

$$WP_4 = \frac{\text{Production}}{\text{Water Beneficially Consumed}} = \frac{\text{Production}}{\text{IE} \times \text{Water Diverted}} \quad [4]$$

$$WP_5 = \frac{\text{Production}}{\text{Net Irrigation Requirements}} = \frac{\text{RIS} \times \text{Production}}{\text{Water Diverted}} \quad [5]$$

The value of the calculated water productivity increases in the sequence WP_1 to WP_5. Except in WP_1, the denominators in the definitions of WP refer to diversion or consumption of irrigation water. In the irrigation context this is more convenient than considering total (rainfall plus irrigation) water.

Some of the concepts of WP can be interpreted through different forms of technical efficiency: WP_3 is related to the Irrigation Consumptive Use Coefficient (Burt et al., 1997) (ICUC, the volume of irrigation water consumptively used divided by the volume of irrigation water applied); WP_4 to the Irrigation Efficiency (Burt et al., 1997) (IE, the volume of irrigation water beneficially used divided by the volume of irrigation water applied); and WP_5 to the Relative Irrigation Supply (Molden et al., 1998) (RIS, water diversion divided by irrigation requirements or crop evapotranspiration minus effective rainfall). In both ICUC and IE, Burt et al. (1997) subtract in the denominator the change of storage of irrigation water. In order to simplify, here we assume that the change in storage is negligible when dealing with the whole irrigation season.

The pertinence of one or another concept of WP depends on the hydrological domain. Although concepts WP_4 and WP_5 are valid at any scale, they are more meaningful at the field level since they are related to agronomic aspects of transforming evapotranspirated or leached water into crop yield. If the water that is used but not consumed (evapotranspirated) in an irrigation unit of the domain cannot be reused within the domain, then WP_2 is pertinent (otherwise it is not comparable across scales). If the water used but not consumed can be reused downstream in the same domain, then WP_3 is more appropriate.

The reutilisation of water depends on the hydrologic arrangement of the irrigation units. The water delivered to an irrigation unit may come from a canal common to several units, or it may be return flow from upstream units. When all the irrigation units receive the water directly from a common canal, those units are said to be in parallel. When an irrigation unit supplies all the water required by another unit located downstream, this downstream unit is said to be in series with the former. Irrigation units may be partially in series and partially in parallel or in complex arrangements. The ICUC of the whole water system will be the ICUC of the irrigation units if they are in parallel (the number of reuses is zero), it will increase with the number of reuses if the units are in series, and it will also increase with the number of units if they are partially in series and partially in parallel, but at a rate smaller than in the perfect series system. An improvement through modernization of the irrigation units' ICUC will be translated into the same improvement for the whole system if the units are in parallel. However, if they are in series or partially in series, the increase of the whole system ICUC due to the increase of the irrigation units' ICUC will be smaller as the number of units in series increases (Mateos et al., 2000).

This analysis extended to river basins is complemented by the concept of "closure" (Seckler et al., 2001). A river basin is said to be open when it has outflows of usable water in the dry season; it is said to be closing when it has no discharges of usable water in the dry season; and it is said to be completely closed when it has no discharges of usable water even in the wet season. Therefore, in closed basins (and more and more basins around the world are facing closure) additional water needs cannot be met through gains in WP_1 or WP_2 (addressing the productivity of used water), but must be met through gains in WP_3, WP_4 or WP_5 (addressing the productivity of consumed water).

Water planners often disregard these scale considerations and expect to transfer improvements in on-farm irrigation efficiency into additional water supply for other districts or to develop new irrigation projects. In many irrigation projects, excess irrigation water is the subject of downstream water rights (Willardson et al., 1994). In such cases irrigation modernization will not result in a net water gain. Moreover, any increase in crop water evapotranspiration will reduce the return flows and therefore interfere with downstream water uses.

These principles have led to the formulation of a water resources paradigm illustrated by Perry (1999) with a series of examples. Two of them are summarized below:

- In a Middle Eastern Country, structural investments improved irrigation efficiency from 40 - 50 % to 60 - 70 %. The purpose was to save water in order to expand the irrigated area. The results were unexpected: Crop yield substantially increased in the area (due to improvements in distribution uniformity and irrigation scheduling). This yield increase was due to an increase in crop evapotranspiration. Therefore, there was no water surplus for irrigation expansion. However, the project did increase water productivity (WP_2), since more agricultural output was produced with the same water stock.

- In the United States a city offered to pay for the lining of a number of neighbouring irrigation canals to save water for domestic and industrial use. The conveyance and surface irrigation efficiency were presumed to be low. A detailed study showed that at the basin level 80-90% of the water was consumed by irrigation. Therefore, potential water "savings" were minimal. A complex cascade water reuse system was responsible for this high global performance. Similar results should be expected in large irrigation projects developed around riparian areas.

Both examples underline frequent misconceptions in irrigation water use, and show how the prospects for water "saving" are bound to fail in most practical situations. Only in cases were water reuse is impossible (particularly when irrigation is performed by the coast) any increase in irrigation efficiency will lead to a net increase in the available water resources.

The water resources paradigm can only be applied to nested hydrological systems. If a subsystem is considered including for instance a reservoir and an irrigation project within a basin, any increase in the project irrigation efficiency will lead to a net increase in the reservoir stock. The term "water conservation" has often been used to refer to this apparent water gain. Water conservation does not enlarge water resources within the basin, but can effectively solve the problems of particular users or areas.

Modernization actions and water productivity

The concept of irrigation modernization has evolved over the last two decades. Originally it was restricted to the introduction of new physical structures and equipment. Now modernization is understood as a fundamental transformation of the management of irrigation water resources aiming to improve the utilization of resources and the service provided to the farmers. The transformation combines changes in rules and institutional structures, water delivery services, farmers irrigation scheduling, technical and managerial upgrading and advisory and training services, all in addition to the introduction of modern equipment, structures and technologies. Specific objectives of modernization include: increasing water productivity, increasing the cost effectiveness of funds, increasing the reliability and flexibility of irrigation deliveries, accepting the demand of other users, and meeting environmental requirements.

In this paper we focus the discussion on the technical aspects of modernization, i.e., water management, systems operation, and upgrading of structures and equipment. The management and operation of the system is not independent of its design. In fact, new voices (Horst, 1998) are claiming that the root of deficient management is improper design of the systems. Nevertheless, the improvement of irrigation management has long been neglected by public planners, and has received very little attention. The advantages of improving water management can be summarized as:

- Cost effective, since its economic return (conserved water / investment) is often orders of magnitude larger than that obtained from improving the structures.

- User appreciated, since it is a “bottom-up” process, in which users perceive management issues as their own. The goal is to obtain a process of slow, endogenous changes.

Referring to irrigation water, two levels can be identified: the farmer and the irrigation district. A discussion of modernization and optimization activities at both levels follows.

The irrigation district

The function of the conveyance and distribution systems and services should be providing sufficient water in a timely manner so that it can be used efficiently for crop production.

Reliability, flexibility and efficiency are then keywords for a modernization plan. The reliability of an irrigation service is the degree to which the irrigation system and its water deliveries conform to the expectations of the users. The farmer may schedule irrigations and integrate other practices such as fertilization and pest control only if the irrigation delivery can be predicted. A reliable service allows efficient irrigation management within the constrains of the system. Moreover, if the irrigation delivery is flexible, the farmer can adapt the irrigation schedules to optimum cropping strategies and tactics that can be adjusted as the crop progresses. Therefore, both reliability and flexibility lead to higher irrigation efficiency and crop yield. Inflexible delivery (i.e., fixed-rotation delivery schedules or irrigation season restricted to a certain period in the year) limits the type of crops that can be grown and constrains agronomic tactics.

An illustration of this argument is given by Plusquellec (2002) referring to the use of groundwater in India. Crop yields obtained with groundwater irrigation are one-third to one-half larger than crop yields obtained with other sources of water. The difference is due to the greater water supply control obtained with groundwater. Irrigation scheduling can be adjusted to meet the crop water requirements. Thus, the use of fertilizers, pesticides and high yielding varieties is more intense, leading altogether to higher yields. A corollary is that the reliability and flexibility of the groundwater supply has resulted in increased water productivity in India and in many other areas of the world.

The improvement of irrigation structures *via* construction works has been the traditional way to improve irrigation efficiency. Many political instances have adopted ambitious plans to improve irrigation structures with objectives such as improving the competitiveness of local irrigated agriculture, rural development, environmental protection and increasing the available water resources (an impossible objective in closed basins, as previously discussed).

As an example, in Spain, the National Irrigation Plan ("*Plan Nacional de Regadíos*", PNR) finances construction works affecting approximately 1.4 M ha out of the 4.0 M ha currently irrigated (Anonymous, 1998). The plan should be completed by 2008, although it is recognized that further actions will be required beyond this date. The typical PNR activity involves upgrading the collective irrigation structures of an irrigation district, often including part of the on-farm irrigation equipment. Districts using open channel conveyance networks and on-farm surface irrigation systems are currently adhering to the PNR in order to change to collective pressurized distribution networks and on-farm sprinkle/trickle irrigation systems. This financing scheme implies that in the following fifty years farmers will pay to the district some 250-300 € $ha^{-1}yr^{-1}$ to cover investment repayment, plus water diversion and operational costs. Farmers rely on the discussed yield increase and the reduction of irrigation labour (due to the automation of the new irrigation systems) to pay the investment back. Farmers' response to the PNR so far is very positive, particularly in strongly rural areas with poor irrigation structures.

In many cases, however, technical efficiency and thus WP may be improved up to a certain degree through simple changes in management. As an example of district water management, the case of the Bardenas V irrigation district of north eastern Spain is presented (Lecina et al., 2005). This district operates 15,000 ha of mostly surface irrigation. Water allocation is performed by flexible arranged rotation from the Bardenas canal. Surface irrigation evaluation and simulation revealed that the current irrigation time in the district was 2.8 h ha^{-1}, while the optimum irrigation time was much shorter: 1.7 h ha^{-1}. If the irrigation time was reduced to its optimum value, the application efficiency would jump from the current value of 44 % to a very adequate value of 70 %. This difference of 26 points can be obtained *via* management improvement alone. A set of hydrological data from two irrigation seasons served to confirm this finding. Figure 1 presents data from the 2000 and

2001 irrigation seasons. While in 2000 irrigation water was virtually unlimited, in 2001 there was a water shortage that induced farmers and district managers to conserve water. According to farmers' interviews, these water conservation practices did not result in significant yield losses. In 2001 the global irrigation efficiency was almost 20 points higher than in 2000, revealing that there are real grounds for water conservation in the district from the management perspective. Since the crops, their yield and their evapotranspiration did not change substantially between both years, the increase in efficiency did not result in a significant increase in the productivity of consumed water (indexes WP_3, WP_4 and WP_5), but increased significantly WP_1 and WP_2.

Two interesting approaches in district water management are the Irrigation Maintenance and Operations Learning Process (Skogerboe and Merkley, 1996) and the Management Improvement Program (MIP), a "coordinated and sustained effort to improve water management in an organization" (Dedrick et al., 2000). These efforts were set up in recognition that if district performance is poor it will not be enough to improve its water structures. The MIP process incorporates: a thorough understanding of the performance of irrigated agriculture in an area (diagnosis analysis); involvement by key decision makers in a joint decision process (management planning); and implementation of the planned changes by responsible operational managers (performance improvement).

On-farm irrigation

In the frame of modernized irrigation systems, technical on-farm irrigation management implies selecting the appropriate irrigation method and strategy according to the water availability, to the characteristics of the climate, soil and crop, to the economic and social circumstances, and to the constraints of the distribution system. It also requires the actual application of the scheduled water, its even distribution over the field, and the storage in the root zone of as much of the applied water as possible. The inherent and management-induced non-uniformity of the irrigation systems implies that some water deficit and/or percolation must occur even with the best irrigation schedule. Thus, there is a trade-off between uniformity, water deficit and percolation, that is illustrated in Figure 2 assuming that the statistical distribution of the infiltrated water follows a normal distribution, and defining the deficit coefficient as the fraction of the root zone that is not filled with irrigation. It can be deduced from the abacus in Figure 2 that the lower the distribution uniformity the lower the application efficiency required to not surpass a target deficit coefficient.

One extended irrigation practice is to apply the water necessary to bring the soil to field capacity. This practice avoids crop water deficit by assuring maximum crop evapotranspiration. But deficit irrigation can be economically desirable depending on the cost of the applied water, the price of the agricultural product and the yield response to water deficit. Regulated deficit irrigation, or the imposition of water deficit at only certain crop development stages, may reduce crop evapotranspiration with minimum or none reduction in yield. Therefore, regulated deficit irrigation may improve all forms of WP, from WP_1 to WP_5. Fereres et al. (2003) foresee potential in the use of regulated deficit irrigation in tree crops (where fruit rather than biomass is the marketable product and fruit quality is important) for reducing water use and consumption while maintaining or even improving grower profit.

Clemmens and Dedrick (1994) reported that all irrigation methods can attain approximately the same levels of efficiency. In spite of this fact, differences among irrigation systems appear in many areas as a consequence of design, management and maintenance. In north-eastern Spain traditional surface irrigation systems often show on-farm efficiencies close to 50 % (Playán et al., 2000; Lecina et al., 2005), while properly designed and managed pressurized systems can attain 90 % efficiency (Dechmi et al., 2003a; 2003b). As a consequence, changing the irrigation system (from surface to sprinkler) in field crops such as maize results in the following effects: 1) A sharp reduction in irrigation water demand (roughly, from 12,000 to 7,000 m^3 ha^{-1}); 2) A relevant increase in crop yield (typically from 10,000 to 12,000 kg ha^{-1}), resulting from improved irrigation uniformity, the control of the irrigation depth, and a flexible irrigation scheduling; and 3) an increase in crop evapotranspiration (typically from 5,000 to 6,000 m^3 ha^{-1}). These changes result in a significant increase in WP_2.

On-farm irrigation management can also result in increases in WP5. Mateos et al. (1991) compared the water productivity of drip and furrow-irrigated cotton. An analysis of the original data adapted to the WP terminology presented in this paper permitted to conclude that, under full irrigation, WP5 was not significantly different for both irrigation systems. However, under deficit irrigation, WP5 was notably greater for drip irrigation than for furrow irrigation. As expected, WP2 was higher for drip irrigation than for furrow irrigation, both under full and deficit irrigation, and WP2 was always lower than WP5 (Table 1).

Perhaps the greatest challenge is not developing new irrigation technology, but finding ways to reduce the large differences in technical efficiency, yield and water productivity that can be found among and within irrigated systems. Figure 3 presents in abscise the relative irrigation supply (RIS, defined as the ratio between the annual water application and the annual irrigation water requirements for maximum yield) and its variation (horizontal bars) crop by crop in the Genil-Cabra irrigation district (Southern Spain) (Lorite et al., 2004). The Genil-Cabra district manages a modern well-operated pressurized-pipe network working on-demand. Despite these features, the RIS of the farms in the whole system has a remarkable standard deviation. Since the irrigation system does not impose any water supply restriction, the variation is due to other internal and external factors.

The first factor determining farmers' decisions is the crop. The RIS of the different crops fell into two different groups: on one hand, four crops, cotton, garlic, sugar beet and maize, had average RIS values from 0.73 to 0.91; by contrast, winter wheat, sunflower and olive had much lower average RIS values, from 0.28 to 0.39. The first group represents the traditionally irrigated crops, while the crops in the second group have been primarily rain fed in the area until recently. Economic (subsidies and crop value) and agronomic (root diseases in the case of olive) reasons explain the attitude of the farmers in relation to the different crops, but the variation within each type of crop can be due only to variations of on-farm irrigation management.

Lorite el al. (2004) used a water balance and crop response model to estimate the variations in WP_2 due to the variations in RIS. Results are also presented in Figure 2, with average values in the ordinate and the variation represented by the vertical bars. The difference in irrigation water productivity among crops (high for garlic, low for sunflower, wheat and maize, and intermediate for olive, cotton and sugarbeet) and the farm to farm variation for each crop, indicate the potential of increasing the WP of the whole district.

In farmer water management, individual decision making affects the choice and use of irrigation equipment and irrigation scheduling. In the following paragraphs, examples will be set to illustrate how management principles can be applied to the optimization of water use in both surface and sprinkler irrigation systems.

In surface irrigation systems, the introduction in the 1970's of laser levelling produced a quiet revolution that has raised potential surface irrigation efficiency to the levels of sprinkler and drip irrigation (Erie and Dedrick, 1979). The quality of land levelling in zero-slope fields can be estimated through the standard deviation of soil surface elevation (SD, mm). A field levelled with conventional equipment will always show a standard deviation higher than 15 mm (typically, 20-40 mm), while using laser levelling the technical limit would be of about 10 mm. Figure 4 presents the evolution of the application efficiency of a particular case as a function of SD (Playán et al., 1996). The figure reveals that the introduction of laser levelling can result in more than ten points increase in efficiency, while in most developed countries the cost of laser levelling is two to three times that of a standard tillage operation.

In sprinkler irrigation one of the keys to efficient irrigation consists of managing the wind. This is particularly true in windy regions, such as the Ebro Valley of Spain. The adverse effects of wind can be summarized in the increment of wind drift and evaporation losses and in a sharp reduction in irrigation uniformity. In the Ebro Valley during the night time wind drift and evaporation losses are reduced to approximately one half of daytime losses (Playán et al., 2005). Irrigation machines (pivots and rangers) result in smaller water losses than solid set systems (about two-thirds). The daily evolution of wind speed, combined with the differences between daytime and night time operation, result in relevant differences in water use arising from the time of irrigation. Figure 5 presents the results of a simulation study in which all maize crop irrigations during the season were scheduled at the same time of the day (Dechmi, 2004). The irrigation scheduling criterion permitted to obtain virtually potential yield in all cases. WP_2 ranged from 0.051 € m^{-3} (irrigating at 12 h GMT) to 0.063 € m^{-3} (irrigating at 0 h GMT). This in turn resulted in a difference of 170 m^3 ha^{-1} of irrigation water to produce the same yield. These results illustrate the relevance of farmers' decisions with respect to WP and crop water use.

Expected outputs of irrigation modernization and optimization

Figure 6 elaborates on the previous discussions, presenting a road map from irrigation modernization and optimization to a number of outputs, including improvements in WP. The map presents alternative paths through the improvement of irrigation structures and irrigation management. Flexibility and efficiency can be attained following both paths, and lead to increased WP through high value crops and increased yield. A third way to these goals, system reliability, can usually be addressed only by actions to improve the irrigation structures. Irrigation efficiency leads to reduced on-farm water application, which only translates to improvements in the productivity of consumed water if the irrigation return flows can not be reused, as often happens in coastal irrigation projects. If this is not the case, it will at least provide for improved water quality and water conservation.

According to Figure 6, from a qualitative stand point, basin-wide water resources are bound to decrease with irrigation modernization and optimization. This will be primarily due to two reasons:

- ***Increased evapotranspiration (even with the same cropping scheme)***. In fact this technical result will follow two effects: the above mentioned increase in crop yield, and the increase in irrigated area following irrigation modernization plans. The latter will be accomplished without extending the water right area. In fact, plots that were marginally cropped or even abandoned before the modernization of the irrigation structures will be intensively cultivated after the modernization project. Following a regional modernization plan all plots must pay the investments back, and therefore all land must be cultivated in full. Figure 7 presents an aerial photography of irrigated land in north eastern Spain in which the differences in crop intensity between the traditional (right) and modernized (left) plots are evident.

- ***Intensified cropping pattern, with more water intensive crops (searching for economic efficiency)***. In fact, this issue needs some further explanation. A high economic return can be obtained with limited water resources, if the proper crops are chosen. As an example, modern vineyards and olive tree plantations rarely demand more than 2,500 m^3/ha of water under Mediterranean conditions, and their WP can not be distinguished from that of cotton or sugar beets, whose evapotranspiration is triple than that of olive trees (see Fig. 3). The increase in evapotranspiration will come from the abandonment of crops such as winter cereals and sunflower, which are often marginally irrigated. These crops are particularly grown in traditional irrigation systems because they are drought resistant and they do not demand irrigation water at the peak of the season.

According to Fig. 3, the choice of crop can induce very large differences in WP. The same figure presents a wide variability in water use for any given crop. As a result, a relevant variability in on-farm WP can be identified, derived from the farmers' search for the optimum economic level of water application. This variability should be reduced through research and extension of optimum water application practices for each crop and environment.

Conclusions

The modernization of the irrigation systems offers the farmers a number of possibilities to expand the economic productivity of water. However, the problem of feeding the world's increasing demands does not have an easy solution from the irrigation point of view. In irrigated agriculture the production of dry matter and yield are determined by plant genetics and a number of environmental factors, including plant water status. Adequate irrigation scheduling can be used to optimise crop yield for a given level of crop evapotranspiration, therefore leading to more yield per unit of evapotranspirated water. However, the magnitude of such expected improvements is small in comparison with the required increment in global food production. Therefore, prospects for the future include a sustained increment in yield, some increment in crop evapotranspiration (m^3 per hectare, following irrigation optimization), and a sharp increment in global agricultural evapotranspiration. Tensions will increase in many regions of the world, since water will be increasingly scarce, and food demand and production (water availability) will not be coincident in space and time. Virtual water is therefore called to play an even more important role in the future.

Research will be required in the next years to assess the quantitative effect of irrigation modernization and optimization plans on basin-level water use. The effects on the socio-economic sustainability of agricultural communities and on water quality in the river basin will also need to be evaluated, so that proper analyses of the benefits and costs of improving water productivity can be developed. Meeting the challenges derived from population growth and human development in the next decades will require accommodating additional evapotranspiration allocations in many watersheds. With water resources over committed in many areas of the world, this will not be an easy task.

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List of Tables

Table 1. *Water productivity of drip and furrow-irrigated cotton at two levels of water supply.* WP_2 *is yield divided by applied water and* WP_5 *is yield divided by evapotranspiration of irrigation water.*

Irrigation supply	Irrigation method	WP_2 (kg m^{-3})	WP_5 (kg m^{-3})
Full	Drip	0.79	0.88
	Furrow	0.52	0.90
Deficit	Drip	1.05	1.15
	Furrow	0.65	1.03

List of Figures

Figure 1. *Hydrological analysis of the Bardenas V irrigation district of North Eastern Spain. Results are presented for the 2000 and 2001 irrigation seasons, representing normal and drought conditions, respectively. Adapted and reprinted from Agric. Wat. Manage., 73 (3), Lecina et al. "Irrigation evaluation and simulation at the irrigation district V of Bardenas (Spain)."pp. 223-245, Copyright (2005), with permission from Elsevier.*

Figure 2. *Relationship between deficit coefficient, application efficiency and distribution uniformity (DU) assuming normal distribution of the infiltrated applied water.*

Figure 3. *Relation between Relative Irrigation Supply (RIS) and* WP_2 *in the Genil–Cabra irrigation district of Southern Spain. Values are averages for four irrigation seasons, and the bars depict twice the standard deviation. Adapted from Figure 5 in Lorite, I.J., Mateos, L., and Fereres, E. 2004. "Evaluating irrigation performance in a Mediterranean environment. II. Variability among crops and farmers." Irrig. Sci. 23, 85-92, with kind permission of Springer Science and Business Media.*

Figure 4. *Simulated effect of the quality of land levelling (characterized by the standard deviation of soil surface elevation, SD) on application efficiency (AE) in a particular case of level-basin irrigation. Adapted and reprinted from Playán et al.1996. "Modeling microtopography in basin irrigation." J. Irrig. and Drain. Engrg., ASCE, 122(6), 339-347. Reproduced by permission of the publisher, ASCE.*

Figure 5. *Effect of the time of sprinkler irrigation on water productivity (*WP_2*, €* m^{-3}*) and water use (*m^3 ha^{-1}*) required to obtain maximum maize yield in the conditions of Zaragoza, Spain. Adapted and reprinted from Dechmi et al. 2004. "A coupled crop and solid set sprinkler simulation model: II.*

Model application." J. Irrig. and Drain. Engrg., ASCE, 130(6):511-519. Reproduced by permission of the publisher, ASCE.

Figure 6. *Flux diagram of the actions, effects, technical results and outputs related to irrigation modernization and optimization.*

Figure 7. *Aerial photograph showing modernized (left) and traditional (right) irrigated areas in Spain. The figure was obtained from the Oil-Producing GIS of the Ministry of Agriculture, Fisheries and Food of Spain (http://www.mapa.es/es/sig/pags/sig/intro2.htm).*

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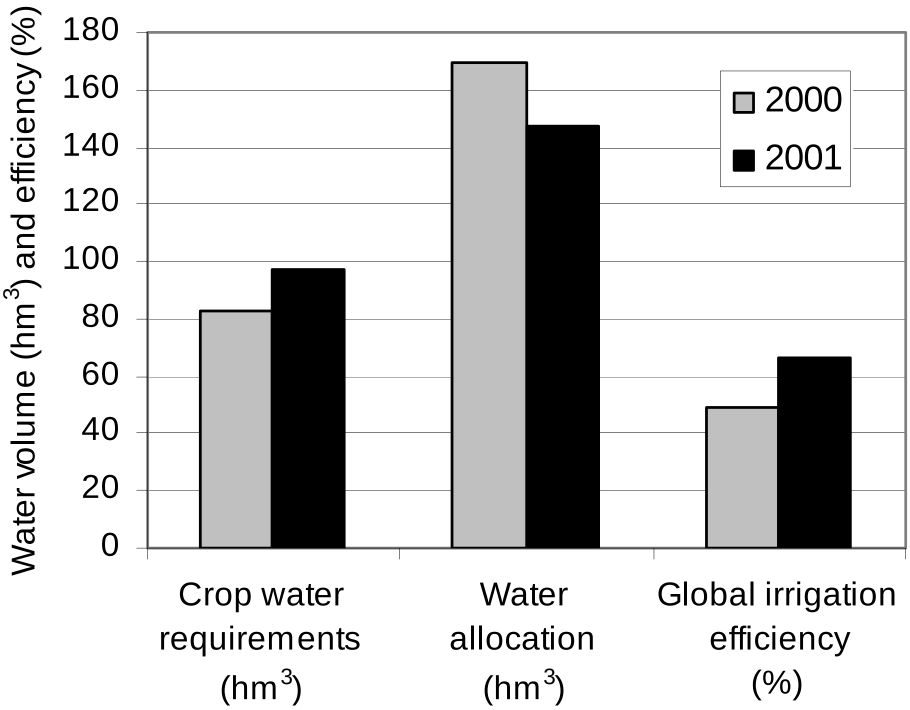

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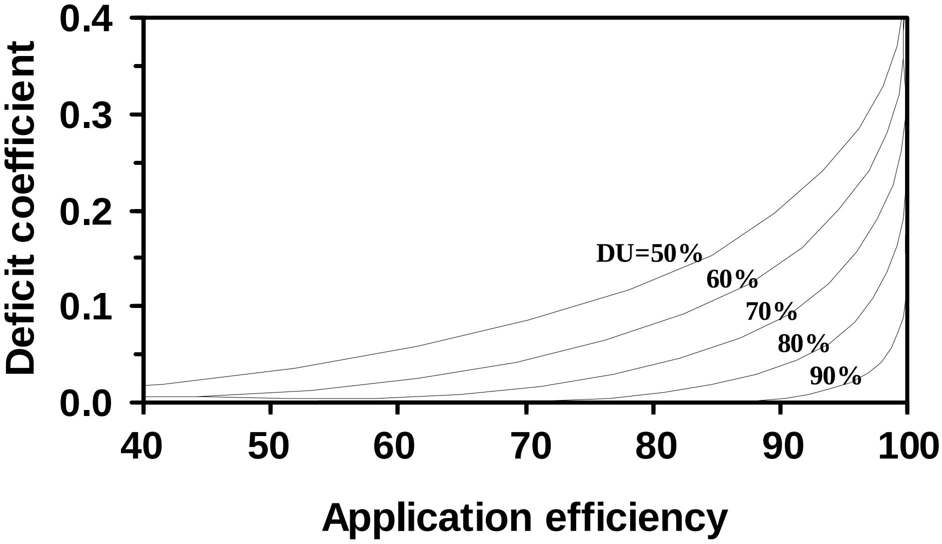

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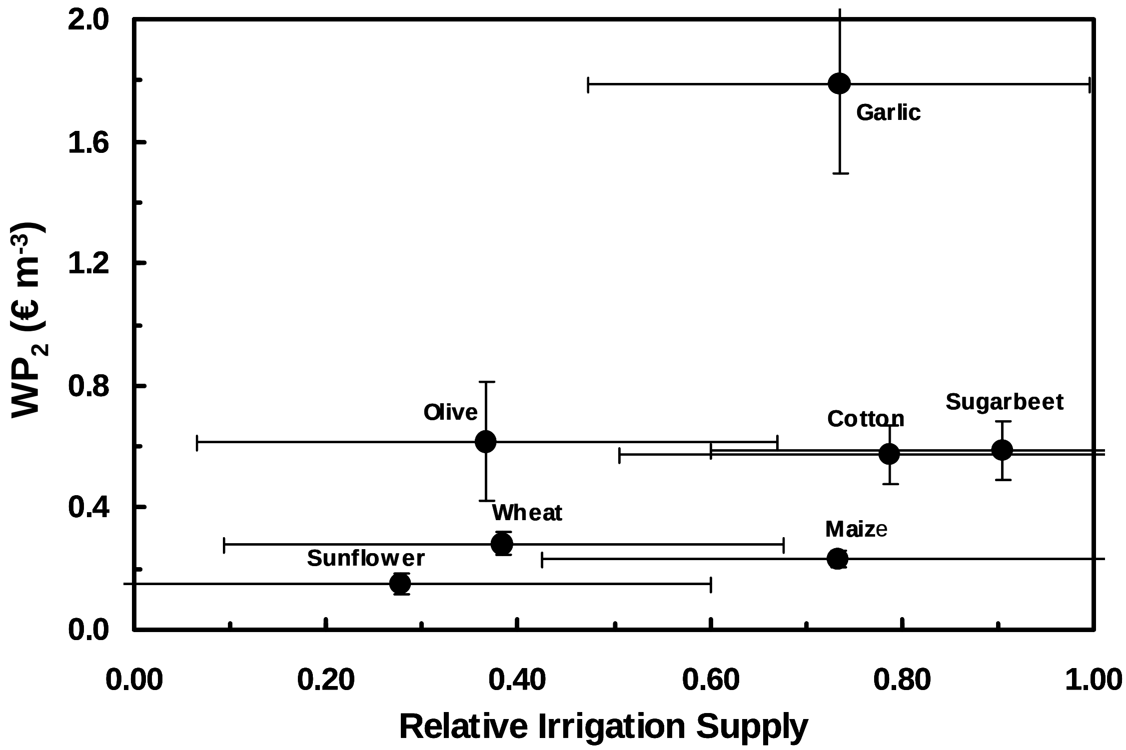

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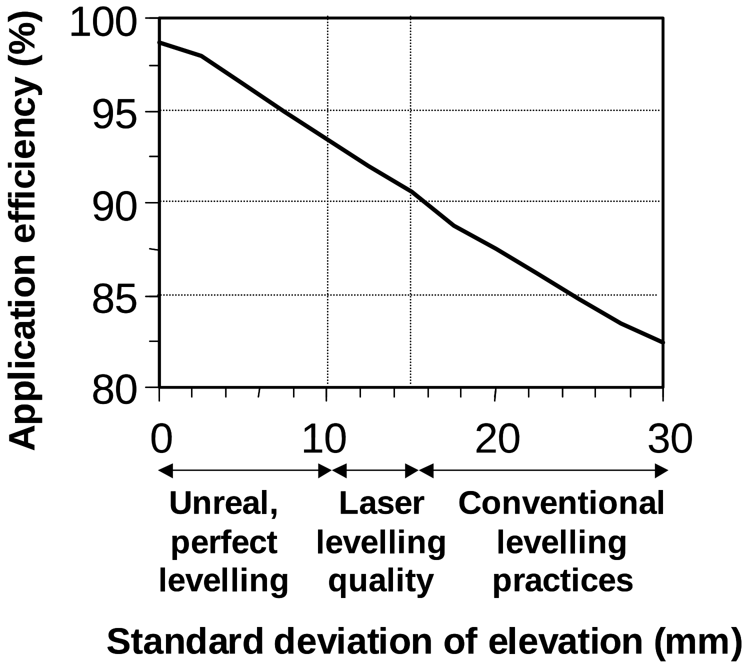

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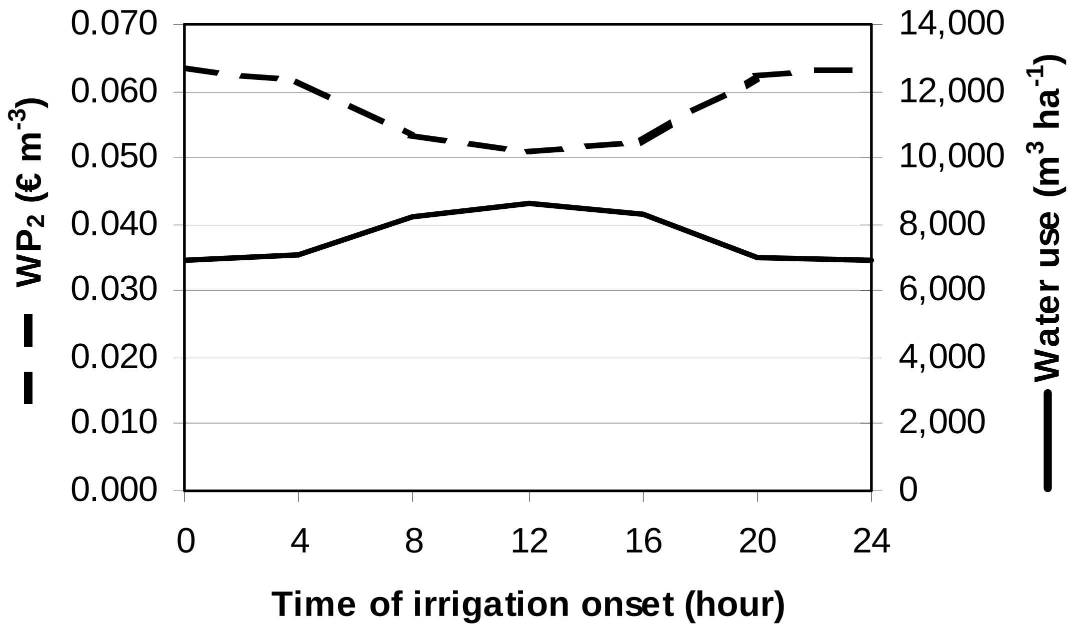

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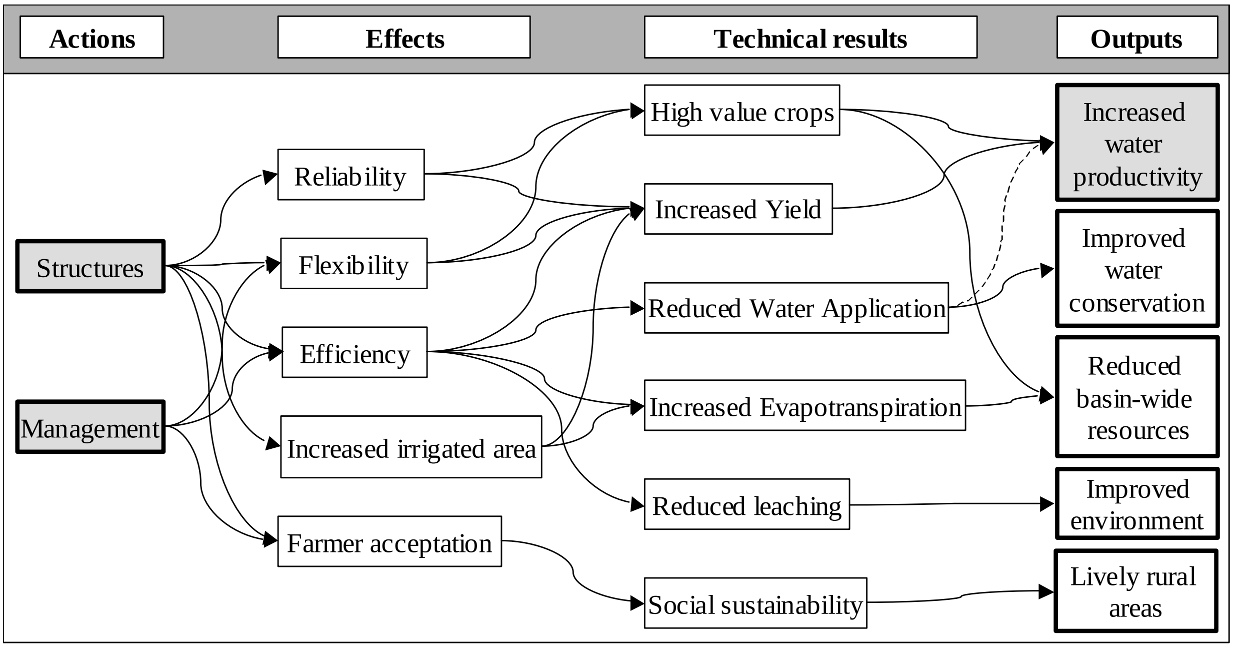

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