Modernization and optimization of irrigation systems to increase water productivity

Enrique Play?n[1] and Luciano Mateos[2]

[1] Estaci?n Experimental de Aula Dei, CSIC. Apdo. 202, 50080 Zaragoza, Spain www.eead.csic.es Email playan@eead.csic.es
[2] Instituto de Agricultura Sostenible, CSIC. Apdo. 4084, 14080 C?rdoba, Spain E-mail ag1mainl@uco.es

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 optimized. 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) divided by some expression of water input. The authors identified five expressions for this indicator, 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, since in many cases irrigation return flows can not be considered as a net water loss from a basin-wide perspective. A number of irrigation modernization and optimization measures are discussed in the paper. Particular attention is paid to the improvement of irrigation management, which shows much better economic return than the improvement of the irrigation structures. In closed basins 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.

Media summary

Water productivity in irrigated agriculture will need to be increased worldwide to meet the growing food demand of the next decades.

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 FAO analysis (FAO, 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:

- 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. 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).
- 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.
- 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 technical 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 (irrigation efficiency) arise from the following facts:

- It is an uncompromising choice. By promoting efficiency improvements decision makers do not intervene in the fragile water equilibrium. They show respect for current water allocation, and at the same time they take a visible action to improve water availability.
- It catalyses some economic sectors, such as construction. Most decision makers fund their decisions in the belief that public investment (particularly in construction) keeps the economic wheel turning.
- 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), and no social group will feel negatively affected by public action.

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. Rural water control produces local well-being and is one of the few sources of rural social and economic power.
- Proper technical management improves the environment, since it effectively reduces the salt and nutrient leaching from irrigated areas (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}) or, when dealing with different crops, crop yield may be transformed into monetary units (i.e., € ha^{-1}). More 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:

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

$$WP_2 = \frac{\text{Production}}{\text{Water Diverted}}$$

$$WP_3 = \frac{\textit{Production}}{\textit{Water Beneficially and Non Beneficially Consumed}} = \frac{\textit{Production}}{\textit{ICUC} \times \textit{Water Diverted}}$$

$$WP_4 = \frac{Production}{Water\ Beneficially\ Consumed} = \frac{Production}{IE \times Water\ Diverted}$$

$$\mathrm{WP}_5 = \frac{\text{Production}}{\text{Net Irrigation Requirements}} = \frac{\text{RIS} \times \text{Production}}{\text{Water Diverted}}$$

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[1]); 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[1]); 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).

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 evapotranspired or leached water into crop yield. If the water that is used but not consumed in an irrigation unit of the domain cannot be reutilized within the domain, then WP_2 is pertinent (otherwise it is not comparable across scales). This is the case of a single field taking all the irrigation water from an irrigation canal. If the water used but not consumed can be reutilized downstream in the same domain, then WP_3 is more appropriate.

The reutilization 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 use (evapotranspiration) will reduce the return flows and therefore interfere with downstream water uses.

These principles have led to the formulation of the “International Water Management Institute (IWMI) water resources paradigm” (Perry 1999), a hydrological approach to water allocation. The discussion of the paradigm was illustrated by a series of anonymous 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, since more agricultural output was produced with the same water stock.
- In the US 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 IWMI water resources paradigm can only be applied to the hydrological basin as a whole. If a subset is considered including for instance a reservoir and an irrigation project, 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 in 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, 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 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.

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 Regad?os*", 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. Irrigation districts in Spain are private farmers' associations covering areas of 1,000 to 15,000 ha. 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. The PNR offers the districts technical project management (*via* public companies) and a 50 year financing scheme. The investment repayment scheme is as follows:

- For the collective irrigation network: During the first 25 years the district subscribes a collective, private loan for one-third of the investment at the market interest rate. During years 26 to 50 the district returns to the Government two-thirds of the investment at zero interest.
- For on-farm equipment: the same scheme applies, only that half of the investment is paid back in each 25 year period.

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 (Play?n et al. 2002). This district operates 15,000 ha of mostly surface irrigation. Water allocation is performed by limited demand 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 with the current irrigation structures. A set of hydrological data from two irrigation seasons served to confirm this finding. Table 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 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).

An interesting concept in district water management is the Management Improvement Program (MIP) (Dedrick et al. 1989; Dedrick et al. 1993). According to these authors, a MIP is a "coordinated and sustained effort to improve water management in an organization" (an irrigation district). This effort was 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; involvement by key decision makers in a joint decision process; and implementation of the planned changes by responsible operational managers. The MIP was defined as a three phase process:

- Diagnostic analysis. The board analyses district performance, resources and limitations and produces a consensus diagnosis of the district status and the aims for the future.
- Management planning. A strategic plan is prepared by the board presenting the basic outlines of the proposed MIP.
- Performance improvement. Activities are developed and a continuous revision process is performed by the board.

Table 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.

Year	Crop water requirements (hm^3)	Water allocation (hm^3)	Global irrigation efficiency (%)
2000	82.6	169.6	49 %
2001	97.4	146.8	66 %

On-farm

Although all irrigation systems can attain approximately the same levels of efficiency (Clemmens and Dedrick 1994), traditional surface irrigation systems often show on-farm efficiencies close to 50 % (Play?n et al. 2000; Lecina et al. 2001). At the same time, properly designed and managed pressurized systems can attain 90 % efficiency (Dechmi et al. 2003a; Dechmi et al. 2003b). As a consequence, changing the irrigation system (from surface to sprinkler) in field crops such as maize in North Eastern Spain often produces results similar to those presented in Fig. 1. A sharp reduction in irrigation water demand can be achieved, following the increase in irrigation efficiency. A combination of improved irrigation uniformity, the control of the irrigation depth, and a flexible irrigation scheduling result in an increase in crop yield, at the unavoidable cost of an increase in crop evapotranspiration, and in a significant increase in WP_2.

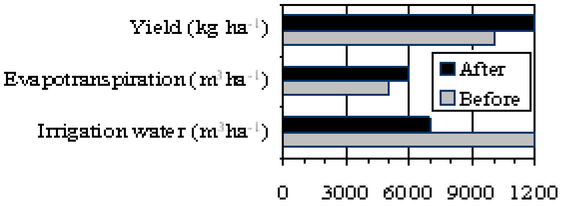

Figure 1. Typical changes in irrigation water, crop water use and yield resulting from the modernization and optimization of irrigated maize fields in North Eastern Spain.

On-farm irrigation management can also result in increases in WP_5. Mateos et al. (1991) compared the water productivity of drip and furrow-irrigated cotton, concluding that, under full irrigation, WP_5 was not significantly different for both treatments. However, under deficit irrigation, WP_5 was notably greater for drip irrigation than for furrow irrigation. As expected, WP_2 was higher for drip irrigation than for furrow irrigation, both under full and deficit irrigation, and WP_2 was always lower than WP_5 (Table 2).

Table 2. 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. Adapted from (Mateos et al., 1991).

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

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 2 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 RIS values from 0.55 to 1.19; by contrast, winter wheat, sunflower and olive had much lower RIS values, from 0.22 to 0.46. 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.

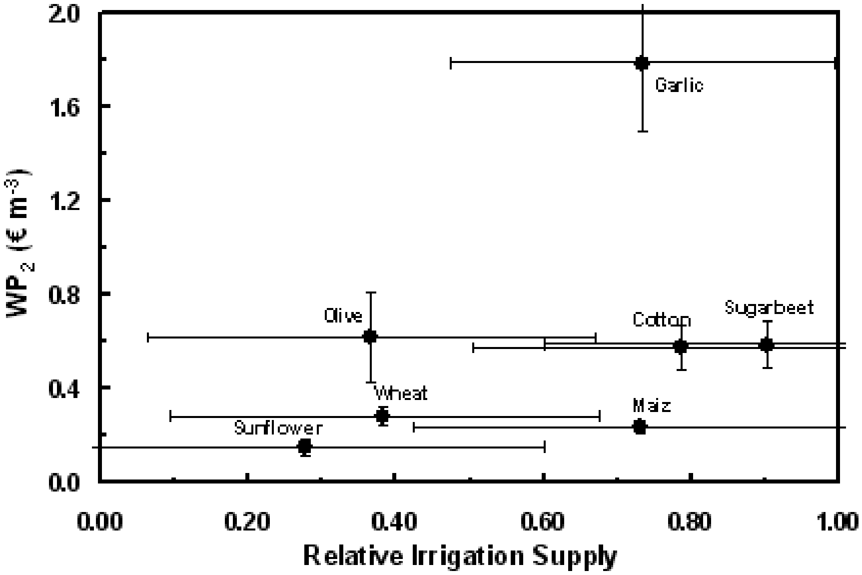

Figure 2. Relation between Relative Irrigation Supply (RIS) and WP2 in the Genil–Cabra irrigation district of Southern Spain. Values are averages for four irrigation seasons, and the bars depict twice the standard deviation.

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 many countries a long tradition of irrigation extension has been discontinued in the last decades. Presently in Spain specialized public irrigation services are taking up this task, and offer advice on on-farm equipment and technology, crop water requirements and scheduling techniques. 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 leveling 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 leveling in zero-slope fields can be estimated through the standard deviation of soil surface elevation (SD). A field leveled with conventional equipment can attain a standard deviation of 20-30 mm, while using laser leveling the technical limit would be less than 10 mm. Figure 3 presents the evolution of the water application efficiency (AE) of a particular case as a function of SD (Play?n et al. 1996). The figure reveals that the introduction of laser leveling can result in more than ten points increase in efficiency, while the cost of the leveling operation is two to three times that of a standard tillage operation.

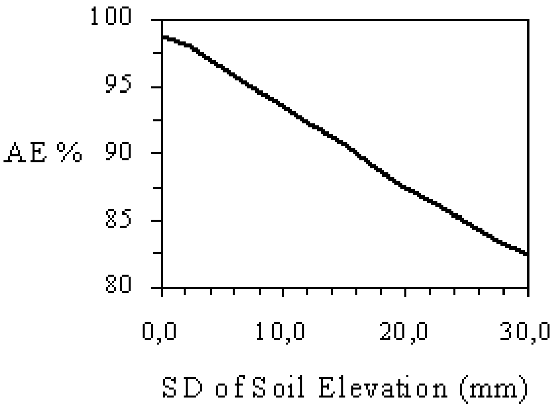

Figure 3. Simulated effect of the quality of land leveling (characterized by the standard deviation of soil surface elevation) on application efficiency in a particular case of level-basin irrigation.

In sprinkler irrigation one of the keys to efficient irrigation consists of managing the wind, particularly in windy regions, such as the Ebro Valley of North Eastern 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 third of daytime losses (Salvador 2003). Irrigation machines (pivots and rangers) result in smaller water losses than solid set systems. The daily evolution of wind speed, combined with the differences between daytime and night time operation, result in differences in water use arising from the time of irrigation.

Figure 4 presents the results of a simulation study in which all maize crop irrigations were scheduled at the same time of the day (Dechmi, 2004). The irrigation scheduling criterion permitted to obtain the same yield in all cases. Irrigation efficiency ranged from 64 % (irrigating at 12 h) to 80 % (irrigating at 0 h). 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 crop water use and WP.

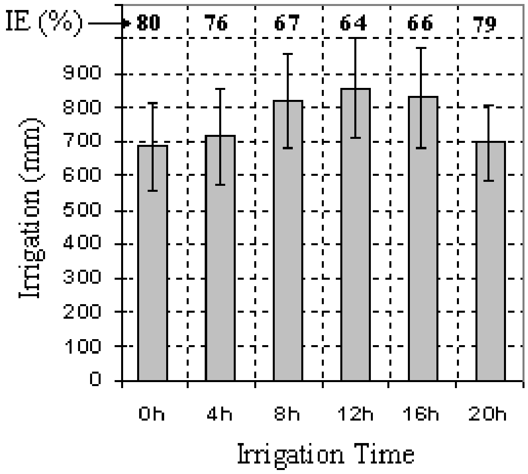

Figure 4. Effect of the time of sprinkler irrigation on the irrigation depth required to obtain maximum maize yield in the conditions of Zaragoza, Spain. Irrigation efficiency estimates are supplied for each case at the top of the figure.

Expected outputs of irrigation modernization and optimization. Conclusions.

Figure 5 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 from following both paths, and lead to increased WP through high value crops and increased yield. A third way to these goals, system reliability, can only be addressed 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 water conservation, which can be a valuable benefit in many situations.

According to Figure 5, 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 6 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 Spanish 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. 2). 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.

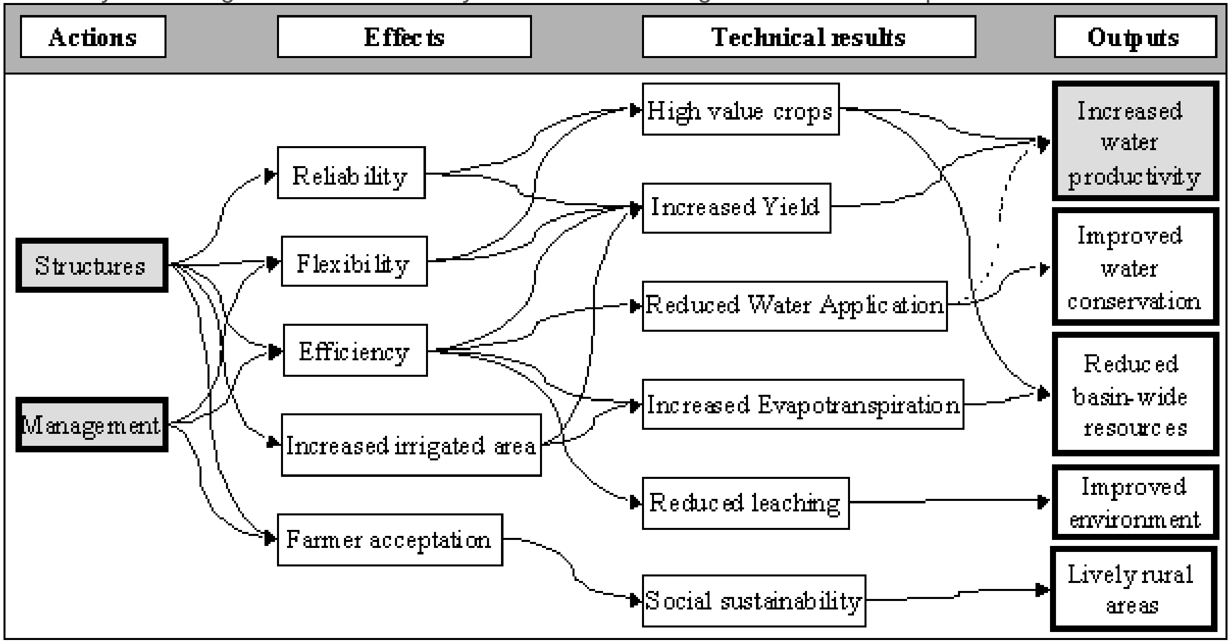

Figure 5. Flux diagram of the actions, effects, technical results and outputs related to irrigation modernization and optimization.

Figure 6. Aerial photograph showing modernized (left) and traditional (right) irrigated areas in North Eastern Spain.

According to Fig. 2, the choice of crop can induce very large differences in WP. However, modern irrigation structures are required to attain the required levels of reliability and flexibility. 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.

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 optimize 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 (per hectare), 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 a proper analysis 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.

References

Abu-Zeid M, and Hamdy A (2002). Water vision for the twenty-first century in the Arab World, World Water Council, International Policy Think Tank. Arab countries vision consultations, Marseille, France.

Allan T (1997). "Virtual water": a long term solution for water short Middle East economies? British Association Festival of Science, water and development session, University of Leeds.

Allan T (1999). Productive efficiency and allocative efficiency: why better management may not solve the problem. Agricultural water management 40, 71-75.

Anonymous (1998). Plan Nacional de Regad?os, horizonte 2008, Ministerio de Agricultura, Pesca y Alimentaci?n, Madrid.

Burt CM, Clemmens AJ, Strelkoff TS, Solomon KH, Bliesner RD, Hardy LA, Howell TA, and Eisenhauer DE (1997). Irrigation performance measures: efficiency and uniformity. Journal of Irrigation and Drainage Engineering 123, 423-442.

Cai X and Rosegrant MW (2003). World water productivity: current situation and future options. In (Kijne JW, Barker R and Molden D, eds.) Water productivity in agriculture: Limits and opportunities for improvement. CABI Publishing, UK, in association with IWMI, Colombo, Sri Lanka. P 163-178.

Cavero J, Beltr?n A, and Arag??s R (2003). Nitrate exported in the drainage waters of two sprinkler irrigated watersheds. Journal of Environmental quality 32(2003), 916-926.

Clemmens AJ, and Dedrick AR (1994). Irrigation techniques and evaluations. Advanced series in agricultural sciences, K. K. Tanji and B. Yaron, eds., Springer-Verlag, Berlin, 64-103.

Dechmi F, Play?n E, Cavero J, Mart?nez-Cob A and Faci JM (2004). A coupled crop and solid set sprinkler simulation model: II. Model application. J. Irrig. and Drain. Engrg., ASCE, in press.

Dechmi F, Play?n E, Faci J, and Tejero M (2003a). Analysis of an irrigation district in northeastern Spain: I: Characterisation and water use assessment. Agricultural Water Management 61(2003), 75-92.

Dechmi F, Play?n E, Faci J, Tejero M, and Bercero A (2003b). Analysis of an irrigation district in northeastern Spain: II: Irrigation evaluation, simulation and scheduling. Agricultural Water Management 61(2003), 93-109.

Dedrick AR, Clyma W, and Palmer JD (1989). A management improvement process to effectively change irrigated agriculture. Planning for water shortages. Water reallocations and transfers. Drought management, Boise, Idaho, 45-58.

Dedrick AR, Clyma W, Tenney OL, Clemmens AJ, Gibson RD, Levine DB, Replogle JA, Rish SA, Ware RE, and Wilson PN (1993). A demonstration irrigation management improvement program. Fifteenth congress, International Commission on Irrigation and Drainage, The Hague, 95-104.

Erie LJ, and Dedrick AR (1979). Level basin irrigation: A method for conserving water and labor. USDA Farmers' Bulletin 2261, 23.

FAO (2003). World agriculture: towards 2015/2030. Earthscan Publications Ltd, London, 432 pp.

Hoekstra AY, Hung PQ (2003). Virtual water trade – a quantification of virtual water flows between nations in relation to international crop trade. www.wateryear2003.org

Horst L (1998). The dilemmas of water division, Considerations and criteria for irrigation system design. International Water Management Institute, Colombo, Sri Lanka, 123 pp.

Lecina S, Isidoro D, Dechmi F, Causap? J, Play?n E, Faci JM, and Laplaza JM (2001). Evaluaci?n de los riegos de la Comunidad de regantes V de Bardenas. XIX Congreso Nacional de Riegos, Zaragoza.

Lorite IJ, Mateos L, and Fereres E (2004). Evaluating irrigation performance in a Mediterranean environment. II. Variability among crops and farmers. Irrigation Science 23, 85-92.

Mateos L, Berengena J, Orgaz F, Diz J, and Fereres E (1991). A comparison between drip and furrow irrigation in cotton at two levels of water supply. Agricultural Water Management 19, 313-324.

Mateos L, Young CA, Wallender WW, and Carlson HL (2000). Simulating spatially distributed water and salt balances. Journal of Irrigation and Drainage Engineering 126, 288-295.

Molden DJ, Sakthivadivel R, Perry CJ, de Fraiture C, Kloezen WH (1998). Indicators for Comparing Performance of Irrigated Agricultural Systems. Research Report 20. International Water Management Institute, Colombo, Sri Lanka

Perry CJ (1999). The IWMI water resources paradigm - definitions and implications. Agricultural water management 40, 45-50.

Play?n E, Faci JM, Mart?nez-Cob A, Arag??s R, Qu?lez D, Cavero J, Beltr?n A, Isidoro D, Lecina S, Causap? J, Dechmi F, and Mantero I (2002). Mejora del uso del agua y de la sostenibilidad medioambiental en comunidades de regantes: el caso de la comunidad V de Bardenas, Gobierno de Arag?n, Zaragoza.

Play?n E, Faci JM, and Serreta A (1996). Modeling microtopography in basin irrigation. Journal of Irrigation and Drainage Engineering, ASCE 122(6), 339-347.

Play?n E, Slatni A, Castillo R, and Faci JM (2000). A case study for irrigation modernisation: II. Scenario Analysis. Agricultural Water Management 42(2000), 335-354.

Plusquellec H (2002). Is the daunting challenge of irrigation achievable?. Irrigation and Drainage 51, 185-198.

Salvador R (2003). Estudio de las p?rdidas por evaporaci?n y arrastre en los sistemas de riego por aspersi?n. Diferencias entre riegos diurnos y nocturnos, Proyecto fin de carrera, Universitat de Lleida, Spain.

Seckler D, Molden D, and Sakthivadivel R (2003). The concept of efficiency in water resources management and policy. In (Kijne JW, Barker R and Molden D, eds.) Water productivity in agriculture: Limits and opportunities for improvement. CABI Publishing, UK, in association with IWMI, Colombo, Sri Lanka. p 37-51.

Tedeschi A, Beltr?n A, and Arag??s R (2001). Irrigation management and hydrosalinity balance in a semi-arid area of the middle Ebro river basin (Spain). Agricultural water management 49(2001), 31-50.

Willardson LS, Allen RG, and Fredericksen HD (1994). Elimination of irrigation efficiencies. 13th Tech. Conf. USCID, Denver, CO, 17 pp.

[1] 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.