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INDICATORS TO SUPPORT DEVELOPING A NEW PARADIGMA FOR IRRIGATED AGRICULTURE

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SUMMARY - Water saving is part of a wide process of adaptation of irrigated agriculture to a new era, where pressures from the society on an improved use of the water make evident several paradoxes. These refer to pressures for decreasing water consumption, paying the full costs of water, improving irrigation efficiency and maximizing water productivity. The ideas behind are essentially correct but they need a serious adaptation to local, real conditions, otherwise they consist in paradoxes as illustrated in the paper. To overcome these problems there is a need to develop and adopt new concepts and consequently new indicators relative to water use performances and to water productivity that support the development of appropriate strategies leading to a more efficient use of water in agriculture and to improved social and economic conditions of farmers. A set of these indicators is discussed in this paper, aiming at developing a new paradigm for irrigated agriculture.

Keywords: irrigation performance, water use indicators, water productivity, economics of irrigation.

INTRODUCTION: PARADOXES OF IRRIGATED AGRICULTURE

For millennia, civilisations developed in water scarce environments. The respective cultural skills are an essential heritage of those nations and peoples, and the humanity as well. However, progress in XX century questioned the traditional know-how, which has been often replaced by modern technologies and management imported from different environments and cultures. A water economic culture is following the technical one, which was introduced, sometimes imposed when the large irrigation schemes were built. Both technologies and management are generally imported from different cultural and institutional environments and their adaptation to local conditions has not always been successfully adopted or accepted by farmers. Management faces therefore difficult challenges due to the fact that irrigators have a perception of problems, practices and objectives different from the non-farmer managers.

The last century has known an increased intervention of governmental and state institutions in water management following the enormous investments made. Traditional institutions lost importance due to increased technical complexity of management and to political trends aiming at increasing the power of the governmental institutions relative to many aspects of the society, including water and land. New centralized institutions were created following such investments and introduced technologies. Nowadays, due to a generalized unsuccessful result of those institutional arrangements, participatory irrigation management is considered in different forms to solve the resulting problems

A turn in viewing traditional irrigation is starting in the international media (Fig. 1) where a new perception of advantages of traditional know-how starts to be evidenced. However, pressures on irrigation farmers are continuing

International Herald Tribune | 17
Saturday-Sunday, August 20-21, 2005

Past methods may be better adapted to local conditions

Old ways of water management spring up again in arid regions

Water-scarce India, too, weighs a return to ancient practices

Fig. 1. Titles of an international newspaper evidencing a new perception on the value of traditional know-how in the water resources area

Pressures relative to water use in irrigation are coming from an ever growing urban society that understands less and less the rural world and, particularly, the small farmers. These include:

Pressures to decrease water consumption

When these should be to control the water demand. Reducing water consumption means reducing crop evapotranspiration (ETc), which is not feasible since yield strongly relates to ETc. Other consumptive uses non directly related with crop yielding may be reduced but with strong technological investments with limited impacts. Controlling the water demand is generally feasible but, often, is not possible because farmers may not have access to technologies better then those they are using after centuries and that made their systems sustainable. Deficit irrigation is the most common approach to reduce demand. It is generally feasible for supplemental irrigation of cereals when decreasing the Gross Margins (GM) per unit land leads is associated to increased GM per unit of water used (El Amami et al., 2001; Zairi et al., 2003). Farmer incomes then reduce but remain higher than the income resulting when reducing the cropped area. However for many summer crops, e.g. tomato in Tunisia, when GM/ha decreases due to less water application the GM/m3 do not increase. It is then questionable to adopt deficit irrigation.

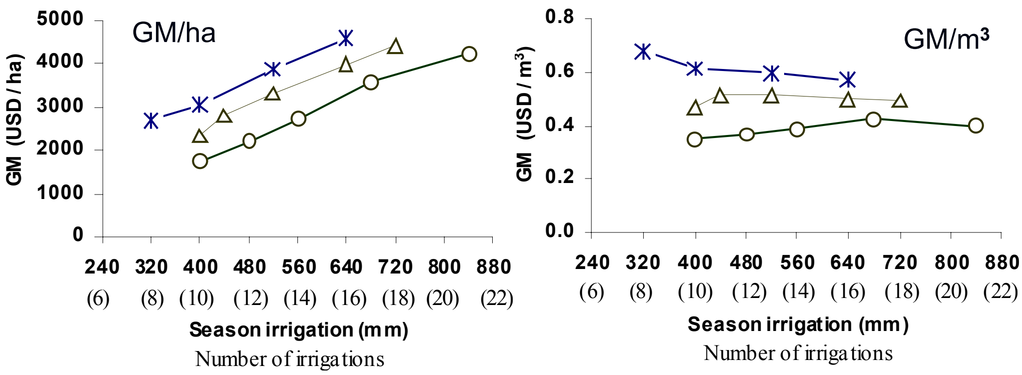


Fig. 2. Gross margins per unit surface (GM/ha) and per unit volume of water applied (GM/m^3) for alternative deficit irrigation strategies of tomato crop in Siliana, Tunisia, for average (—✳—), high (—△—) and very high (—○—) demand conditions (Zairi et al., 2003).

Pressures to pay the full costs of water

Often not considering impacts of yield prices and farmers' revenues and, more often, not taking into account the externalities of irrigation such as aquifer recharge and flood control. Impacts of water costs on water demand are very strong when common agricultural commodities are produced, but less important for high price commodities. Several papers demonstrate that such a high level of water costs would lead to not only a decrease in water demand but to a decrease in irrigated areas, farmers revenues and employment in agriculture as illustrated in Fig. 3 relative to a Portuguese case study by Pinheiro and Saraiva (2002). If the multifunctions of irrigated agriculture are recognized, the water is "fully" valued and farmers will pay what is socially and economically acceptable.

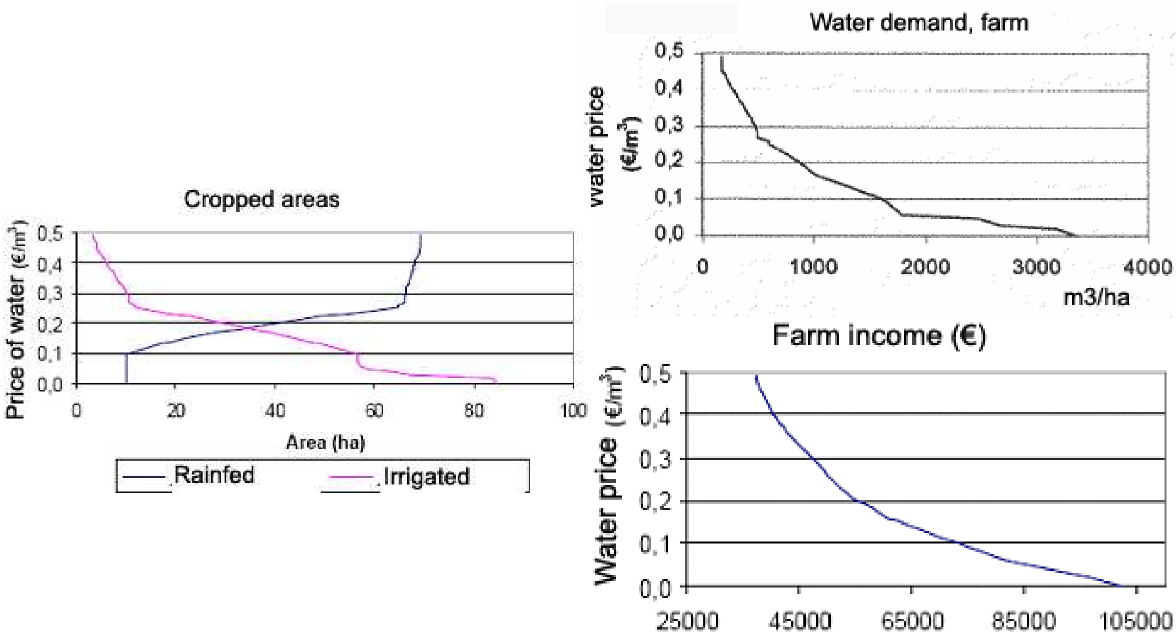


Fig. 3. Impacts of water costs on water demand, irrigated cropped areas and farmers' income in case of Alentejo. Portugal (Pinheiro and Saraiva, 2002)

Pressures to improve irrigation efficiency as considering that such an improvement would lead to water saving. This question is well discussed by many authors relative to the poor understanding that may be behind the concepts of irrigation efficiency (e.g. Jensen, 1996; Burt et al., Pereira et al., 2002a, b) or the impacts that occur at system and watershed level (Goussard, 1996; Bos et al., 2005). Farmers generally know they need to apply water in excess to leach salts, to store water in the soil when deliveries are not reliable, or to overcome the poor distribution uniformity of the system. The farmer will increase the application depth (D) as much as the risk for not having enough water at the next irrigation or as poor are the land conditions regarding uniformity of water application through the field.

It is well known that the depth D depends upon the technologies available as it is well analysed by Keller and Bliesner (1990) relative to sprinkler irrigation. Improving technologies to achieve a high uniformity - defined by the classical coefficient of uniformity (UC) – which could provide for approaching D to its optimal value Dopt is an economic decision. On the one hand, it depends on the costs of required equipments; on the other hand, it depends upon the relationship between the price of the yield commodity (PY) and the cost of the water (PW) as analysed by Mantovani et al. (1995). If the ratio PY/PW is high, i.e. the irrigation costs are a small fraction of the yield value, the farmer may not be interested in saving water and in achieving high uniformities; when that ratio is small, then irrigation costs are high and a strategy may be to use a system that provides for high UC (Fig. 4). However, if the required investments are high the strategy may be to irrigate another crop that provides a higher GM without such a costly investment.

Instead of putting the pressure on increasing irrigation efficiencies, it is more rational to look for conditions that favour improving irrigation uniformity.

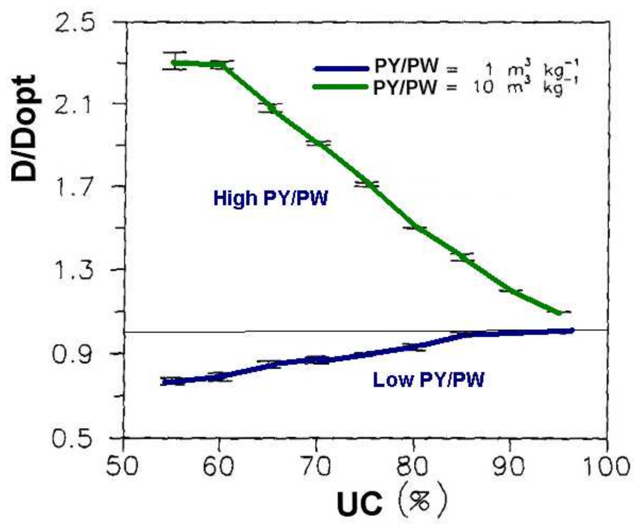


Fig. 4. Relationships between the application depth ratio D/Dopt and the coefficient of uniformity UC for conditions of high and low yield to water costs ratios (adapted from Mantovani et al., 1995)

Pressures for increasing water productivity, commonly said “more crop per drop”. Attaining a high water productivity (WP) in irrigation is extremely important (Molden et al., 2003; Shideed et al., 2005) but this may be achieved by improving agronomic practices and water use, not decreasing water use. Moreover, for a small farmer, for whom the limiting factor is not water but land, the priority is to increase land productivity (LP) because the total revenue depends on the available land.

There is a contradiction between water and land productivity that is solved differently by a water manager, who calls for Max(WP) and a farmer which primary objective is Max(LP). Maximizing yields, i.e. LP, or maximizing WP follow different objectives which relate to the socio economic farming conditions. A key issue is to know the relationship among “applied water” - “costs” - “revenues” (Fig. 5) as discussed in a previous paper (Pereira, 2006).

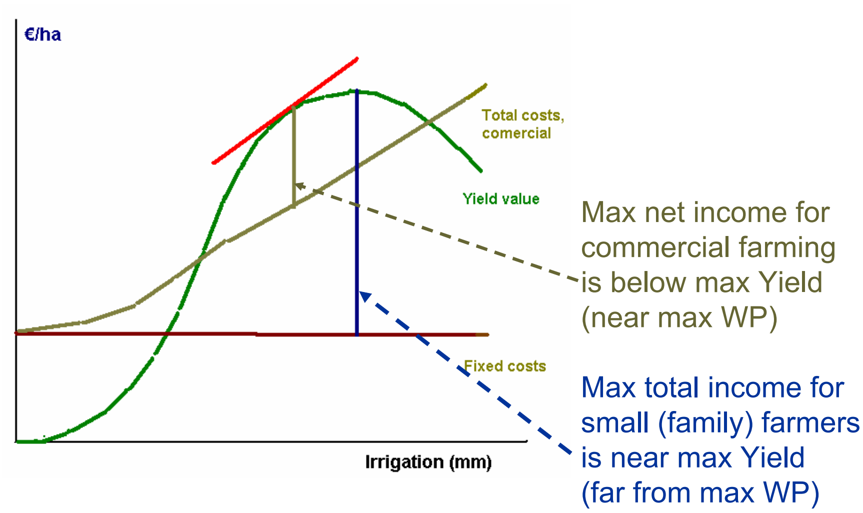


Fig. 5. Schematic representation comparing how maximizing farm incomes for a commercial and a family farm lead to different approaches to economic water productivity (costs relative to water volumes used are not considered for simplification) (Pereira, 2006).

WATER USE AND INDICATORS AIMED AT IMPROVED WATER USE

The objectives of irrigation demand management can be summarised as follows:

- *Reduced water demand* through selection of low demand crop varieties or crop patterns, and adopting deficit irrigation, i.e. deliberately allowing crop stress due to under-irrigation, which is essentially an agronomic and economic decision.

- *Water saving / conservation,* mainly by improving the irrigation systems, particularly the uniformity of water distribution and the application efficiency, reuse of water spills and runoff return flows, controlling evaporation from soil, and adopting soil management practices appropriate for augmenting the soil water reserve, which are technical considerations.
- *Higher yields per unit of water,* which requires adopting best farming practices, i.e. practices well adapted to the prevailing environmental conditions, and avoiding crop stress at critical periods. These improvements result from a combination of agronomic and irrigation practices.
- *Higher farmer income,* which implies to farm for high quality products, and to select cash crops. This improvement is related mainly to economic decisions.

Efficient water use in irrigation may be achieved through adopting best farming practices and appropriate irrigation technologies. However, technologies face a peculiar paradox: the market is oriented for commercial farms, not to small farms, when small producers largely dominate worldwide.

Excellent performances may be achieved with surface irrigation when land levelling and irrigation technologies are appropriate. A challenge is to provide incentives and support to farmers for improving their systems. The challenge is to make available the required tools and facilities that allow surface irrigation to produce an efficient water use. Modern sprinklers may produce excellent performances if design is adequate and the selected system is appropriate for the local environmental constraints and farming conditions. When micro-irrigation – drip, SDI, micro-sprinkling - are well designed and managed, performances can be excellent, but these are not achievable without appropriate support to farmers. Field evaluations in farmer fields, extensive use of design models such DSS, expert systems and Information Technologies for supporting farmers. These aspects have been previously reviewed (Pereira, 1999; Pereira et al., 2002a, b).

To solve the identified paradoxes and make irrigation viable also for small farmers there is the need to develop a new irrigation paradigm and adopt new indicators that support such paradigm. Water use indicators must be universal, not specific of irrigation, and supported by a logic analysis of water use paths such as in Fig. 6.

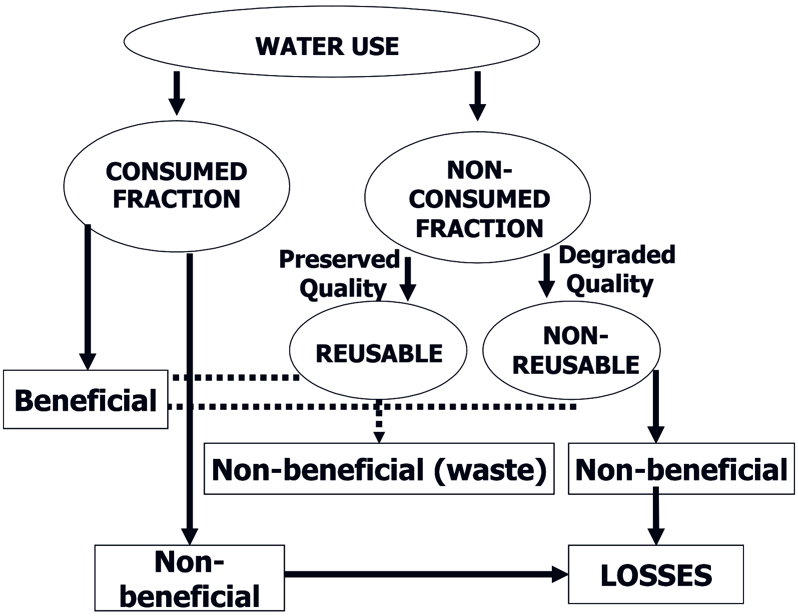


Fig. 6. Water use and consumption, beneficial and non-beneficial, wastes and losses

The scheme in Fig. 6 applies to irrigation and non-irrigation water uses such as for industry and urban uses (Pereira et al., 2002b). Relative to irrigation, it is more interesting than to know which water use is beneficial or not (Fig. 7) than to know if a system or an irrigation event is more or less efficient, or to know which and how much water is lost or can be reused in the farm or by other users downstream.

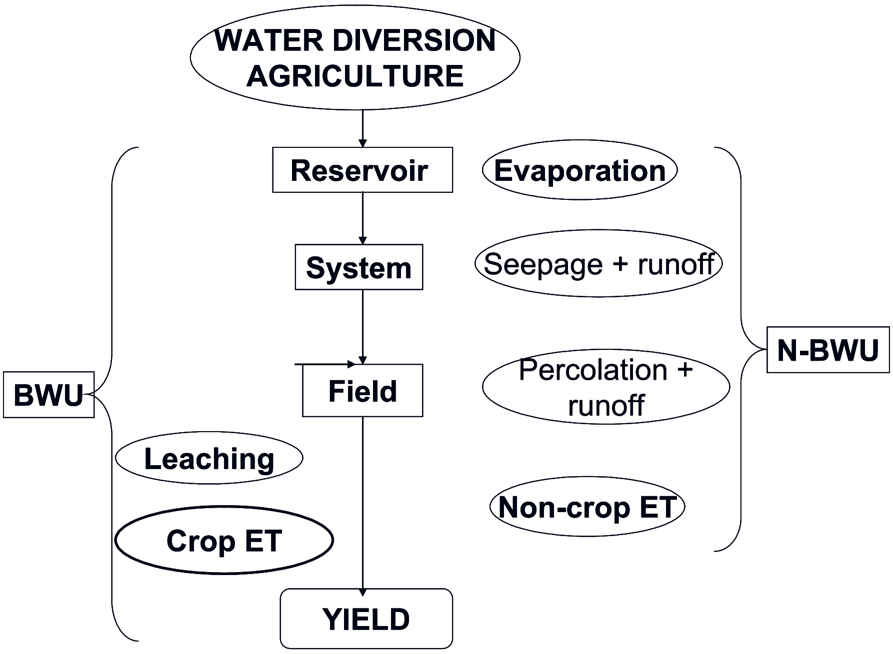


Fig. 7. Beneficial and non-beneficial water uses in irrigated agriculture

The logics of schematic representations in Figs. 6 and 7 supports new water use indicators (Pereira, 2003). These can be defined as follows for both irrigation and non-irrigation water uses:

The consumed or consumptive use fraction (CF), consisting of the fraction of diverted water which is evaporated or incorporated in the product, or consumed in drinking and food, which is no longer available after the end use. For irrigation water use it is

$$CF_{IRRIG} = \frac{E + ET_{crop} + ET_{weeds} + IN_{product}}{TWU} \tag{1}$$

and for non-irrigation and non-agricultural water uses is

$$CF_{NonIrrig} = \frac{E + ET_{landscape} + ET_{weeds} + IN_{food} + IN_{product}}{TWU} \tag{2}$$

where the numerator refers to process evaporation (E) and evapotranspiration (ET) and incorporation in products (IN) and the denominator is the total water use (TWU). Subscripts identify the main sinks of water consumption.

For both cases one should identify in CF the beneficial consumed fraction (BCF):

$$BCF_{IRRIG} = \frac{ET_{crop} + IN_{product}}{TWU} \tag{3}$$

$$BCF_{NonIrrig} = \frac{E_{processes} + ET_{landscape} + IN_{food} + IN_{product}}{TWU} \tag{4}$$

and the non-beneficial consumed fraction (NBCF)

$$NBCF_{IRRIG} = \frac{E + ET_{weeds}}{TWU} \quad (5)$$

$$NBCF_{NonIrrig} = \frac{E_{non\text{-}processes} + ET_{weeds}}{TWU} \quad (6)$$

The reusable fraction (RF), consisting of the fraction of diverted water which is not consumed when used for a given production process or service but which returns with appropriate quality to non degraded surface waters or ground-water and, therefore, can be used again:

$$RF_{IRRIG} = \frac{(\text{Seepage} + \text{Percolation} + \text{Runoff})_{\text{non-degraded}}}{TWU} \quad (7)$$

$$RF_{\mathbf{NonIrrig}} = \frac{(\text{Seep} + \text{Perc} + \text{Run})_{\textbf{non-degraded}} + (\text{Ret flow} + \text{Effl})_{\textbf{treated}}}{TWU} \quad (8)$$

where the numerator consists of non-consumptive use processes that did not degrade the water quality, thus allowed further uses, including when the return flows (Ret flow) and effluents (Effl) are treated. As above, RF should be divided into a beneficial reusable fraction

$$BRF_{IRRIG} = \frac{(\text{Runoff}_{\text{processes}} + LF)_{\text{non-degraded}}}{TWU} \quad (9)$$

$$BRF_{NonIrrig} = \frac{(LF_{landsc} + Run_{proces})_{\text{non-degraded}} + \text{Contr Effl}_{\text{treated}}}{TWU} \quad (10)$$

which include water used for salts leaching, runoff necessary to the processes such as furrow and border irrigation, and controlled effluents (Contr Effl) required by non agricultural uses, as the case for many domestic uses. The non-beneficial reusable fraction (NBRF) is then

$$NBRF_{IRRIG} = \frac{(\text{Seepage} + \text{ExcessPerc} + \text{ExcessRunoff})_{\text{non-degraded}}}{TWU} \quad (11)$$

$$NBRF_{NonIrrig} = \frac{(\text{Seep} + \text{Perc} + \text{ExcRunoff})_{\text{non-degraded}} + \text{Exc Effl}_{\text{treated}}}{TWU} \quad (12)$$

and refers to excess water use in the processes involved such as seepage and leaks from canals and conduits, spills from canals, excess percolation in irrigation uses or excess runoff that are non-degraded, and effluents due to waste of water in non-agricultural uses when treated.

c) ***The non-reusable fraction*** (NRF), consisting of the fraction of diverted water which is not consumed when used for a given production process or service but which returns with poor quality or returns to degraded surface waters or saline ground-water and, therefore, cannot be used again

$$NRF_{IRRIG} = \frac{(\text{Seepage} + \text{Percolation} + \text{Runoff})_{\text{degraded}}}{TWU} \quad (13)$$

$$NRF_{NonIrrig} = \frac{(Seep + Perc + Run)_{degraded} + (Ret\ flow + Effl)_{non\text{-}treated}}{TWU} \quad (14)$$

which refer to the same process as the RF but where the water looses quality and not being treated can not be used again or is added to water bodies non-usable for normal processes, such as saline groundwater, saline lakes and the oceans. The NRF shall also be divided into a beneficial non-reusable fraction (BNRF)

$$BNRF_{IRRIG} = \frac{(Runoff_{\ processes} + LF)_{\ degraded}}{TWU} \quad (15)$$

$$BNRF_{NonIrrig} = \frac{(LF_{landsc} + Run_{proces})_{degraded} + Contr\ Effl_{non\text{-}treated}}{TWU} \quad (16)$$

and a non-beneficial non-reusable fraction

$$NBNRF_{IRRIG} = \frac{(Seepage + ExcessPerc + ExcessRunoff)_{\ degraded}}{TWU} \quad (17)$$

$$NBNRF_{NonIrrig} = \frac{(Seep + Perc + ExcRunoff)_{degraded} + ExcEffl_{non\text{-}reated}}{TWU} \quad (18)$$

An illustration of main processes of water use in irrigation referring to the above described water use fractions is presented in Table 1. The corresponding processes for non-agricultural uses are given in Table 2.

Indicators shall be used to assess how water use could be improved in any water system, not to detect low performances but to identify the pathways for improvement. Indicators must be selected according the nature of problems and processes in view of allowing a deeper understanding about measures and practices to be implemented and improved. This applies not only to irrigation but to any water use. The framework in Fig. 8 shows that indicators allow to identify the water use pathways and then which processes require improvements, including water productivity. In other words, indicators referred are meant to provide for efficient water use.

Table 1. Consumptive, reusable and non-reusable water fractions in irrigation water uses

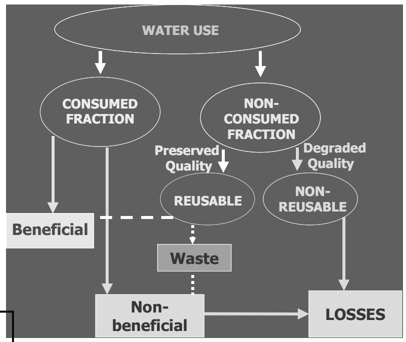
	Consumptive	Non-Consumptive but Reusable	Non-Consumptive and Non-Reusable
Beneficial uses	▪ ET from irrigated crops ▪ evaporation for climate control ▪ water incorporated in product	▪ leaching water added to reusable water	▪ leaching added to saline water
Non-beneficial uses	▪ excess soil water evaporation ▪ ET from weeds and phreatophytes ▪ sprinkler evaporation ▪ canal and reservoir evaporation	▪ deep percolation added to good quality aquifers ▪ Reusable runoff ▪ Reusable canal spills	▪ deep percolation added to saline groundwater ▪ drainage water added to saline water bodies
	Consumed fraction	**Reusable fraction**	**Non-reusable fraction**

Table 2. Consumptive, reusable and non-reusable water fractions in non-agricultural water uses

	Consumptive	Non-Consumptive but Reusable	Non-Consumptive and Non-Reusable
Beneficial uses	▪ human and animal drinking water ▪ water in food and drinking ▪ water incorporated in industrial products ▪ evaporation for temperature control ▪ ET from vegetation in recreational and leisure areas ▪ evaporation from swimming pools and recreational lakes	▪ treated effluents from households and urban uses ▪ treated effluents from industry ▪ return flows from power generators ▪ return flows from temperature control ▪ non-degraded effluents from washing	▪ degraded effluents from households and urban uses ▪ degraded effluents from industry ▪ degraded effluents from washing ▪ every non degraded effluent added to saline and low quality water
Non-beneficial uses	▪ ET from non beneficial vegetation ▪ evaporation from water wastes ▪ evaporation from reservoirs	▪ deep percolation from recreational and urban areas added to good quality aquifers ▪ leakage from urban, industrial and domestic systems added to good quality waters	▪ deep percolation from recreational and urban areas added to saline aquifers ▪ leakage from urban, industrial and domestic systems added to low quality waters and saline water bodies
	Consumed fraction	**Reusable fraction**	**Non-reusable fraction**

Pathways to improve water use

➢Identify the water pathways



Maximized beneficial uses

Minimized non-beneficial uses

Controlled, avoided water losses

High water productivity

➡ **Efficient water use**

Fig. 8. Pathways for efficient water use.

WATER PRODUCTIVITY

Water productivity (WP) was analysed in detail in a previous paper (Pereira, 2006) but, as evidenced in Fig 8, it has to be considered for any water use analysis. Adopting the framework defined in Fig. 9, main indicators should be referred,

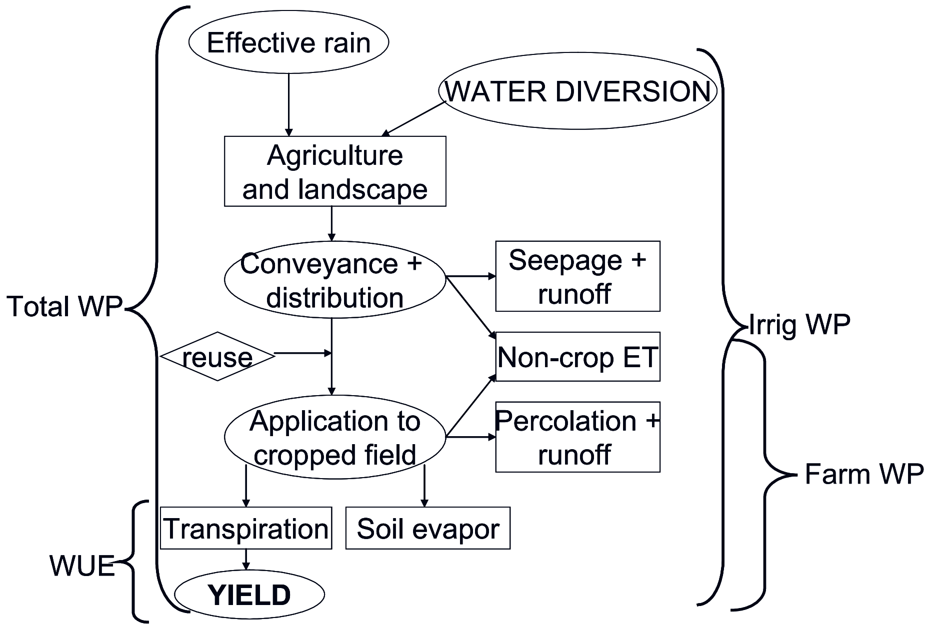


Fig. 9. A framework for defining water productivity in irrigated agriculture

WP is defined by the ratio

$$\text{Water poductivity} = \frac{\text{Actual yield}}{\text{Actual water use}} \tag{19}$$

or, referring to the sources of water use

$$WP = \frac{Ya}{P + CR + \Delta SW + Irrig} \qquad (20)$$

where Ya is the actual yield, P is rainfall, CR is the cumulative capillary rise, ΔSW is the contribution from stored soil water and Irrig is the season irrigation depth. If considering the concepts defined above (see Fig. 7), WP is defined by

$$WP = \frac{Ya}{ETa + LF + NBWU} \qquad (21)$$

where the denominator is the sum of actual crop ET, the leaching fraction and the non-beneficial water uses NBWU with NBWU = NBCF + NBRF + NBNRF that are defined in the previous section.

In equations above it may be more interesting to replace the yield quantity by the yield value or by the gross margin resulting from that yield, which defines the economic WP (EWP), because the EWP is helpful to understand how much the farmers are able to pay for water.

Fig. 9 evidences that when rainfall is not considered WP refers only to irrigation water and should be termed irrigation water productivity (Irrig WP). If only the water applied at farm level is considered, then it becomes farm WP. When the objective is to analyse the plant or crop efficiency, then soil water evaporation is not considered and the ratio WUE = Yield/Transpiration defines the water use efficiency. However, since in the farming practice it is not possible to avoid soil evaporation, this concept of WUE is of reduced interest in water use analysis.

WATER USE AND ENERGY

Energy is main concern in the XXI century not only because mining the fossil energy sources may lead to problems in future but because energy uses are a main causes of emissions responsible for the climate change problems that we want to avoid in future. In addition, the energy prices are contributing to increase the costs of irrigation. Biodiesel and sunfuel are now products of agriculture and when hydrogen will become usable agriculture will also contribute for that energy source (Fischer and Finnell, 2006).

Because agriculture is both a consumer and a producer of energy, and irrigated agriculture is a high consumer while market conditions may bring opportunities for irrigated crops to be used for energy production, it is important to recognize how water use may relate with energy efficiency in crop production. Different from indicators above, which were proved in several analyses, indicators relative to energy are just an attempt to contribute for a rational use of energy in irrigated agriculture. The framework for defining the respective indicators is shown in Fig. 10 and it was developed similarly to water productivity concepts (Fig. 9).

There is, however, a problem of terminology. The term energy ratio was preferred relative to energy efficiency. Both are non-dimensional but while the first is neutral the second may imply some judgements or opinions. Of course, these concepts apply to any crop, whatever irrigated or non-irrigated.

The first term defined is crop energy productivity (EP_{crop}) and intends to show that a crop is an energy converter, particularly from sun but using other sources of energy. It represents the ratio between the fuel equivalent energy and the cropped area. It corresponds to the land productivity of any cereal or forage crop.

$$\text{Energy Productivity}_{\text{crop}} = \frac{\text{Energy in crop yield}}{\text{Area cropped}} \text{ (L diesel eq/ha)} \qquad (22)$$

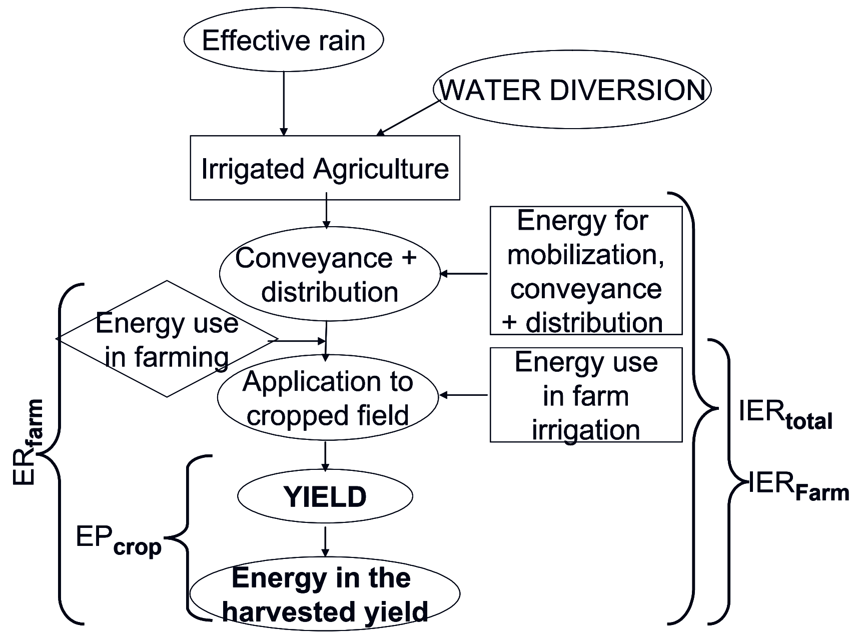


Fig. 10. A framework for defining energy performance in irrigated agriculture

The energy performance may be defined at farm level by the farm energy ratio (ER_{farm}) defined as

$$\text{Energy ratio}_{\textbf{farm}} = \frac{\text{Energy use at farm}}{\text{Energy in crop yield}} \tag{23}$$

or may be defined relative to an irrigated crop by the irrigation energy ratio (IER_{total}) referring to the ratio of energy used for the processes relative to irrigation, e.g. pumping and tractors usage in operations relative to irrigation

$$\text{Irrigation ER}_{\textbf{total}} = \frac{\text{Total energy in irrgation processes}}{\text{Energy in crop yield}} \tag{24}$$

It may be defined for all farming operations relative to the irrigated crops (IERfarm) irrigation or it may refer to just a given irrigated crop.

$$\text{Irrigation ER}_{\textbf{farm}} = \frac{\text{Energy use in farm irrigation}}{\text{Energy in crop yield}} \tag{25}$$

What is important at this time is to consider that improvements in water use require also the consideration of energy factors and that an efficient water use implies not only limiting water wastes and losses and high water productivity, but also a rational use of energy.

EXAMPLE APPLICATIONS OF WATER USE AND PRODUCTIVITY CONCEPTS

These concepts were adopted in studies developed for improved water use in irrigated agriculture of North China, and in Uzbekistan. For the analysis it was required to perform field studies at system and farm level and to use models that provide for a rational data analysis. DSS models were therefore developed since it was required to consider not only the physical results in terms of water use but also relative to economic impacts at farm level since the technical solutions have to be feasible for the main irrigation actors.

The case for China was recently presented in the framework of WASAMED as described by Gonçalves and Pereira (2005). It applies to the Upper Yellow River Basin, an arid region, with very cold winter and rain < 200 mm, where main crops are rice, wheat and maize, often intercropped. Main problems consist of excess water diversion, insufficient drainage that produced watertable rising and salinity, and less good irrigation systems, Pre-conditions for farm water savings and increased productivity were identified in relation to these problems; 1st: cut to about half the diversions from the river but improve delivery conditions; 2nd: rehabilitate the drainage system (without great investments); and 3rd: reduce percolation to the level required for leaching. Using a DSS multicriteria model applied to the system to analyse the foreseen improvements, results relative to water use and to utilities show that more stringent improvements (after level 4 or 4th year of implementation) have relatively reduced impacts (Figs. 10 and 11)

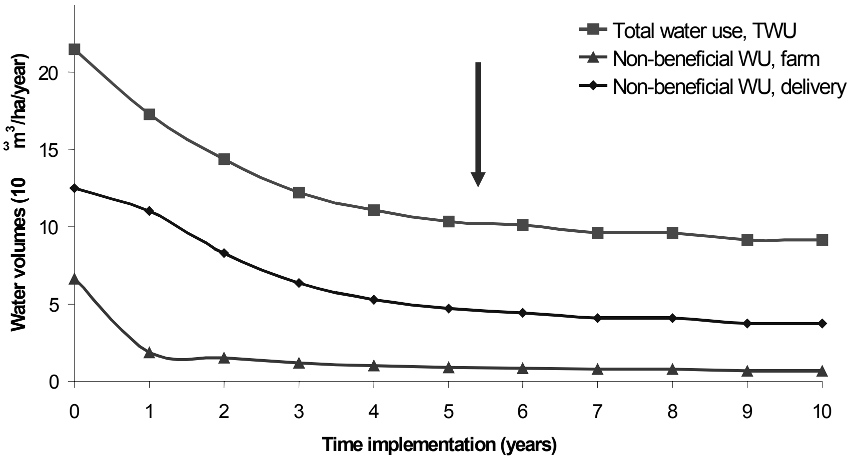


Fig. 11. Foreseen dynamics of total water use and non-beneficial water use at farm and system levels along the process of implementation of improvements in irrigation and drainage systems

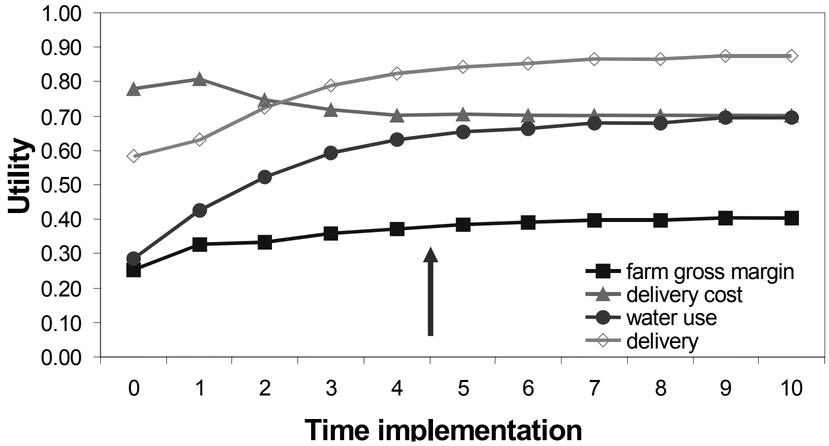


Fig. 12. Foreseen evolution of utilities - farm gross margin, delivery costs, water use and delivery water use –along the process of implementation of improvements in irrigation and drainage systems (Gonçalves and Pereira, 2005)

Fig 10 shows that non-beneficial water uses could be well identified and the selection of actions with help of the DSS model could focus on limiting them both at farm and system levels. Fig. 12 identifies two problems: 1) considering the existing economic conditions, mainly relative to production costs and prices of products, impacts on farmers revenues are quite small, so reducing the interest in further application of more demanding modern technologies; 2) water saving and drainage improvements are not economically interesting for the deliver system managers without changing cost recovery policies but these would imply further charges to the farmers that are not in conditions to pay for higher water costs. This example supports the analysed paradoxes and calls for a new irrigation paradigm.

Analysing the economic water productivity expressed by the gross margin per unit irrigation water use it becomes evident that EWP increases substantially while non-beneficial water uses are controlled (compare Fig. 13 with Fig. 11). Conditions for more stringent improvements at farm and system level do not lead EWP to increase enough to make modernisation interesting for this farmers community.

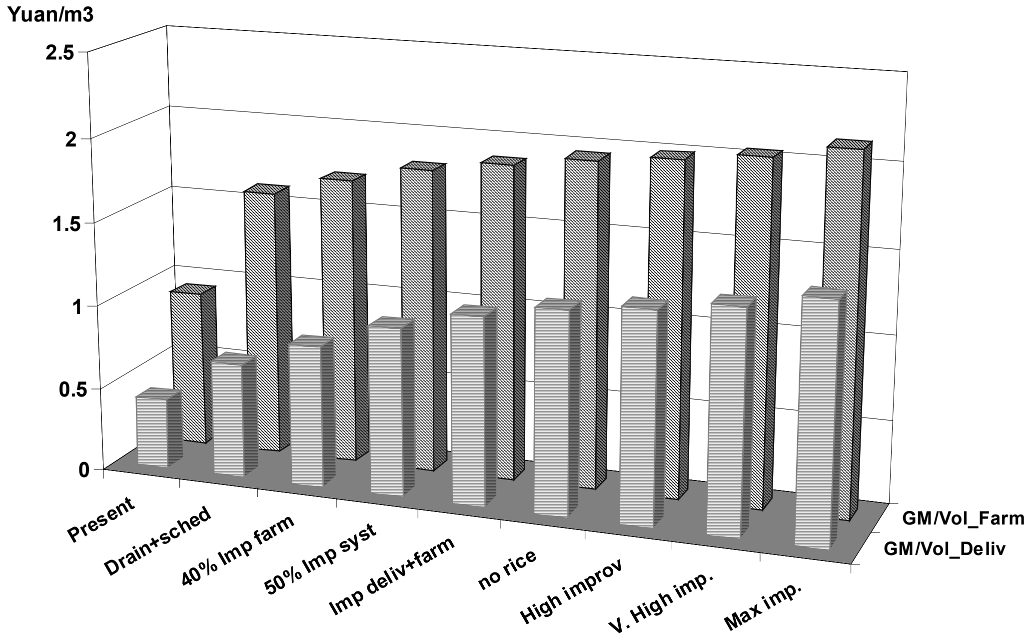


Fig. 12. Foreseen evolution of the economic water productivity as a function of the progressive irrigation and drainage improvements at farm and system level (Gonçalves and Pereira, 2005)

The second case study application concerns furrow irrigation in Fergana Valley, Uzbekistan, which is a great irrigated oasis in the Aral Sea Basin (Gonçalves et al., 2005a, b; Horst et al., 2006). The area is characterized by an arid climate and main crops are wheat and cotton, furrow irrigated. Because excessive water use has been the rule in the Aral Sea Basin, enormous changes in the Aral Sea and the river ecosystems have been produced, A reduced demand for irrigation is therefore required. With this objective, since furrow irrigation is by far the dominant method, alternative processes were evaluated together with improvements in irrigation scheduling. Only a few aspects referring to cotton are referred.

Every furrow continuous flow provides for maximizing yields (Ya/Ymax) but to minimal water use ratios such as CF and BWUF. Opposite, alternate surge irrigation do not achieve maximal yields but the highest irrigation WP, the highest beneficial water use fraction and the highest water consumed fraction (Fig. 14).

Comparing alternative improvements through a multi-criteria analysis (Fig. 15), results expressed in terms of utilities show that for the actual farming economic conditions in Fergana, the best alternatives are the present one – no changes - or adopting an improved irrigation scheduling and alternate furrow irrigation (Sched + AC in Fig. 15). If the multicriteria option would be dictated by water saving criteria then the best solutions are those relative to the application of surge flow applied to alternate furrows (Surge + Alt); further deficit irrigation (Def) do not lead to better results.

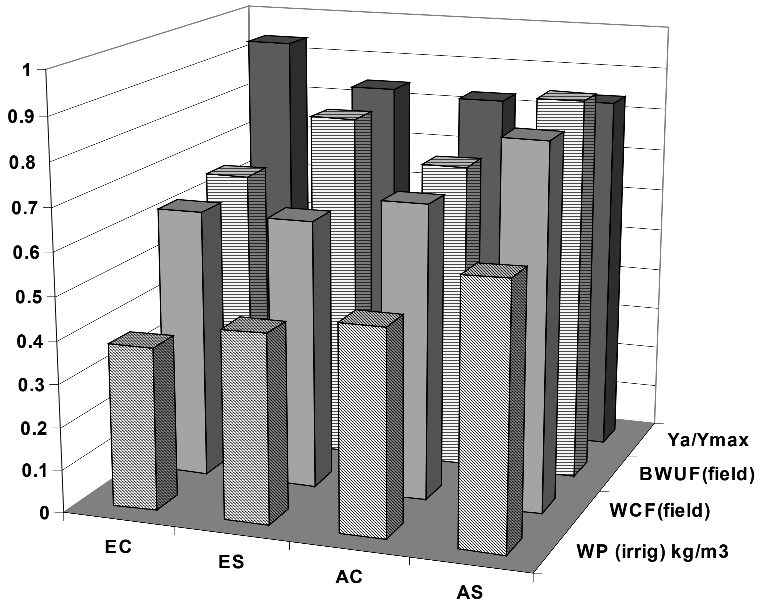


Fig. 14. Relative yield, beneficial water use fraction, consumed fraction, and water productivity relative to four improved furrow irrigation conditions: EC and ES – every furrow irrigation with respectively continuous and surge flow; AC and AS – irrigation of alternate furrows with continuous and surge flow (based on Horst et al., 2006)

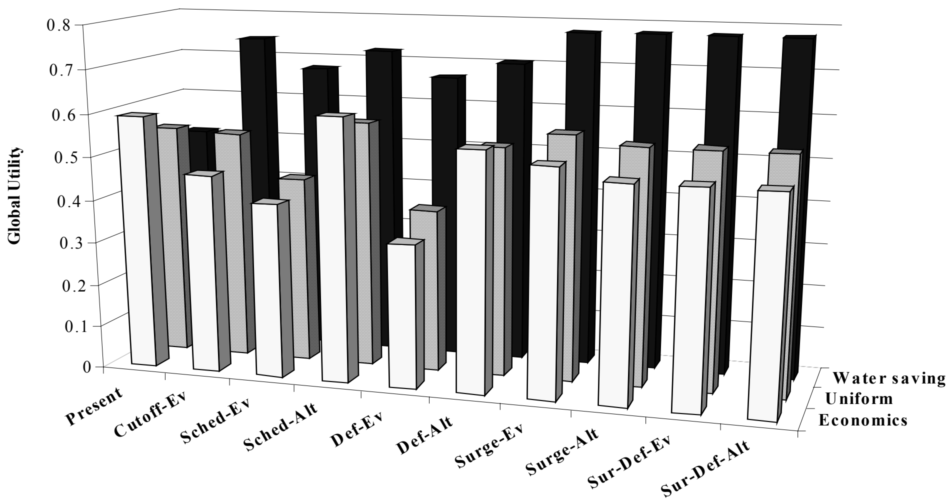


Fig. 15. Global utilities relative to several alternative furrow irrigation improvements when criteria refer to priorities to water saving, priorities to farm economic results or a uniform weighing is adopted (based on Gonçalves et al., 2006b)

Results show that the price of products, cotton, do not compensate for improving farm irrigation, i.e. to pay for investment and increased labour. Surge flow, contrarily to commercial farms, has not enough economic return to be used as a water saving practice. Results also show that when prices of production factors are high and those of commodities are low the farmer option is to maximise the land productivity, Again results evidence the referred paradoxes and support the need to develop a new paradigm.

CONCLUSIONS

The present irrigation paradigm is leading to several paradoxes related to Insufficiencies in current efficiency indicators, contradictory uses of water productivity indicators, social and economic issues relative to small farms, practical availability and use of technological developments, which were also demonstrated in examples given.

Solving the paradoxes requires developing a new paradigm. Knowledge and technologies exist that allow to make a more efficient use of water in irrigation and therefore to find a sound base for such new paradigm. Innovation in using indicators should help adopting a new irrigation paradigm. With this objective, indicators must be:

- universal, i.e. be applied as well to irrigation and to other non-irrigation water uses
- simple and able to make light on water use in terms of both quantity and quality of water use
- able to identify the pathways for improved water use
- adapted to support an economic (and social) analysis of benefits of improved water use and productivity, both at farm and of-farm system level
- covering aspects relative to other resource uses, e.g. land and energy, and to non-tangible benefits of water use, such as landscape and cultural heritage

The availability of technologies should mean capability to transfer into practice and to improve the existing irrigation, both at farm and system levels. However, knowledge and technologies progress much faster than technology transfer in case of small family and peasants farms. Technologies are easily available when manufacturers have an easy market, as it is for a variety of irrigation scheduling equipment adopted by commercial farms and for sprinkler and micro-irrigation equipment, In case of surface irrigation such market is generally not existing and surface irrigation becomes synonymous of "old fashion"

Knowledge and technologies that exist to provide for a more efficient use of water in irrigation need that appropriate quality control of equipments and management tools be enforced to support farmers in modernizing the systems. The constraints imposed to farmers, which they know well, need to be recognized, such as inappropriate delivery conditions, high costs of production factors, of irrigation equipments, low prices of commodities, low incomes, lack of technical assistance and poor systems design.

Using indicators need to be carefully done and taking into consideration the irrigator constraints, not to be used to describe environmental and managerial objectives.

Incentives that compensate for the upgrading costs, society responsibilities, recognition of cultural skills, and farmers decision making need innovative approaches.

REFERENCES

Bos, M.G., Burton, M.A., Molden, D.J., 2005. Irrigation and Drainage Performance Assessment. Practical Guidelines. CABI Publ. Wallingford.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Engng. 123: 423-442.

El Amami H, Zairi A, Pereira LS, Machado T, Slatni A, Rodrigues PN, 2001. Deficit irrigation of cereals and horticultural crops. 2. Economic analysis. Agricultural Enginnering International (www.agen.tamu.edu/cigr/) Vol. III, Manuscript LW 00 007b.

Fischer J.R., Finnell J.A., 2006, Hydrogen Technologies: Fueling the future. Resource, 13(8): 7-8.

Gonçalves J. M., Horst M., Muga A., Rolim J., L.S. Pereira, 2005. Impacts of soil infiltration on alternative furrow irrigation scenarios and performance using the DSS SADREG. In: A. Hamdy (ed.) Water, Land and Food Security in the Arid and Semi-Arid Regions (Proc. Int. Conf. CIHEAM/MAIBari, September 6 – 11, 2005), IAM, Bari, CD-ROM paper.

Gonçalves J. M., Muga A., Mateus P., L.S. Pereira, 2005. Analysing irrigation demand and delivery scenarios with the SEDAM DSS model. In: A. Hamdy (ed.) Water, Land and Food Security in the Arid and Semi-Arid Regions (Proc. Int. Conf. CIHEAM/MAIBari, September 6 – 11, 2005), IAM, Bari, CD-ROM paper.

Gonçalves JM, Pereira LS, 2005. Multicriteria analysis for improved water use and saving in a large surface irrigation district. In: N. Lamaddalena, F. Lebdi, M. Todorovic and C. Bogliotti (eds.) Irrigation systems performance (Proc. 2nd WASAMED Workshop, Hammamet, Tunisia, June 2004), Options Mediterranéennes, Série B, 52: 31-48.

Goussard, J., 1996. Interaction between water delivery and irrigation scheduling. In: M. Smith et al. (eds.) Irrigation Scheduling: From Theory to Practice. FAO Water Reports 8, ICID and FAO, Rome, pp. 263-272.

Horst M. G., Shamutalov Sh. Sh., Gonçalves J. M., Pereira L. S., 2006. Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. Agric. Water Manage. (in press).

Jensen, M. E., 1996. Irrigated agriculture at the crossroads. In: L. S. Pereira, R. A. Feddes, J. R. Gilley, and B. Lesaffre (eds.) Sustainability of Irrigated Agriculture. Kluwer Acad. Publ., Dordrecht, pp. 19-33.

Keller, J. and Bliesner, R. D., 1990. Sprinkler and Trickle Irrigation. Van Nostrand Reinhold, New York.

Mantovani, E. C., Villalobos, F.J., Orgaz, F., Fereres, E., 1995. Modelling the effects of sprinkler irrigation uniformity on crop yield. Agri. Water Manage. 27: 243-257.

Molden, D., Murray-Rust, H., Sakthivadivel, R., Makin, I., 2003. A water-productivity framework for understanding and action. In: Kijne JW, Barker R, Molden D (eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement, IWMI and CABI Publ., Wallingford, pp 1-18.

Pereira, L.S., 1999. Higher performances through combined improvements in irrigation methods and scheduling: a discussion. Agric. Water Manage. 40 (2): 153-169.

Pereira, L.S., 2003. Performance issues and challenges for improving water use and productivity (Keynote). In: T. Hata and A H Abdelhadi (Eds) *Participatory Management of Irrigation Systems, Water Utilization Techniques and Hydrology* (Proc. Int. Workshop, The 3rd World Water Forum, Kyoto), Water Environment Lab., Kobe University, pp. 1-17.

Pereira, L.S., 2006. Relating water productivity and crop evapotranspiration. Proceedings of Amman Workshop, WASAMED, Options Méditerranéennes (in press).

Pereira, L.S., Oweis, T., Zairi, A., 2002a. Irrigation management under water scarcity. *Agric. Water Manag*. 57: 175-206.

Pereira, L.S., Cordery, I., Iacovides, I., 2002b. *Coping with Water Scarcity*. UNESCO IHP VI, Technical Documents in Hydrology No. 58, UNESCO, Paris, 267 p. (accessible through http://unesdoc.unesco.org/images/0012/001278/127846e.pdf)

Pinheiro A.C., Saraiva J.P., 2002. Avaliação da sustentabilidade do regadio no Alentejo face à directiva quadro da água: uma simulação com programação multi-objectivo. Congresso Ibérico de Sevilla, Fondación Nueva Cultura del Agua,

Shideed K., Oweis T.Y., Gabr M., Osman M., 2005. Assessing On-Farm Water-Use Efficiency: A New Approach. ICARDA, Aleppo.

Zairi, A., El Amami, H., Slatni, A., Pereira, L.S., Rodrigues, P.N., Machado, T., Teixeira, J.L., 2002. Irrigation scheduling strategies for cereals and field horticultural crops under limited water availability in Tunisia. In: G. Rossi, A. Cancellieri, L.S. Pereira, T. Oweis, M. Shatanawi, and A. Zairi (Eds.) Tools for Drought Mitigation Mediterranean Regions, Kluwer, Dordrecht, pp. 181-201.