Water and Agriculture: Facing Water Scarcity and Environmental Challenges

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ABSTRACT

Agricultural water use is the main one among all water uses. Despite this use plays an essential role in food and fiber world supplies, provides for mitigating poverty in many regions, and produces a main source of income in many countries, irrigation water use faces severe competition from non-agricultural users and is challenged by opinion makers and decision makers relative to environmental impacts and the so-called less efficient water use. These conditions create important challenges to farmers, managers, engineers and researchers to develop and adopt practices and techniques that favour the sustainable use of water in agriculture. In addition, the every growing water scarcity exacerbates the competition by non-agricultural users and the environmental consequences of irrigation. Overall, these conditions create a challenge to agricultural engineers since water use problems imply not only water management and engineering but also soil and land resource conservation, appropriate equipment engineering, improving working and health conditions, higher water and land productivity, as well as an improved adoption of models and information systems. Facing water scarcity environmental challenges implies, on the one hand, a better knowledge of processes, from the causes to the mitigation issues; on the other hand, it requires that innovation be the object of a chain of interventions, from the creation to the assessment of impacts, from the researchers to the practitioners. Moreover, it is required that progresses in agricultural water use are related to the local people and the landscape where to be applied.

Keywords. Water scarcity, water use and consumption, improving water use, irrigation demand management, deficit irrigation, supply management, research priorities

1. INTRODUCTION

Water is becoming increasingly scarce worldwide. Aridity and droughts are the natural causes for scarcity. More recently, man-made desertification and water shortages are aggravating the natural scarcity while population is growing and the demand for water faces an increased competition among water user sectors and regions. Not only rainfall is not enough abundant in many regions, thus limiting the quantity of water resources available, but also the quality of water is increasingly degraded making that water resources become unavailable for more stringent requirements. Agriculture is therefore forced to find new approaches to cope with water scarcity but adopting sustainable water use issues.

The sustainable use of water - resource conservation, environmental friendliness, appropriateness of technologies, economic viability, and social acceptability of development issues - is a priority for agriculture in water scarce regions. Imbalances between availability and demand, degradation of surface and groundwater quality, inter-sectorial competition, inter-regional and international conflicts, often occur in water scarce regions, mainly in the Mediterranean region. Innovations are therefore required, particularly relative to water use in agriculture, concerning both management and practices since the agriculture sector is far ahead in demand for water.

Policies and practices of irrigation water management under water scarcity must focus on specific objectives according to the causes of water scarcity. On the one hand, a coupled environmental, economic, and social approach is required in valuing the water. On the other hand, an integrated technical and scientific approach is essential to develop and implement the appropriate irrigation management practices relative to demand and supply management, which are briefly discussed in the following sections.

2. WATER SCARCITY REGIMES

Water scarcity has various origins, natural and man-made, and corresponds to several regimes (Table 1): natural aridity and drought, and man-made desertification and water-shortage (Pereira *et al*., 2002a).

Table 1. Nature and causes of water scarcity in dry environments.

Water Scarcity Regime	**Nature produced**	**Man induced**
Permanent	***Aridity***	***Desertification***
Temporary	***Drought***	***Water shortage***

Aridity is a nature produced permanent imbalance in the water availability consisting in low average annual precipitation, with high spatial and temporal variability, resulting in overall low moisture and low carrying capacity of the ecosystems. Aridity affects large regions of the world as shown in Fig. 1.

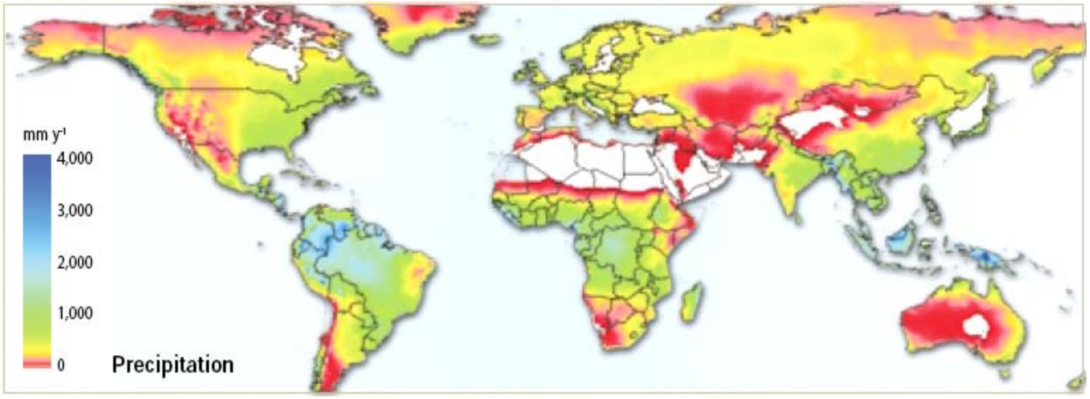

Figure 1. World distribution of annual average rainfall (IWMI, 2004).

Aridity is associated with high pressure on natural resources, strong competition for water that aggravates the limiting resource for agriculture, frequent soil salinization, including due to poor management of irrigation, and vulnerable and fragile ecosystems. Therefore, the sustainable use of water to cope with aridity implies the effective implementation of integrated land and water resources planning, the improvement of water and irrigation supply systems, water allocation policies favouring water conservation and water productivity, valuing the water as an economic, social and environmental good, measures for augmenting the available water resource, including wastewater and drainage water re-use, adoption of irrigation technologies that favour efficient water use, and increased users' awareness on the implications of water scarcity.

Drought is a nature produced but temporary imbalance of water availability, consisting of a persistent lower-than-average precipitation, of uncertain frequency, duration and severity, the occurrence of which is difficult to predict, resulting in diminished water resources availability and carrying capacity of the ecosystems. Droughts are hazards because they are natural accidents of almost unpredictable occurrence, and disasters because they consist of the failure of the precipitation regime, causing the disruption of the water supply to the natural and agricultural ecosystems as well as to the human activities. Water management under drought requires measures and policies which are common with aridity such as those to avoid water wastage, reduce demand, make water use more efficient and increase the public awareness on the proper use of water. Other issues relate to adopting preparedness measures favouring the effectiveness of reactive mitigation measures, changes in water allocation and delivery policies, and users adoption of reduced demand practices:

Desertification is a man-induced permanent imbalance in the availability of water that occurs in arid, semiarid and sub-humid climates, which is combined with damaged soil, inappropriate land use, mining of groundwater, increased flash flooding, loss of riparian ecosystems and a deterioration of the carrying capacity of the ecosystems. Soil erosion and salinity are associated with desertification, which make many definitions to focus on land degradation. Drought strongly aggravates the process of desertification when increasing the pressure on the diminished surface and groundwater resources. Climate change also contributes to desertification and constitutes a serious threat to large areas around the world, mainly in semiarid and subhumid climates. There is a general acceptance about the fact that temperature will rise but there is a great uncertainty about how much it will rise and where, and it is also uncertain how precipitation and runoff will change but they will very likely change (Fig. 2).

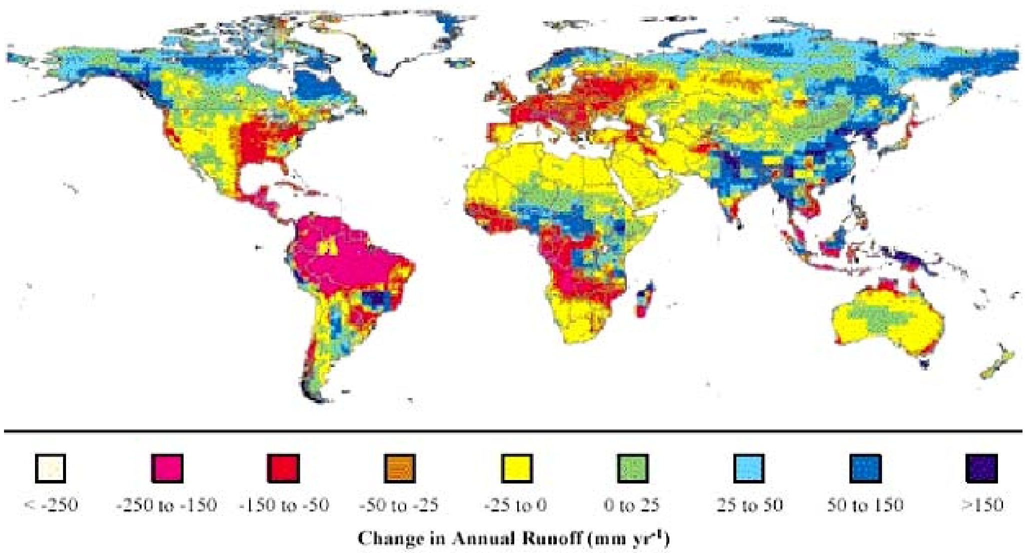

Figure 2. Model prediction of changes in annual runoff (mm/year) by 2050 (IPCC, 2001).

Water shortage is also man-induced but temporary water imbalance including groundwater over exploitation, reduced reservoir capacities, disturbed and reduced land use, and consequent altered carrying capacity of the ecosystems. Degraded water quality is often associated with water shortages and, like drought, aggravates related impacts.

Combating desertification and water shortage requires that particular attention be given to environmental issues in water use, i.e., re-establishing the environmental balance in the use of the natural resources, restoring the soil quality, strengthening erosion control and soil and water conservation, combating soil and water salinization, controlling groundwater withdrawals and favouring aquifers recharge, minimising water wastes, and managing the water quality. Preventing desertification and related water problems requires that particular attention be paid to climate change issues.

3. WORLD DISTRIBUTION OF WATER AVAILABILITY AND WATER SCARCITY

The world situation relative to water resources is well described in various reports, e.g. Shiklomanov (2000), Gleick (2002) and UNEP (2002). Data in Table 2 evidence great differences in the available water resources among main regions of the world.

Table 2. Water resources availability in selected regions (Shiklomanov, 2000).

Region	*Population per 10^6 km^2* (1994)	*Water resources (average)* (km^3/year)	*Potential water availability (10^3 m^3/year)* Per km^2	Per capita
Europe	685	2,900	277	4.24
Northern	23	705	534	30.40
Central	293	617	333	2.12
Southern	188	546	335	3.19
Africa	708	4,050	135	5.72
Northern	157	41	13	0.71
Central	63	1,770	444	28.80
Southern	84	399	86	5.29
Asia	3,445	13,510	311	3.92
Western	232	490	72	2.11
Central Asia	54	181	51	3.78
North China & Mongolia	482	1,029	124	2.13
South East	1,404	6,646	965	4.78
Southern	1,214	1,998	476	1.76
North America	453	7,890	325	17.40
South America	314.5	12,030	672	38.30
Australia	18	352	46	19.7
Oceania	11	2,050	1,614	190.00
The World	**5,633**	**42,780**	**316**	**7.60**

The Northern African countries are those with smaller average per capita availability, which is below the 1000 m^3/capita considered the threshold for water scarcity. Western and Central Asia have reduced water availability but much less population than other Asian regions where the total water is greater but population is very large. This makes that per capita water availability in Asia is generally small, close to water scarcity. If the analysis would be made with more detail it could be observed that within countries like China and India there are regions where water scarcity is quite large. Results in Fig. 3 evidence these considerations.

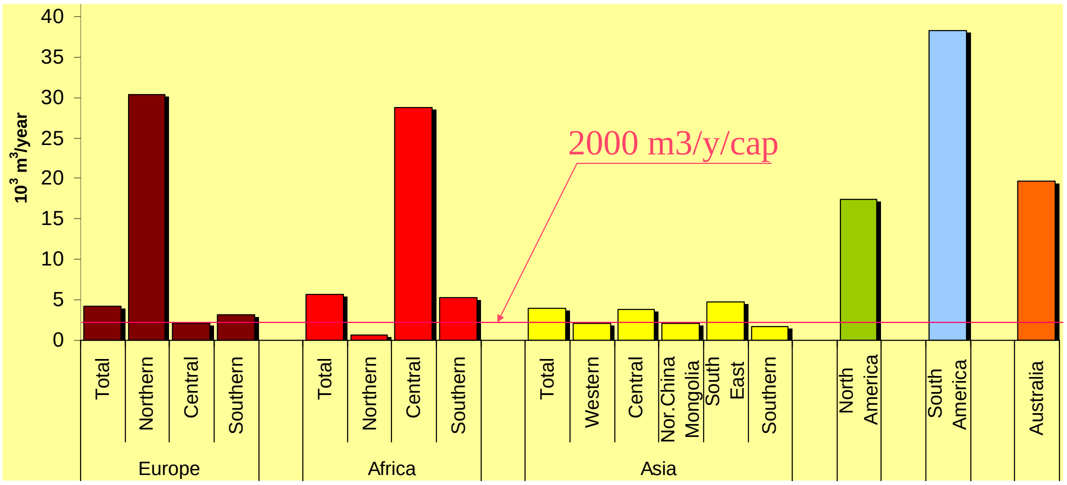

Figure 3. Per capita potential water availability for selected regions of the world (adapted from Shiklomanov, 2000).

Data shows that water scarcity is an actual problem that tends to increase in future. Shiklomanov (2000) analyzed the trends in water withdrawal for the XX century and produced a forecast for the first quarter of the XXI century (Table 3).

Table 3. Dynamics of water withdrawal in selected world regions in km^3/year (adapted from Shiklomanov, 2000).

Region	*1900*	*1960*	*1995*	*2010*	*2025*
Europe	37.5	226	455	535	559
Northern	1.4	7.3	11.0	12.7	13.4
Central	12.8	87.2	154	172	176
Southern	16.1	95.3	186	204	204
Africa	40.7	89.2	219	275	337
Northern	36.6	68.3	110	127	145
Central	0.1	0.4	2.6	4.9	9.2
Southern	1.9	9.4	27.3	34.4	44.8
Asia	41.4	1163	2,231.0	2,628.0	3,254.0
Western	42.8	133	249	299	356
Central Asia	28.7	67.4	154	174	182
North China & Mongolia	37.0	153	268	319	372
South East	99.0	357	631	760	949
Southern	201	426	887	1,023	1,339
North America	69.6	410	686	744	786
South America	15.1	65.6	167	213	260
Australia & Oceania	1.6	14.5	30.4	35.7	39.5
The World	**579**	**1,968**	**3,788**	**4,431**	**5,235**

Data shows an enormous increase in water withdrawals from 1900 to 1995, and a trend to continue increasing in future, corresponding to a factor of 10 from 1900 to 2025.

Such increase is larger where water is more abundant and smaller where water availability is reduced and the financial resources are lesser. In some areas like central Asia an increase by six times produced the well-known Aral sea disaster. In others, like North America and Southern Europe, an increase of eleven times did not produce such desertification problems. This relates to the fact that an increased water withdrawal in an arid region affects ecosystems that are much more vulnerable than those of humid and sub-humid climates. This calls for a careful attention to the environment, which behaviour and vulnerability were not known some decades ago.

These data shows that such increase in water abstractions could not result in a consequence different from that known today: water is scarce. Unfortunately, water quality is also degraded by return flows after use and large part of the available water resources is not appropriate for many uses and is a source of water related diseases. The forecasts by Shiklomanov (2000) and other authors show a trend for a slower growth in water withdrawals during the XXI century because water resources are limited, technologies provide for reduced water wastes and losses, water recycling and reuse has a large potential to increase, and water management measures may lead to optimise water allocation and use. These are the aspects that agricultural engineering may contribute to achieve in agricultural water use.

Forecasts also depend upon population dynamics and relate to the sectorial water use as shown in Table 4. It is assumed that the present growth rate of the population, which has already diminished during the last quarter of the XX century, will drastically reduce this XXI century. However, the trend in population growth is variable from a country to another, mainly in relation with culture and, often, religion, thus a strong growth rate is likely to continue in Southern and West Mediterranean areas while it drastically drops in other regions such as in China, Europe and North America. However, decreased population growth rates will not reduce the pressure on water resources. Management, practices and attitudes of the users have to change while decision makers shall better value water and the water uses.

Table 4. Dynamics of water use (km^3/year) at the world scale (Shiklomanov, 2000).

Sector	***1900***	***1960***	***1995***	***2010***	***2025***
Population (million)		3,029	5,735	7,113	7.877
Irrigated land (106 ha)	47.3	142	253	288	329
Agricultural use (km^3/yr)	513	1,481	2,504	2,817	3,189
Municipal use (km^3/yr)	22	118	344	472	607
Industrial use (km^3/yr)	44	339	752	908	1.170
Total use (km^3/yr)	579	1,968	3,788	4,431	5,235

To feed the every increasing population, irrigation water use heavily increased during the past century: the irrigated area has grown more than 5 times and the water use for agriculture increase by near 5 times too. The forecasted trend is to keep increasing the irrigated areas but at a smaller rate than in the past (near 1%/year against the former

2%/year), as well as to keep increasing water use for irrigation but again with a smaller rate. Much larger rates of growth are considered for municipal and industrial water uses. The first correspond to the need for increasing the percentage of populations served with safe water and sanitation, which is relevant in terms of human health and quality of life of populations, as well as to respond to the increased demand of tourism. The second concerns the existing trend to develop the industry, mainly out of the high-income countries. Data in Table 4 indicate that the competition for freshwater from the non-agricultural sectors will increase the pressure on water resources, thus leading to the need for using non-conventional water resources in agriculture.

Problems are extremely aggravated by droughts, which are quite frequent throughout many regions of the world, including the Mediterranean area (Rossi *et al*., 2003). Several approaches, such as exploiting global circulation models in relation to the ENSO and the NOA anomalies together with monitoring the relevant weather variables, may produce appropriate drought forecasts/predictions as for the USA (CPC, 2003). An alternative, when these means are not accessible, may be to adopt stochastic modelling (Paulo *et al*., 2003), which may help providing some lead time for implementing drought mitigation measures, of great importance in agriculture.

Desertification is also aggravating the problems of water resource availability despite more often identified land degradation problems do not relate to water but to soil erosion, salinity hazards and overgrazing in the semi-arid pastoral areas. However, these problems are quite complex and have social relevancy (Fig. 4).

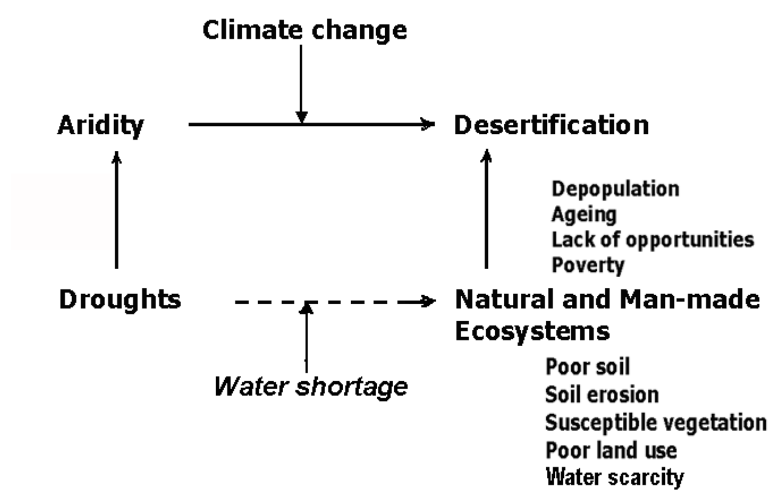

Figure 4. The desertification cycle as influenced by climate, land resources, land and water use, and socio-economic and human resources.

In areas identified as susceptible to desertification population density is generally low to very low and the respective growth rate is also low or negative. Consequently, aging is increasing with the dependency on aged people for every activity at local level.

The fact is that these negative socio-economic conditions in the vulnerable areas are related with the poor land resources, mainly soil and water, less adequacy of ecosystems to support development, low response capacity to climate forcing, and non existence of alternative activities to agriculture and forestry. Thus, when external economic forces act over such fragile systems they tend to collapse, i.e., the existing equilibriums brake easily. Therefore, conditions are created for the climate forcing to exacerbate the vulnerability to desertification, mainly when scarce water resources do not allow improved land use. This brings to the water scarcity scene the socio-economic dimension in addition to the environmental one.

4. WATER USE PERFORMANCE *vs*. EFFICIENCY

The term efficiency is often used to express the performance of water supply systems and water use activities. More recently, the use of the term water use efficiency is expanding. However, there are no widely accepted definitions, and both terms are used with different meanings, including as synonymous of both water conservation and water saving (cf. Pereira *et al*., 2002a). A more consistent conceptual approach is required.

The term efficiency is often used in case of irrigation systems and it is commonly applied to each irrigation sub-system: water storage, conveyance, distribution off- and on-farm, and application at the farm. It can be defined by the ratio between the water depth delivered by the sub-system under consideration and the water depth supplied to that sub-system, usually expressed as a percentage. For farm irrigation systems, the application efficiency may be defined by the ratio between the average water depth added to the root zone storage to the average water applied. However, this indicator should be used together with others, mainly those relative to distribution uniformity (Burt *et al*., 1997; Pereira, 1999: Pereira and Trout, 1999). The irrigation system efficiency corresponds to the integrated effects of all subsystems and may be computed by the product of the average efficiencies of those sub-systems. Adopting an output/input non-dimensional ratio, the term efficiency could be applied to evaluate the performance of any irrigation and non-irrigation water system. However some misunderstandings in using that term must be avoided.

It is often said that improving irrigation or water supply efficiencies is of great importance under water scarcity regimes because that improvement represents the capability for achieving near optimal use of the available water. This is true when considering the specific system or sub-system under analysis because higher output to input ratios indicate that less water is diverted to produce the same yield or service quantity. It is also common that people says that improving irrigation efficiencies would lead to water savings, i.e. water would then become available for other users or uses. However, this is only true when the excess water is added to degraded water bodies and made not available to reuse by other users downstream. It is also said that low irrigation efficiencies mean high water losses. Nevertheless, they do not necessarily indicate high water losses because a fraction of the non-consumed volumes may be returned with acceptable quality to the natural water bodies and be re-used, thus not consisting in actual losses. Moreover, part of the so-called losses may be beneficial, such as the water used for salts leaching when irrigating in saline environments. To avoid misunderstandings, Bos (1997) proposed to abandon the efficiency terms and replace them by ratio indicators, e.g. conveyance ratio and distribution ratio.

Another term commonly used in irrigation is water use efficiency (WUE). Some authors refer to it as a synonymous of application efficiency, so as a non-dimensional output/input ratio. Others adopt it to express the productivity of the irrigation water, so as a yield to water ratio. To avoid misunderstandings, the term water use efficiency should be limited to physiological and eco-physiological purposes, and the term water productivity, defined by the ratio of the yield quantity to the amount of water used, could be adopted as an irrigation indicator (Pereira *et al*., 2002a, b). The idea that improving the water use efficiency (or the water productivity) leads to water savings is also not entirely true because it is also required to distinguish between consumptive and non-consumptive uses. The same amount of grain yield depends not only on the amount of irrigation water used but also on the amount of rainfall water that the crop could use, which relates to rainfall distribution during the crop season.

Improving conveyance and distribution efficiencies or ratios may be an objective of farmers management of irrigation systems when the operational losses by seepage, leaking or overflow would decrease availability of water to tail-end distributor canals and tail-end farmers or when those improvements relate to easier control of deliveries to branch canals, distributors and farmers. However, the perspective of water saving and conservation is rarely assumed by itself. In other words, the interest of farmers mostly relates to improved service performances. Then, indicators such as reliability, dependability or equity (Molden and Gates, 1990; Bos, 1997; Pereira *et al*., 2003a) are those that interest farmers and managers.

The improvement of farm application efficiencies is not seen by farmers as a must. Application efficiencies become higher when farmers apply water timely and the distribution uniformity is higher. Improved uniformities decrease differences in amounts of water made available for the crop in the under-and over-irrigated parts of the field. As discussed by many authors, e.g. Keller and Bliesner (1990) and Mantovani *et al.* (1995), this leads to more even crop development and higher yields. When the farmer adopts an appropriate irrigation scheduling, then yields are positively impacted and, in addition, the application efficiency becomes higher as well as the economic results of irrigation (Ortega *et al*., 2004). Thus, improving irrigation efficiency is not a farmer's objective but to achieve higher yields and economic profit. Higher water productivities are also not an objective of farmers except when water is the limiting economic factor. When the limiting factor for achieving higher economic returns is land, as it is the case for small farmers, their objective is to optimize the total yield. Their gross margins are so small that optimizing the water productivity is not achievable.

The analysis above leads to conclude that more efforts must be developed to adopt performance indicators that effectively respond to farmer objectives and, at same time, respond to the need for water resource conservation and improved water use by the society. In particular, it is required that indicators do not lead to misunderstandings and misleading approaches that create less appropriate pressures on the irrigator farmers but support policies that help them to improve water use and productivity, control the demand for water, and avoid water pollution and soil degradation.

New concepts to clearly distinguish between consumptive and non-consumptive uses, beneficial and non-beneficial uses, and reusable and non-reusable fractions of the non-consumed water diverted into an irrigation system or subsystem are proposed by several authors (Allen *et al.*, 1997; Burt *et al.*, 1997; Pereira *et al.*, 2002a). As described in Fig. 5, only a fraction of the water used or mobilized for a given production or service is consumed and the non-consumed fraction may be reusable or not according the degree of degradation during that first use.

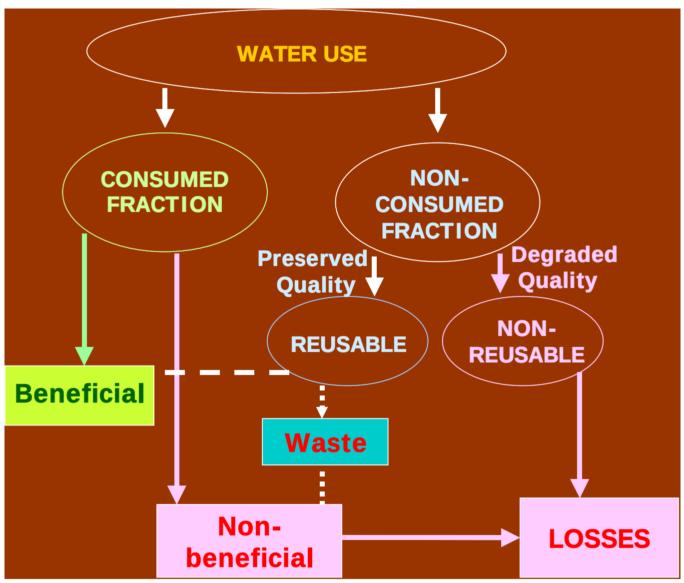

Figure 5. Water use and consumption, beneficial and non-beneficial uses, water wastes and losses.

One may then clearly distinguish between what is a water loss, i.e., non-usable again, from what is wasted, which involved costs to be mobilized for use but is reusable by others and at a later time, so not lost. One should also distinguish between beneficial and non-beneficial uses, the first being those uses required to achieve the production or the service and the second corresponding to misuses or uses in excess to the requirement.

These concepts and indicators are easy to adapt and extend to non-irrigation water uses to identify the respective performances under the perspective of water resources conservation as described in Table 5. These are useful for water resources planning and management under scarcity and should lead to less misinterpretation than the term "efficiency".

Essentially, three water use fractions are considered (Pereira, 2003):

- the *consumed fraction*, 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,
- the *reusable fraction*, 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, and
- the *non-reusable fraction*, 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.

Each of the above fractions is then divided into two parts, corresponding respectively to the beneficial and the non-beneficial uses. Therefore, it is then easier to identify how water use could be improved, and how water savings should be oriented.

Assuming those concepts above, it is possible to identify the pathways to improve water use as described in Fig. 6. However, the first step is to recognize how the water is being used which gives a stronger rational to water conservation and saving, clearly better than saying only that efficiency must be improved, what does not applies in many cases.

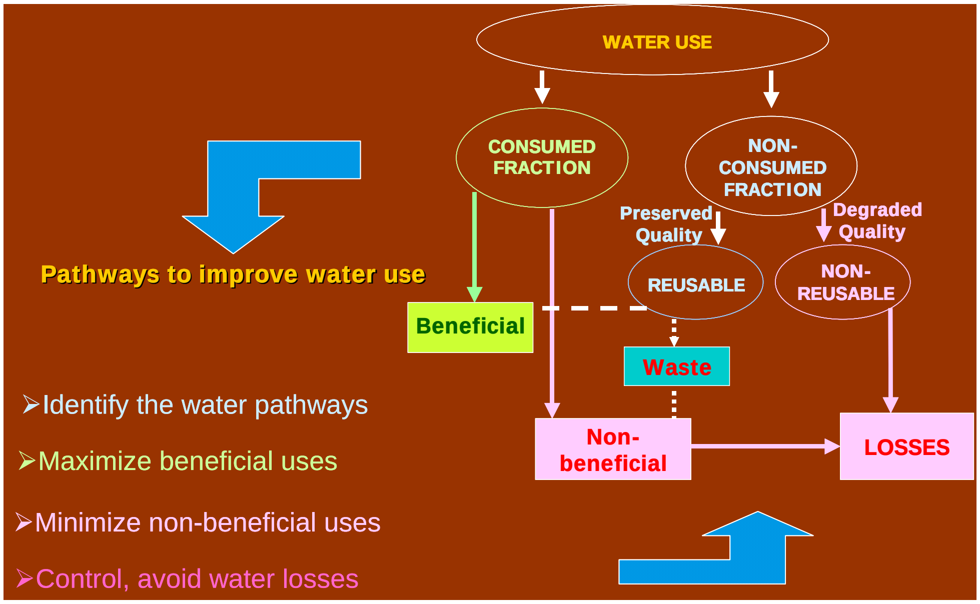

Figure 6. Pathways to improve water uses by recognizing how water is used.

Table 5. Irrigation and non-agricultural water use, consumptive and non-consumptive uses (Pereira *et al*., 2002a).

	Consumptive	*Non-Consumptive but Reusable*	*Non-Consumptive and Non-Reusable*
Beneficial uses	***Irrigation:*** ▪ ET from irrigated crops ▪ evaporation for climate control ▪ water incorporated in product	***Irrigation:*** ▪ leaching water added to reusable water	***Irrigation:*** ▪ leaching added to saline water
	Non-irrigation 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 artificial recreational lakes	***Non-irrigation uses:*** ▪ 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	***Non-irrigation uses:*** ▪ 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	***Irrigation:*** ▪ soil water evaporation ▪ phreatophyte ET ▪ sprinkler evaporation ▪ canal and reservoir evaporation	***Irrigation:*** ▪ deep percolation added to good quality aquifers ▪ Reusable runoff ▪ Reusable canal spills	***Irrigation:*** ▪ deep percolation added to saline groundwater ▪ drainage water added to saline water bodies
	Non-irrigation uses: ▪ ET from non beneficial vegetation ▪ evaporation from water wastes ▪ evaporation from reservoirs	***Non-irrigation uses:*** ▪ deep percolation from recreational and urban areas added to good quality aquifers ▪ leakage from urban, industrial and domestic systems added to good quality waters	***Non-irrigation uses:*** ▪ deep percolation from recreational and urban areas added to saline aquifers ▪ leakage from urban, industrial and domestic systems added to low quality waters
	Consumed fraction	**Reusable fraction**	**Non-reusable fraction**

Adopting the indicators as shown in Table 4, it can be concluded that water losses are those corresponding to the non-beneficial consumed water fraction and to the non-consumptive and non-reusable quantities of water used, which define the non-reusable fraction. However, in the case of saline environments, part of that water loss is beneficial to the crop and the soil because it is used for leaching of salts and, therefore this loss cannot be avoided.

The non-consumptive but reusable quantities of water are in reality not lost because other users or the same system downstream can use them again, mainly when reuse facilities are available. This reusable fraction, like the non-reusable, may be due to poor or less than optimal management, but may be required by the production or service process under consideration. It is often considered as lost but in fact it is only a temporary loss to the system and cannot be considered a loss from a hydrological perspective or under the overall water resource economy. However, the size of the reusable fraction influences the cost of the system or sub-system operation and management and, moreover, it represents a non-necessary part of the demand, thus inducing negative impacts on the water allocation process and on the conservation of the resource.

Assuming the concepts above, an efficient water use is no more the one which system shows a high efficiency ratio but that where the non-beneficial consumptive uses are minimized, the non-reusable fraction of the diverted water is controlled, and the non-beneficial but reusable fraction is reduced. Of course this applies to irrigation as well as to non-agricultural water uses and may be of particular importance when low-quality water is applied since this implies particular attention to the control of non-consumed return flows.

5. SUPPLY MANAGEMENT AND USE OF LOW-QUALITY WATERS

The importance of supply management strategies to cope with water scarcity in irrigation is well identified in the literature and observed in practice. Table 6 summarizes the most common approaches to supply management.

Table 6 Supply management objectives and technologies.

Objective:	***Technology:***
Increase storage	▪ small reservoirs for runoff storage
	▪ groundwater recharge from excess runoff
Increase water yield	▪ water harvesting
	▪ vegetation management to control runoff
	▪ spate irrigation
Increased use of rainfall	▪ micro-catchments, land forming
	▪ terracing
	▪ conservation tillage
Add to available supplies	▪ unconventional water systems including reuse of municipal wastewater
	▪ reservoirs, conveyance and intra-basin transfer

Supply management should be considered under the perspective of systems operation, mainly related to delivery scheduling (Hatcho, 1998). It includes the exploration of hydrometeorological networks, data bases and information systems that support the improved management of reservoirs and irrigation systems, provide information on droughts initiation and dissipation, and may also be used as information to support farmers' irrigation decisions. Complementarily to these networks are the agrometeorological irrigation information systems, which include a variety of tools for farmers and managers to access information, comprising models, information systems such as GIS, and decision support systems. Particularly relevant for system managers are the modern technologies relative to reservoir and supply systems operation and management, which provide the effective use of automation and remote control, as well as planning for droughts, mainly through establishing allocation and delivery policies and operation rules. Simulation models, information systems and DSS can be relevant to support farmers' selection of water use options, including crop patterns and irrigation systems, and to implement appropriate irrigation scheduling.

Supply management also refers to farm water conservation. This includes a variety of soil management and conservation tillage practices, the use of vegetation management to control runoff, mulches to limit evaporation from the soil (Unger and Howell, 1999). Small farm reservoirs, water harvesting and spate irrigation play a central role in dry semiarid and arid zones (Prinz, 1996; Oweis *et al*., 1999; Sharma, 2001).

The role of farmers in reducing the demand is limited both by the farm system constraints and by their capabilities to be in control of the discharge rate, duration and frequency of irrigation. These limitations are due to the fact that farmers require some flexibility in the deliveries to decide the optimal irrigation timings and depths, as well as that deliveries be reliable, dependable along the irrigation season and equitable among upstream and tail end users. Therefore, the adoption of reduced demand strategies largely requires improved quality of supply management.

Another facet of supply management is the use of non-conventional water supplies, mainly treated wastewater and saline or brackish water. Municipal wastewater contains relatively small concentrations of suspended and dissolved organic and inorganic solids. In arid and semi-arid countries, because water use is often fairly low, sewage concentration tends to be very strong as compared with that in water abundant areas (Pescod, 1992; Al-Nakshabandi *et al.*, 1997). Municipal wastewater also contains a variety of inorganic substances from domestic and industrial sources, including potential toxic elements and heavy metals, which may be at phytotoxic levels or originate health risks. However, health risks are mainly due to pathogenic micro- and macro-organisms. To avoid health hazards and damage to the natural environment wastewater must be treated before it can be used for agricultural and landscape irrigation (Pescod, 1992; Westcot, 1997). Discussions on the desirable level of treatment according to uses including for recharge of potable groundwater and surface water reservoir augmentation are given by Bouwer (2000), Loudon (2001) and Goosen and Shayya (2001) among others. Monitoring and quality certification (Westcot, 1997) is another main issue. Monitoring should include the control of health risks due to the use of untreated or insufficiently treated wastewaters. The application of crop restrictions, following the risk categories referred above, is often considered the most effective measure to protect the consumers. However, crop restrictions need a strong institutional framework and the capacity to monitor and control compliance with the regulations (Pereira *et al*., 2002a).

The quality of irrigation water is of particular importance in arid zones where high rates of evaporation occur, with consequent salt accumulation in the soil profile. The physical and mechanical properties of the soil, such as dispersion of particles, stability of aggregates, infiltration, and permeability, are very sensitive to the type of exchangeable ions present in irrigation water. Basic recommendations regarding the use of low-quality water are provided among others by Rhoades *et al.* (1992). The literature is abundant on salinity impacts and control in irrigated agriculture (e.g. the consolidated guidelines resulting from Indian research by Tyagi and Minhas, 1998, and the reviews by Minhas, 1996 and Katerji *et al*., 2001). Irrigation methods should be selected and managed in agreement with the quality of water to avoid health impacts as well as soil degradation and minimizing crop yield reductions (Pereira *et al*., 2002a, b).

6. DEMAND MANAGEMENT

6.1. General Aspects

Demand management for irrigation under water scarcity includes practices and management decisions of multiple natures: agronomic, economic, and technical, as summarized in Table 7.

Table 7. Farm irrigation management under water scarcity (Pereira *et al*., 2002a).

Objective	*Technology*
Reduced demand	▪ Low demand crop varieties/crop patterns ▪ High performance irrigation systems ▪ Deficit irrigation
Water saving and conservation	▪ Cultivation practices for water stress control (e.g. planting dates, avoiding competition by weeds) ▪ Improved irrigation systems uniformity and management ▪ Reuse water spills and runoff return flows ▪ Surface mulch and soil management for controlling evaporation from soil ▪ Soil tillage for augmenting soil infiltration and the soil water reserve
Higher yields per unit of water	▪ Improved farming practices (e.g. fertilizing, pest control) ▪ Avoid crop stress at critical periods
Higher farmer incomes	▪ Select cash crops ▪ High quality of products

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 mainly related to economic decisions.

Agronomic and economic decisions and farming practices, including those related to the use of improved crop varieties, are often dealt with in the literature (e.g. Bucks *et al*., 1990; Tarjuelo and de Juan, 1999). Often, issues for irrigation demand management refer mainly to irrigation scheduling, therefore giving a minor role to the irrigation methods. However, a combined approach is required (Pereira, 1999), particularly when wastewater and low quality saline water are used (Pereira *et al*. 2002b).

6.2. Farm irrigation systems

Factors influencing the distribution uniformity and the application efficiency are analysed by Pereira *et al*. (2002b) for surface, sprinkler and micro-irrigation systems. The distribution uniformity, which indicates how uniform is distributed the water over the irrigated field, is the main performance parameter to be considered to improve the farm irrigation systems aiming at adopting reduced demand and high water productivity. In general, the distribution uniformity values observed are the upper limits of the application efficiency when keeping system variables unchanged.
In traditional systems, the water control is carried out manually. In small basins or borders and in short furrows, the irrigator cuts off the supply when the advance is completed. This practice induces large variations in the volumes of water applied at each irrigation event and from one field to the next, and over-irrigation is often practised. On the contrary, in modernised systems some form of control of discharge is used and the fields are often precision levelled, thus it is easy to control "how much" water should be applied.

The improvement and modernization of traditional surface irrigation systems constitutes therefore a main challenge instead of replacing it by pressurized irrigation systems. In fact, surface systems generally show good system performance, often higher than sprinkler systems, but the application efficiency is hampered by lack of appropriate land levelling and flow rate and duration controls. Field evaluations play a major role in improving surface irrigation systems, as they provide information required to improve systems and practices. However, because they are very demanding, they are very seldom performed.

The role of precision levelling in basin irrigation is well analysed by Clemmens *et al.* (1999) referring to improving irrigation management in Egypt, and by Li and Calejo (1998) relative to applications in North China. When water of inferior quality is used, precision levelling is required to appropriately control the leaching fraction and provide for an uniform soil leaching. This was identified as one main factor to improve environmental conditions and reduce the demand up to 200 mm in two case study areas in the Yellow River basin (Pereira *et al*., 2003b).

System and delivery constraints (Goussard, 1996) require that irrigation scheduling is simple. The use of simplified irrigation calendars, such as irrigation scheduling charts produced with irrigation scheduling simulation models to take into consideration the average or the actual climatic demand, are in general useful and easy to use. Several examples are given in the literature including when leaching requirements are considered; examples for North China are produced in Pereira *et al*., 1998 and Liu *et al*., 2000).

Several studies show the benefits of sprinkler and, mainly microirrigation to reduce crop irrigation demand; e.g. Ayars *et al*. (1999) show the benefits of subsurface drip applied to several crops in maximising yields and reducing water demand relatively to other methods. However, the performance of these systems in the farmers practice is often much below than potential. In fact, the irrigation uniformity (DU) in sprinkler and micro-irrigation systems depends essentially on equipment and variables characterising the system, which are set at the design phase. Similarly, the application efficiency (AE) depends upon the same system variables as DU and on the management variables relative to the duration and the frequency of the irrigation events. Therefore, the irrigator can do little to improve the uniformity of irrigation and is constrained by the system characteristics to improve AE even when adopting a good irrigation schedule. Field evaluations provide good advice to farmers to improve management and to introduce limited changes in the system, as well as useful information to designers and to the quality control of design and services (Ortega *et al*., 2004). Summarising, reduced demand with low impacts on yields requires, first, that the system be able to produce a high uniformity and, second, that appropriate irrigation scheduling be adopted.

Based on field evaluations, Mantovani *et al.* (1995) showed that, when the cost of irrigation is low, the farmers tend to optimise yields not taking care on the water use. On the contrary, if water is expensive, farmers under-irrigate for low system uniformity, so accepting lower than potential yields, and only fully irrigate when systems can achieve high DU. This fact makes useful to adopt a target DU for sprinkler and micro-irrigation design (Bralts *et al*., 1987; Keller and Bliesner, 1990) but this requires the use of simulation models with friendly interfaces written in the language of the users (e.g. Pedras and Pereira, 2001).

The ability of the farmer plays a major role in maintaining the systems and controlling water applications but his capability to achieve higher performances is definitely limited by several variables and constraints, including off-farm delivery and the decisions taken when a system is designed or purchased. This means that it is not appropriate to say that farmers must adopt enhanced target management rules without identifying both off– and on-farm system constraints and when conditions are not created to give them support on decisions that help them to improve irrigation practices.

6.3. Deficit irrigation

Deficit irrigation, as reviewed by English and Raja (1996), is an optimising strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction. The adoption of deficit irrigation implies appropriate knowledge of crop ET, crop responses to water deficits, including the identification of critical crop growth periods, and the economic impacts of yield reduction strategies.

Deficit irrigation implies the adoption of appropriate irrigation schedules, which are built upon validated irrigation scheduling simulation models (e.g. Sarwar and Bastiaansen, 2001; Zairi *et al*., 2003) or are based on extensive field trials (e.g. Oweis *et al*., 1998; Oweis and Hachum, 2001). When strategies for deficit irrigation are derived from multi-factorial field trials, as for the supplemental irrigation (SI) of cereals, the optimal irrigation schedules are often based on the concept of water productivity (Oweis and Zhang, 1998).

The present general practice in irrigated agriculture is to maximise crop yield per unit land by applying full crop irrigation requirements and often over-irrigating. For some crops, such as cereals, maximising yield is at the account of WP. In areas where water is the most limiting resource to production, maximising WP may be more profitable to the farmer than maximising crop yield. Results for the supplemental irrigation of wheat show (Fig. 7) that deficit irrigation is generally economically feasible (Zairi *et al*., 2003). However, for spring-summer crops having a relatively low gross margin, deficit irrigation is often questionable (Fig. 8); despite WP increases when less water is applied, the best economic option when water is limited such as under drought may be to crop only a fraction of the land and apply there an optimal irrigation schedule (Rodrigues *et al*., 2003).

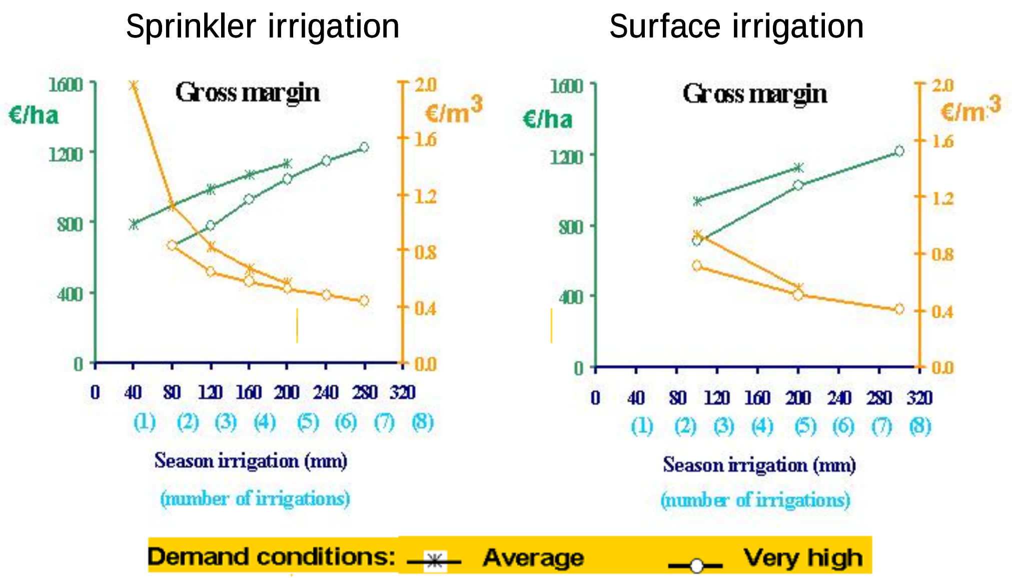

Figure7. Gross margins per unit surface (€/ha) and per unit water applied (€/m^3) as a function of irrigation depths in supplemental irrigation of winter wheat, Tunisia

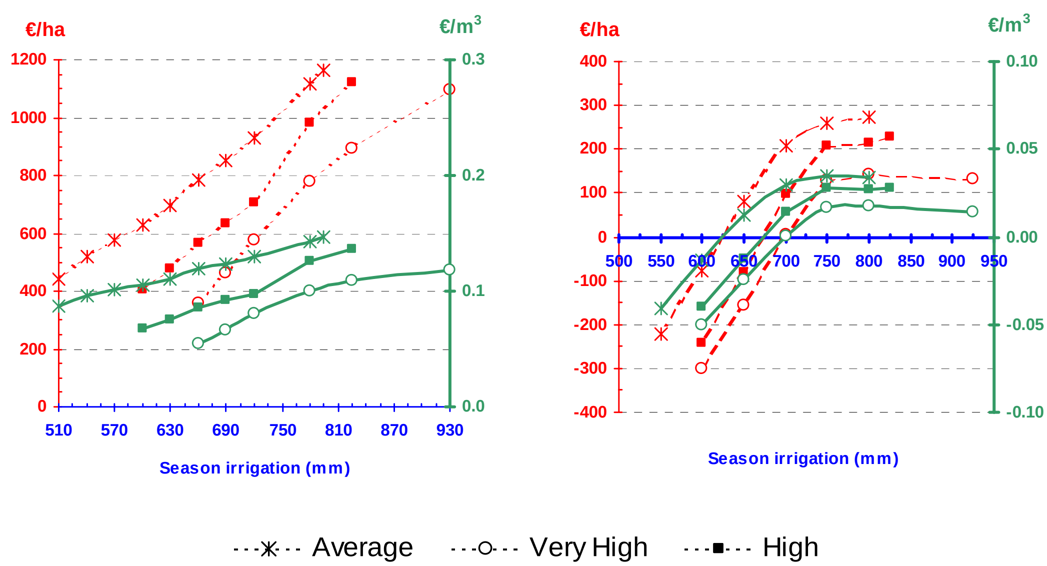

Figure 8. Gross margins per unit surface (€/ha) and per unit water applied (€/m^3) as a function of irrigation depths in sprinkler irrigated maize, Southern Portugal

More research approaches are required to relate yield responses with gross margin or revenue responses to water deficits. The development of decision support tools integrating irrigation simulation models, namely for extrapolating field trials data, economic evaluation and decision tools should be useful to base the appropriate irrigation management decisions for water scarcity conditions.

7. NEED FOR INNOVATIVE ISSUES

Problems identified above call for innovative issues in water management in such a way that development not only sustains the fast growing and urbanised population, but be sustainable. A Research Agenda on sustainability of water resources utilisation in agriculture was developed few years ago (Pereira *et al*., 1996). The resulting primary issues and priorities concern the different components and implications of sustainability such as: resource conservation; technical appropriateness; environmental concerns; economic viability; and social and institutional adequacy. They include management techniques, innovative technologies; evaluation, assessment and monitoring methodologies, as well as measures, rules, guidelines and training tools.

The priority area concerns *environmental and health impacts* which are essential to deal with problems referred above, including the increased use of non-conventional waters in irrigation to replace high quality freshwater required to more stringent uses. Issues include:

(a) evaluating the potential of irrigation as a means for environmentally sustainable land use and food production;
(b) developing appropriate tools for assessing and controlling the impacts of using low quality water in irrigation, and appropriate techniques for the maintenance of wastewater reuse systems;
(c) the control of water-related diseases, including monitoring health hazards;
(d) improve land evaluation criteria and methodologies for irrigation planning to include the assessment of the impacts on the environment.

Water quality management is another priority area that complements the one described above. It includes:

(a) water quality monitoring, including the development of reduced cost methods of assessment and standards;
(b) economic and effective mechanisms for disposal or reuse of drainage water, salts and agricultural wastes in arid and semiarid lands;
(c) appropriate methods for wastewater treatment for agriculture reuse;
(d) best management practices to minimise water quality degradation in irrigated agriculture and improve the productivity of irrigated agriculture.

The technical issues that received higher priority relate to farm and off-farm irrigation systems rehabilitation and modernisation which are required to implement water conservation and saving, avoid water wastes and losses and effectively control the impacts of water, fertilisers and agro-chemicals used in irrigated agriculture, as well as control the effects of salts and other substances when low quality water is applied. Therefore, *rehabilitation and modernisation of irrigation systems* relate to:

(a) procedures for integrated planning and management of irrigation and drainage systems;
(b) development of locally-adapted water-efficient on-farm irrigation technologies;
(c) integrated irrigation and fertiliser management, including fertigation, chemigation and irrigation scheduling;
(d) low cost technologies for canal construction and improvement, and appropriate techniques for improved water regulation and control;
(e) strategies for sustained increases in output per unit input of water and land;
(f) control sediment in irrigation and drainage systems;
(g) enhanced methods for field evaluation of on-farm and off-farm system performances and system monitoring.

Also high priority is assigned to the *technologies and rules for use of wastewater and saline water*. Despite many efforts developed by many international and national agencies, the safe use of those waters still is far from desirable. Particularly, it is mainly required to:

(a) improve knowledge on salinity and solute processes under irrigated agriculture;
(b) develop and implement methods, techniques and guidelines for use, control and management of low quality water for irrigation;
(c) expand research on adaptation of crops and cropping systems to use low quality and saline water;
(d) adopt and effectively enforce criteria and guidelines for the use of saline water and for saline water table management.

Institutional and policy issues also receive high priority to make water management effective. They concern the mechanisms to improve user's participation and to strengthen the institutions involved in water resources planning and management, as well as the laws and regulations relative to water policies. Issues to enhance *user's participation* in management of irrigation and drainage systems are receiving high priority at international level, which are known now under the acronym PIM, participatory irrigation management. They include:

(e) the improvement of programs aiming at the transfer of responsibility from government to users relative to the operation, maintenance, and management of irrigation and drainage systems;
(f) guidelines for user organizations to administer water for different uses;
(g) the recognition of indigenous knowledge, human reluctance to change, and traditional social arrangements;
(h) mechanisms which can improve the coordination and division of responsibility between government, public and water user institutions and the irrigation industry.

Other priority area concerns *policy issues for water management:* (a) appropriate procedures for allocation of surface and ground water for different purposes and uses; (b) water laws and rights which provide for equity in water distribution and allocation; (c) legal instruments and procedures for implementing water conservation and efficient management practices. Similarly, innovative issues for *institutional building,* which mainly concern human resource development, are also receiving priority since the application of new technologies and improved management can not be successful when maintaining outdated the knowledge of the irrigation actors, as well as their perception of problems.

Innovative issues as mentioned above are essential to reduce the demand for irrigation water and to implement supply management oriented to satisfy and control the demand when the availability of water falls below current demand.

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