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Trends for Irrigated Agriculture in the Mediterranean Region:

Coping With Water Scarcity

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Abstract: The use of water for agricultural production in water scarcity regions requires innovative and sustainable research issues, and an appropriate transfer of technologies. This is the case for the Mediterranean region where water is scarce due to the aridity of the climate, frequent droughts, and man-made desertification and water shortage hazards. To respond to increased water scarcity constraints, competition for water by the non-agricultural sectors, competitiveness of production in a globalised economy, needs to improve living conditions of rural populations, environmental concerns and cultural values, irrigated agriculture must innovate. First, policies to cope with the water stressed regimes have to be developed, understood by all actors and implemented in a comprehensive and holistic way, including water conservation and water saving tools and practices. Competition for water gives priority to the use of non-conventional water resources, which require improved farm irrigation practices and management adequate for the use of treated wastewater and saline waters. The competitiveness of irrigated production calls for increased water productivity and crop patterns and cropping techniques that better respond to the quality requirements of produced goods. Improving the living conditions of rural populations concern both the increased revenues and improved labour conditions, including health safety related to water born diseases. The need to improve the environmental friendliness of irrigated agriculture calls for the betterment of farming practices aimed at controlling adverse impacts of agriculture on the groundwater, surface waters, soils and nature. The preservation of cultural values concerns the involvement of the communities in water management, the respect for traditional values relative to water and land, and the functioning of institutions in agreement with such values, not following imported values of efficiency or efficacy. Responding to these challenges requires innovative technologies at both off- and on-farm levels. The modernisation of supply management to cope with water scarcity requires includes the adoption of information technologies, enhanced regulation and control, and more flexible, reliable and equitable delivery schedules. In addition, particularly when low quality waters are used, follow-up and monitoring systems are expected to develop, as well as better links with the farming practices. At farm level, the achievement of higher irrigation performances is required including the appropriate selection and implementation of irrigation methods and irrigation scheduling. Demand management should focus the improvement of the distribution uniformity as a fundamental tool to reduce the demand for water, to control the negative environmental impacts of over-irrigation, to improve salts leaching and increase the effectiveness of scheduling strategies. Field evaluations, quality of systems design, quality of equipment, and expertise of extension and training officers are also considered. The need to adopt emerging technologies for water management as well as to develop appropriate methodologies for the analysis of social, economic, and environmental benefits of improved irrigation management are also among trends identified.

Key words: water scarcity, irrigation performances, supply management, non-conventional waters, demand management, irrigation methods, deficit irrigation, sustainability of irrigated agriculture.

1. INTRODUCTION

Water is becoming increasingly scarce in the Mediterranean region. Aridity and droughts are the physical causes for scarcity which occur in the region since we know the history of our common Mediterranean civilizations. More recently, man-made desertification and water shortages are aggravating the natural scarcity while population is increasing and the demand for water faces a higher competition among water user sectors and regions. Not only rainfall is not enough abundant, thus limiting the quantity of water resources available, but 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 scarcity, but coping in a sustainable way.

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 the Mediterranean region. Innovations are therefore required, particularly relative to irrigation management and practice since the agriculture sector is far ahead in demand for water in the region.

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 is associated with high pressure on natural resources, strong competition for water that aggravates the limiting resource for agriculture, frequent soil salinisation due to poor management of irrigation, and vulnerable and fragile ecosystems. Therefore, the sustainable use of water to cope with aridity implies: (a) the effective adoption and implementation of integrated land and water resources planning; (b) the improvement of irrigation supply systems to achieve an increased service performance and induce more efficient water use and production; (c) the adoption of water allocation policies favouring conservation and efficient use; (d) valuing the water as an economic, social and environmental good, including for nature conservation; (e) measures for augmenting the available water resource, including wastewater and drainage water re-use; (f) the adoption of irrigation technologies that favour efficient water use and contribute to avoid water wastes and losses; and (g) the users' awareness on the implications of water scarcity as well as their participation in water resources and water systems management.

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 (a) the need of preparedness measures are paramount to cope with droughts, (b) the requirement for adopting reactive mitigation measures including those of financial nature, (c) changes in water allocation and delivery policies, as well as in the management of water and irrigation systems, to face the reductions in supply, and (d) the need for farmers to be able to adopt reduced demand practices.

Desertification is a man-induced permanent imbalance in the availability of water, 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. Climate change also contributes to desertification, which occurs in arid, semiarid and sub-humid climates. Drought strongly aggravates the process of desertification when increasing the pressure on the diminished surface and groundwater resources.

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: (a) re-establishing the environmental balance in the use of the natural resources, (b) restoring the soil quality, (c) strengthening erosion control and soil and water conservation, (d) combating soil and water salinisation, (e) controlling groundwater withdrawals and favouring aquifers recharge, (f) minimising water wastes, and (g) managing the water quality.

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. These aspects are not treated herein but they are subjacent to the aspects analysed. 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 discussed in the following sections under the perspective of detecting future trends for the Mediterranean irrigated agriculture.

2. WATER AVAILABILITY AND SCARCITY IN THE MEDITERRANEAN REGION

The world situation relative to water resources has been well summarised by The World Bank (1992) and later by Shiklomanov (2000). Results for the first are shown in Table 1. They evidence a great variation in the available water resources and allow to identify the South and Eastern areas of the Mediterranean region as those where water availability is scarce. The same data shows that, world-wide, the irrigated agriculture is the main water use sector, particularly in the low to medium income countries and the North Africa and Middle East region.

Table 1. World availability of water Resources (source: The World Bank, 1992)

Country group	Total annual internal renewable water resources (10^6 m^3)	Total annual water withdrawal (10^6 m^3)	Annual withdrawal as a share of total water resources (%)	Annual internal renewable water resources, (m^3/capita)	Sectorial withdrawal as a share of total water resources (%)		
					Agriculture	Domestic	Industry
Low and middle income	28,002	1,749	6	6,732	85	7	8
Sub-Saharan Africa	3,713	55	1	7,488	88	8	3
East-Asia and Pacific	7,915	631	8	5,009	86	6	8
South Asia	4,895	569	12	4,236	94	2	3
Europe	574	110	19	2,865	45	14	42
Middle East and North Africa	276	202	73	1,071	89	6	5
Latin America and the Caribbean	10,579	173	2	24,390	72	16	11
High income	8,368	893	11	10,528	39	14	47
OECD members	8,365	889	11	10,781	39	14	47
Other	4	4	119	186	67	22	12
World	40,856	3,017	7	7,744	69	9	22

The more recent study by Shiklomanov (2000) used a different data source and different data aggregation, so their results (Table 2) are difficult to compare with those of The World Bank (1992). However data show clearly the differences among main regions of the world. For Europe, the Mediterranean countries, which may be identified as the Southern ones, have much less available water then the Northern ones particularly when the per capita volumes are considered. Similarly for Africa, the Northern countries which include the South Mediterranean countries are also defavorised relatively to other African regions particularly Central Africa. The average per capita availability is below the 1000 m^3/capita considered the threshold for water scarcity. Western Asia countries include the Middle East Mediterranean countries and, together with Southern Asia have the lowest water availability in Asia. Comparing data in Table 2 relative to the regions referring to the Mediterranean basin with those for other regions it is confirmed that water scarcity is a main problem in the region.

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

Region	Population (1994)	Water resources (km^3/year) (average)	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
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
Asia	3,445	13,510	311	3.92
Western	232	490	72	2.11
Central Asia	54	181	51	3.78
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 & Oceania	28.7	2,404	269	83.80
The World	**5,633**	**42,780**	**316**	**7.60**

Shiklomanov (2000) analysed the trends in water withdrawal for the X century and produced a forecast for the first quarter of this century. Results using the same aggregation are shown in Table 3. For the Southern European countries there is evidence of a growth in water withdrawal during the XX century, with volumes by the end of the century corresponding to eleven times those by 1900. The growth for the North Africa countries is also high but not exceeding 3 times those at the beginning of the century due to less available resources and more difficulties in mobilising the resources available. The Middle East countries are in an intermediate situation relative to South Europe and North Africa, having a growth in withdrawals of about six times from the beginning of the period. Together with North America, Central and Southern Asia, the Mediterranean countries are among those where water withdrawals have grown more. The forecasts by Shiklomanov (2000) show a trend to have a slower growth during the XXI century: this hypothesis relies on several aspects: 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.

Forecasts also depend upon population dynamics and relate to the sectorial water use as shown in Table 4. On the one hand 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 in XXI century. However, the trend in population trend 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 the Mediterranean area while it drastically drops in other regions such as in China. 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. Results in Table 4 indicate that the competition for freshwater from the non-agricultural sectors will increase the pressure placed on water resources, thus leading to the need for using non-conventional water resources in agriculture.

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	226.0	455.0	535.0	559.0
Northern	1.4	7.3	11.0	12.7	13.4
Southern	16.1	95.3	186.0	204.0	204.0
Africa	40.7	89.2	219.0	275.0	337.0
Northern	36.6	68.3	110.0	127.0	145.0
Central	0.1	0.4	2.6	4.9	9.2
Asia	414	1,163.0	2,231.0	2,628.0	3,254.0
Western	42.8	133.0	249.0	299.0	356.0
Central Asia	28.7	67.4	154.0	174.0	182.0
Southern	201	426.0	887.0	1,023.0	1,339.0
North America	69.6	410.0	686.0	744.0	786.0
South America	15.1	65.6	167.0	213.0	260.0
Australia & Oceania	1.6	14.5	30.4	35.7	39.5
The World	**579.0**	**1,968.0**	**3,788.0**	**4,431.0**	**5,235.0**

Table 4. Dynamics of water use at the world scale (adapted from 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

Analysis relative to the Mediterranean countries has been recently produced by Hamdy and Lacirignola (1999) and Correia (1999). From the last study, it can be observed that several countries in the Mediterranean region face heavy to extremely severe water scarcity conditions (Table 5). These results oppose existing conditions in the Northern Mediterranean to those in South and East, where the per capita total available water resources are often below 1000 m^3, in several cases much less. Therefore, the sectoral share of water withdrawals also varies from country to country. The trend is to have a larger share for irrigation in North Africa and Middle East and a larger share for municipal water uses in areas where the resource is more limited. However, the variability in water availability and in the share of water withdrawals also occurs within all the countries, where often the southern areas face more acute scarcity problems then northern areas.

Problems are extremely aggravated by droughts, which are quite frequent throughout the Mediterranean area (Cancelliere and Rossi, 2003). Meanwhile, progresses in drought prediction for the Mediterranean basin are insufficient. However, several approaches such as exploiting global circulation models in relation to the ENSO and the NOA anomalies (Bordi and Sutera, 1999) or adopting an in-depth characterisation of droughts with the standard precipitation index, SPI (Paulo et al., 2003) open promising perspectives that may help the mitigation of drought impacts.

Table 5. Available water resources and water withdrawals in the Mediterranean countries (data relative to 1994, adapted from Correia, 2000)

Country	Population	Annual internal renewal resources	Annual total resources	Annual withdrawals		Sectoral withdrawal (%)		
	(millions)	(m^3 per capita)	(m^3 per capita)	(% total)	(m^3 per capita)	Domestic	Industry	Irrigation
Portugal	10.3	3450	6380	16	1075	15	37	48
Spain	39.2	2820	2840	41	1188	12	26	62
France	56.1	2970	3300	24	778	16	69	15
Italy	57.1	3100	3280	30	996	14	27	59
Former Yugoslavia	23.8	6260	11130	3	393	16	72	12
Albania	3.2	3020	6550	1	94	6	18	76
Greece	10.1	4430	5840	12	721	8	29	63
Turkey	55.9	3190	3460	12	433	24	19	57
Cyprus	0.7	1280	1280	60	807	7	2	91
Syria	12.5	570	2830	9	435	7	10	83
Lebanon	2.7	1690	1690	16	271	11	4	85
Jordan	4.0	240	350	32	173	29	6	65
Israel & Palestine	4.6	330	470	86	410	16	5	79
Egypt	52.4	50	1110	97	1028	7	5	88
Libya	4.6	140	140	374	692	15	10	75
Malta	0.4	70	70	92	68	76	8	16
Tunisia	8.2	450	530	53	317	13	7	80
Algeria	25.0	720	770	16	160	22	4	74
Morocco	25.1	1140	1140	36	412	6	3	92

Desertification is also aggravating the problems of water resource availability, particularly in the North Africa and Middle East countries (Balabanis et al., 1999). More frequent land degradation problems relate to soil erosion, salinity hazards and overgrazing in the semi-arid pastoral areas. Estimates by FAO (1986) indicate that in the Near East 8% of the land is threatened by salinity, 17% is affected by water erosion and 35% by wind erosion. These problems are well identified in the recent publication by Zdruli et al. (2001). Adding to desertification, water shortage is also being produced due to water quality degradation and contamination and over-exploitation of the groundwater resources (Mourits et al., 1997).

The problems outlined above show that the Mediterranean countries, particularly those from the Eastern and Southern regions, face a great challenge to cope with water scarcity and limited land, while natural resources are threatened by several degradation processes. The challenge is definitely increased by the population growth. According to Hamdy and Lacirignola (1999) the present very high growth rate may lead to double the population in several of these countries by 2025. Therefore, there is the need to seek for new trends in irrigated agriculture that may help to cope with the adverse environment and water scarcity. In fact, an increased population requires that food be produced in abundance and quality, thus needs that the irrigated agriculture be effectively sustainable.

3. SUPPLY MANAGEMENT

The importance of supply management strategies to cope with water scarcity in irrigation is well identified in the literature and observed in practice.

Supply management includes: (a) increased storage capacities, including those to favour supplemental irrigation; (b) improved irrigation conveyance and distribution systems that provide increased flexibility of deliveries and reduce system water wastages; (c) enhanced operation and maintenance; in which farmers participation and the training of irrigation agents and farmers should be considered, and (d) the development of new sources of water supplies. The latter include treated wastewater and saline groundwater and drainage water, the use of which in irrigation requires improved irrigation practices and management, mainly to avoid impacts on health and minimise those on the environment. These subjects are briefly outlined in Table 6.

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. Recent developments along these lines are presented by Rossi et al. (2003).

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). These aspects are outlined by Pereira et al. (2002b) aimed to water conservation and saving to cope with water scarcity.

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.

Supply management is generally considered under the perspective of enhancing reservoir and conveyance capabilities to provide higher reliability and flexibility of deliveries required for improved demand management. Therefore, supply management also includes:

- *hydrometeorological networks*, data bases and information systems to produce appropriate information for effective implementation and exploration of real time operation of irrigation systems,
- *agrometeorological irrigation information systems* including tools for farmers to accede to information, often comprising GIS, to support local or regional irrigation management programs, as well as decision support systems serving the reservoir operation, the water system management, and the users to select crop patterns, irrigation scheduling and irrigation systems, and
- *planning for droughts* to establish allocation and delivery policies and drought operation rules.

Table 6. Issues for improved management of irrigation supply systems to cope with water scarcity (adapted from Pereira et al., 2002b)

Management techniques	Benefits and limitations
Improved reservoirs operation	
▪ Develop and implement information systems, including remote sensing, GIS, models for optimised operation and management	▪ Non limited but expensive for small schemes
▪ Hydrological forecasting and drought watch systems for Improved assessment of supplies	▪ At large scale, large projects or regional level
▪ Upgrading monitoring for improved use of operation tools	▪ Needs to be part of OM&M activities
▪ Application of optimisation, risk, and decision models Optimised management rules; and water allocation	▪ Non limited but expensive for small schemes
Conveyance and distribution systems	
▪ Canal lining for improved management and avoidance of seepage losses	▪ Limited by costs
▪ Improved canal regulation and control aimed at higher flexibility, better service and reduced operation losses	▪ Needs investment and technology
▪ Automation and remote control in canal management when real time delivery management has to be implemented	▪ High technological requirements
▪ Low pressure pipe distributors in surface irrigation to reduce spills and leaks, higher flexibility, and easier water metering	▪ Limited by costs but easy to implement
▪ Change from supply oriented to demand oriented delivery schedules to favour farmers water saving irrigation management and adoption of real time management	▪ Needs communication tools between farmers and managers
▪ Intermediate storage (in canal, reservoirs, farm ponds) for increased flexibility and reduced operation losses	▪ Requires innovative management tools
▪ Farmers participation in management decisions including delivery schedules planning to cope with limited supply to allow farmers to adopt best management practices	▪ Needs appropriate institutional arrangements
▪ Adopt demand delivery scheduling in pressurised systems for higher flexibility and water savings at farm	▪ Only constrained by the system characteristics
▪ Water prices in relation to volumes of water diverted to induce farmers to save water and to irrigate by night (automation)	▪ Needs appropriate water metering and pricing
▪ Use of information systems to support optimised operation, maintenance and management	▪ Primarily to large schemes
▪ Application of optimisation methods to schedule deliveries that favour increased reliability and equity, and reduced farm demand	▪ Needs feed-back information from farmers
Maintenance and management	
▪ Adopt effective systems maintenance to avoid spills and leaks and improve system operation conditions	▪ Requires planning and trained staff
▪ Water metering for both system operation and billing	▪ Needs equipment
▪ Monitoring system functioning for identification of critical areas and system losses, mainly when non-conventional water is used	▪ Requires planning and trained staff
▪ Assessment of system performances (physical, environmental and service) to follow-up water saving programmes and system operation	▪ As above
▪ Personnel training to support improved management and the implementation of more demanding technologies	▪ Not high costly when well planned
▪ Information to farmers on the system constraints and saving issues as pre-condition for their effective participation in management	▪ General
Improved supply for drought mitigation	
▪ Development of new sources of surface water, including short distance water transfers	▪ Needs integrated planning
▪ Increased groundwater pumping including mining	▪ Needs control/monitoring
▪ Transfer of water rights for easy re-allocation of available water	▪ In accordance with existing water laws
▪ Increased use/reuse of low quality water (treated wastewater and drainage water) for irrigation and landscape	▪ Depending on crops and uses. Monitoring required
▪ Conjunctive use of available rainfall and water resource including non-conventional waters	▪ Needs appropriate planning and management

4. NON-CONVENTIONAL WATER SUPPLIES

Municipal wastewater contains relatively small concentrations of suspended and dissolved organic and inorganic solids. Organic substances include carbohydrates, lignin, fats, soaps, synthetic detergents, proteins and their decomposition products, as well as various natural and synthetic organic chemicals from the process industries. In arid and semi-arid countries, because water use is often fairly low, sewage 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. Pathogenic viruses, bacteria, protozoa and helminths may be present in raw municipal wastewater and will survive in the environment for long periods (e.g. Mara and Cairncross, 1989, Pescod, 1992, Hespanhol, 1996). Main health hazards are associated with the contamination of crops or groundwaters with irrigation water, particularly with cumulative poisons, principally heavy metals, and carcinogens, mainly organic chemicals. The World Health Organisation has guidelines for drinking water quality (WHO 1984) that can be adopted directly for groundwater protection purposes. To consider the possible accumulation of certain toxic elements in plants (e.g. cadmium and selenium), their intake through eating the crops irrigated with contaminated wastewater must be assessed.

Pathogenic organisms constitute the greatest health concern in the use of wastewaters in irrigation. Negative health effects were only detected in association with the use of raw or poorly treated wastewater, while appropriate wastewater treatment should provide for health protection. The health risks associated with pathogens are well reviewed by several authors (e.g. Mara and Cairncross, 1989, Pescod, 1992; Hespanhol, 1996).

To avoid health hazards and damage to the natural environment wastewater must be treated before it can be used for agricultural and landscape irrigation. The required quality of effluent will depend on the aimed water uses, crops to be irrigated, soil conditions and the irrigation system. The most appropriate wastewater treatment is that which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements. Adopting a level of treatment as low as possible but achievable is desirable, especially in developing countries (Arar, 1988; Oron et al. 1999). Treatment to remove constituents that may be toxic or harmful to crops, aquatic plants and fish is normally not economically feasible. Good reviews on treatment of wastewater for irrigation are provided by Pescod (1992) and 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.

Factors influencing transmission of disease include the degree of wastewater treatment, the crops grown, the irrigation method used to apply the wastewater, and the cultural and harvesting practices used (Westcot, 1997). International guidelines for the microbiological quality of irrigation water were established by the WHO (Mara and Cairncross, 1989). The guidelines may be used for monitoring and quality certification (Westcot, 1997), eventually completed with standards responding to other local requirements. 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. Crop restrictions should mainly focus on crops that are eaten raw. However, crop restrictions need a strong institutional framework and the capacity to monitor and control compliance with the regulations (Mara and Cairncross, 1989).

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 by Ayers and Westcot (1985) and Rhoades et al. (1992) including those to estimate the leaching requirements and to appropriately manage the crops to avoid salinity hazards and soil degradation. 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).

5. DEMAND MANAGEMENT: IMPROVEMENT OF IRRIGATION MANAGEMENT

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

Agronomic and economic decisions and farming practices are often dealt with in the literature. Several papers reviewed these issues for irrigated agriculture (Bucks et al., 1990; Pereira, 1989; Tarjuelo and de Juan, 1999), including the aspects relative to water allocation (Recca et al., 2001).

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 These aspects are reviewed by Pereira et al. (2002a).

Factors influencing the distribution uniformity and the application efficiency are analysed by Pereira et al. (2002a) for surface, sprinkler and microirrigation systems the distribution uniformity 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 efficiencies when keeping the 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. Over-irrigation is often practised. In modernised systems, some form of control of discharge such as siphons, gated pipes, lay-flat tubes or gates, and some form of automation is used. The fields are often precision levelled, while the advance and supply times as well as the inflow rate can be measured or estimated. Therefore, in these systems, in contrast with the traditional ones, it is easy to control “how much” water should be applied.

The ability of the farmer plays a major role in controlling the management variables but his capability to achieve higher performances is definitely limited by the system and the soil characteristics and, often, by off-farm delivery decisions. This means that it is not enough to tell the farmers to adopt target management rules when the off- and on-farm system constraints are not identified and measures are not taken to improve the irrigation system.

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 / 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. fertilising, pest and diseases control) Avoid crop stress at critical periods
Higher farmer incomes	Select cash crops High quality of products

The importance of uniformity in surface irrigation is well evidenced in literature. The role of level precision in basin irrigation is well analysed by Clemmens et al. (1999) for improving irrigation management in Egypt and constitutes an updated case study. Field evaluations play a fundamental role in improving surface irrigation systems, as they provide information for design and for advising irrigators on how to improve their systems and practices. When water of inferior quality is used, and in the irrigation of saline soils, a leaching fraction has to be added for salts control in the root zone. Then, over-irrigation is often practised, mainly when the field surfaces are uneven. It is required that the leaching fraction should be appropriately limited. Adopting precise land levelling, as for an application in North China (Fabião, 2001), leads to quite uniform infiltration depths (Fig. 1) and, therefore to an uniform soil leaching with a much smaller demand. The resulting water savings for the wheat crop season range from 150 to 210 mm (Campos et al., 2001). This exemplifies the need for high distribution uniformity when the irrigation demand has to be controlled, namely when salinity has to be managed, including when wastewater or saline water has to be used.

System and delivery constraints 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 (e.g. Smith et al., 1996; Camp et al., 1996).

The irrigation uniformity (DU) in sprinkler and micro-irrigation systems depends essentially on variables characterising the system (Pereira et al., 2002a), 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. 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. Despite it would be easier than for surface irrigation systems, the irrigators are often not in control of the water depths applied.

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. Based on field evaluations, Mantovani et al. (1995) show that, when the price of water is low, the farmers tend to optimise yields not taking care on the water use. Then, for DU near 40%, farmers use 2.25 times the required application depth and just 1.25 times when DU is close to 85%. 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 is explained by the fact that as low as DU is, larger is the difference between applied depths in the over-irrigated and the under-irrigated parts of the field. This fact makes useful to adopt a target DU for sprinkler and micro-irrigation design (Keller and Bliesner, 1990, Bralts et al., 1987). An extensive analysis by Ayars et al. (1999) shows the benefits of subsurface drip applied to several crops in maximising yields and reducing water demand relatively to other methods. 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.

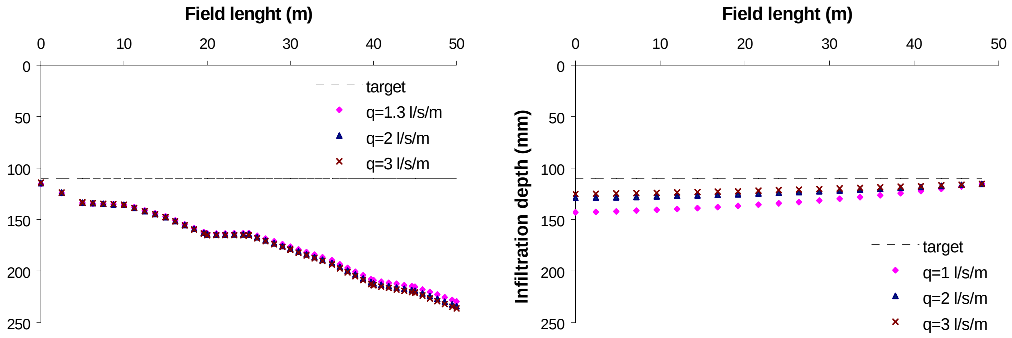

Figure 1. Basin infiltration depth curves simulated for: present field surface conditions, on left, and a precision zero levelled basin, on right, for a target infiltration depth of 100 mm and 10 % leaching fraction, with inflow rates ranging from 1 to 3 l/s/m, Huinong Irrigation District, China (adapted from Fabião et al., 2001).

6. DEMAND MANAGEMENT: SUITABILITY OF IRRIGATION METHODS FOR USING NON-CONVENTIONAL WATERS

The irrigation methods have specific characteristics that determine their appropriateness to be used with wastewater and saline water. The factors influencing such behaviour relate to the capabilities offered by the corresponding irrigation systems to easily minimise/avoid the risks associated with the use of those waters. In what concerns salinity, risks refer to:

- soil salinisation, which relate to the easiness to leach the salts in the root zone, in relation to the capability to apply the leaching requirement evenly and in a controlled manner;
- plant toxicity related to direct contact of the water with the plant leaves;
- difficulties in infiltrating the applied water without excessive runoff; and
- crop stress and yield reduction, including that due to inability to maintain adequate water availability in the soil.

The main aspects characterising the suitability of the irrigation methods to be adopted for saline water irrigation are updated by Pereira et al. (2002a) as well as for wastewater irrigation. In this case the suitability of the irrigation methods is considered by minimising:

- toxicity hazards relative to foliar contact of the wastewater;
- contamination hazards associated with the direct contact of water with the fruits and the harvestable parts of the plants;
- salinity hazards relative to salts in the root zone; and
- health hazards occurring through direct human contact with the wastewater.

Sprinkler systems and, to a certain extent, micro-sprinkler systems are less appropriate to control health and contamination hazards, as well as toxicity hazards. On the contrary, drip irrigation looks to be more easily suitable as advocated by many authors, e.g. Oron (1999). However, when waters contain high TDS drip systems may easily be affected by clogging. Appropriate filtering and the treatment of the irrigation water with acid and chlorine are then required (Al-Nakshabandi et al., 1997). However, in case of effluents from agricultural processing industry, which generally are not associated with health, contamination and toxicity risks, sprinkler systems are the most appropriate, e.g. rain-guns for application of effluents of the sugarcane industry. The selection of the irrigation method is also related with the respective equipment because wastewaters and low quality waters may have constituents that are corrosive to the equipment or may create difficulties for filtering, or easily affect control and automation devices, therefore originating risks of system failure.

7. DEMAND MANAGEMENT: DEFICIT IRRIGATION AND WATER PRODUCTIVITY

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. Zairi et al., 2003; Rodrigues et al., 2003; Sarwar and Bastiaansen, 2001) 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, WP (kg/m^3), earlier named water-use efficiency (e.g. Zhang et al., 1998; 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 that deficit irrigation is generally economically feasible in Tunisia (Zairi et al., 2003), in agreement with results for Portugal (Rodrigues et al., 2003). However, for potato different results were obtained. When average climatic conditions prevail, the crop uses irrigation water in addition to relatively abundant rainfall, which makes deficit irrigation feasible. Under drought, the climatic demand highly increases because rainfall is less available. Then, despite WP increases when less water is applied, the best economic option for less available water is to crop only a fraction of the land and apply there an optimal irrigation schedule. Similar unfeasibility for deficit irrigation of summer crops observed by Rodrigues et al. (2003).

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.

8. NEED FOR INNOVATIVE ISSUES

Problems identified above call for new 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 developed few years ago (Pereira et al., 1996) may be useful to identify innovation needed. The resulting primary issues and priorities are listed in Table 8. These issues 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.

Table 8. Research agenda on the sustainable use of water in irrigated agriculture (adapted from Pereira et al., 1996)

Priority	*Issues*
1	Environmental and health impacts
1	Water quality management
2	Rehabilitation and modernisation of irrigation systems
3	Technology and rules for use of waste and saline water
3	Policy issues
3	User participation for planning and managing irrigation and drainage systems
4	Basin wide integrated water resources planning
4	Human resources development
5	Irrigation and drainage system performance
5	Water savings methodologies
6	Rainfed agricultural water management and water harvesting
6	Economics of development of both irrigated and rainfed agricultural schemes
7	Land and water institutional issues
8	Availability of land and water resources

The priority area concerns environmental and health impacts which are essential to deal with problems identified earlier, particularly with 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, as well as the potential adverse environmental impacts resulting from neglecting or abandoning irrigation systems;
(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, environmental management for vector control, and expand the epidemiological studies relative to wastewater and drainage water reuse;
(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 for chemical, physical and biological loads, and the aspects relative to pollution from agrochemicals;
(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 with the efficient delivery of water.

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 agrochemicals 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, i.e., the improvement of on-farm irrigation performances;
(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, including water supply, water quality, salinisation and environmental, economic and social impacts.

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:

(a) 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;
(b) guidelines for user organizations to administer water for different uses;
(c) the recognition of indigenous knowledge, human reluctance to change, and traditional social arrangements;
(d) 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.

6. CONCLUSIONS

The trends for irrigated agriculture in the Mediterranean region are basically those that shall adapt water management to cope with water scarcity.

Supply management should focus on higher reliability and flexibility of deliveries to better match supply with demand and favour the adoption of reduced demand by farmer users. Adding wastewaters and saline waters is also a main trend which requires an appropriate control of health and environmental impacts. The impacts relative to wastewater reuse relate to the level of treatment of the effluents, the crops grown, the farming practices and the irrigation methods used. Related issues concern monitoring, namely in relation to crop restrictions in areas using wastewater, and appropriate selection of suitable irrigation methods and practices. Similarly, for saline water use, monitoring and the appropriate choice of the irrigation methods and management are essential.

Reduced demand needs adopting improved farm irrigation systems. The improvement of irrigation systems is closely related with higher irrigation uniformity. This implies better design, appropriate selection of irrigation equipment, careful maintenance and the extended use of field evaluation. Higher uniformity is required to apply low quality waters with lesser impacts on the environment. The review has shown that economic impacts resulting from improving irrigation performances are not sufficiently known since a great number of factors influence them.

In water scarcity areas, in general water, not land, is the most limiting resource. This may be achieved by adopting deficit irrigation. However, while it is feasible for supplemental irrigation of cereals, there is no evidence of its practicability for summer crops. Water scarce areas need guidelines to determine irrigation schedules that maximise water productivity and farm profitability.

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