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Review

# Irrigation management under water scarcity

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**Abstract**

The use of water for agricultural production in water scarcity regions requires innovative and sustainable research, and an appropriate transfer of technologies. This paper discusses some of these aspects, mainly relative to on-farm irrigation management including the use of treated wastewater and saline waters. First, the paper proposes some concepts relative to water scarcity, concerning aridity, drought, desertification and water shortage, as well as policies to cope with these water stressed regimes. Conceptual approaches on irrigation performances, water use and water savings are reviewed in a wide perspective. This is followed by a discussion of supply management to cope with water scarcity, giving particular attention to the use of wastewater and low-quality waters, including the respective impacts on health and the environment as water scarcity is requiring that waters of inferior quality be increasingly used for irrigation. The paper then focuses on demand management, starting with aspects relating to the improvement of irrigation methods and the respective performances, mainly the distribution uniformity (DU) as a fundamental tool to reduce the demand for water at the farm level, and to control the negative environmental impacts of over-irrigation, including salt stressed areas. Discussions are supported by recent research results. The suitability of irrigation methods for using treated wastewaters and saline waters is analysed. Supplemental irrigation (SI) and deficit irrigation strategies are also discussed, including limitations on the applicability of related practices. The paper also identifies 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.
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## 1. Water scarcity concepts and water management implications

Water is becoming scarce not only in arid and drought prone areas but also in regions where rainfall is abundant: water scarcity concerns the quantity of resource available and the quality of the water because degraded water resources become unavailable for more stringent requirements.

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 these regions. Innovations are, therefore, required mainly relative to irrigation management and practice since the agriculture sector is far ahead in demand for water in those regions.

Water scarcity may be due to different causes, relative to different xeric regimes, nature produced and man-induced (Vlachos and James, 1983; Pereira, 1990), as indicated in Table 1. Pereira et al. (2002) present an in-depth discussion on these concepts.

*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.

*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 both a hazard and a disaster. A hazard because it is a natural accident of almost unpredictable occurrence but of recognisable recurrence. A disaster, because a drought corresponds to 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.

*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. Climate change also contributes to desertification, which occurs in arid, semi-arid and sub-humid climates. Drought strongly aggravates the process of desertification when increasing the pressure on the diminished surface and groundwater resources. Different definitions are used for desertification, mainly focusing on land degradation and sometimes not referring to water. However, when dealing with water scarce situations it seems more appropriate to define desertification in relation to the water and nature imbalances produced by the misuse

Table 1
Xeric regimes causing water scarcity

| Duration | Nature produced | Man-induced |
|---|---|---|
| Permanent | Aridity | Desertification |
| Temporary | Drought | Water shortage |

of water and land resources, thus, calling attention to the fact that desertification, including land degradation, definitely is a cause for water scarcity.

*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.

Policies and practices of irrigation water management under water scarcity must focus on specific objectives according to the causes of water scarcity. Valuing the water as an economic, marketable good may be insufficient since water acts not only for producing but is also supporting other natural resources. A coupled environmental, economic, and social approach is required in valuing the water, while an integrated technical and scientific approach is essential to develop and implement the management practices appropriate to deal with water scarcity.

Among other characteristics, *aridity* is very often 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 resources under aridity implies the following:

- the effective adoption and implementation of integrated land and water resources planning;
- the improvement of water and irrigation supply systems to achieve an increased service performance which would induce more efficient water use and production;
- the adoption of water allocation policies favouring conservation and efficient use;
- valuing the water as an economic, social and environmental good, including for nature conservation;
- measures for augmenting the available water resource, including wastewater and drainage water reuse and the conjunctive use of water from different origins and qualities;
- the adoption of appropriate water and irrigation technologies that favour efficient water use and contribute to avoid water wastes and losses; and
- users' awareness on the implications of water scarcity as well as their participation in water resources and water systems management.

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 or increase the public awareness on the proper use of the scarce water resources. Other measures which are peculiar to drought conditions are as follows:

- because droughts are difficult to predict or unpredictable in certain areas, preparedness measures are paramount to cope with droughts;
- as they have pervasive long-term effects and their severity may be very high, appropriate reactive mitigation measures are required;
- since a break in the natural water supply occurs, changes in water allocation and delivery policies are necessary, as well as in the management of water and irrigation systems;
- consequently, it is required that farmers be able to adopt reduced demand practices; and

- because farmers' incomes may be drastically reduced, other appropriate measures including those of financial nature are also required to support farmers in coping with droughts.

*Desertification* and *water shortage*, as they are man-induced and are associated to problems such as land degradation due to soil erosion and salinisation, over exploitation of land and water resources, and water quality degradation, require that policies and measures be oriented to solve the existing problems. Combating desertification and water shortage requires the following:

- re-establishing the environmental balance in the use of the natural resources;
- restoring the soil quality;
- strengthening erosion control and soil and conservation;
- combating soil and water salinisation;
- controlling groundwater withdrawals and favouring aquifers recharge;
- minimising water wastes; and
- managing the water quality.

Summarising, coping with water scarcity requires measures and policies of water management that may be grouped into two main areas: demand and supply management. These two complementary facets of water management are presented and discussed in the following sections preceded by a short review on concepts relative to water use, consumption, losses and performances to base the analyses on supply and demand management, which is the main objective of this paper.

## 2. Water use, water losses and irrigation performances

The term efficiency is very often used to express irrigation systems performance. It is commonly applied to each irrigation sub-system: storage, conveyance, distribution off- and on-farm, and on-farm application sub-systems. 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 (Wolters, 1992; Bos, 1997; Pereira, 1999). However, it is often misused, mainly when adopted as synonymous of irrigation performance.

The concept of efficiency is not enough to evaluate the performance of reservoir, conveyance and distribution systems when is intended to assess the reliability and flexibility of deliveries required for improved demand management. IWMI research produced innovative issues on this respect mainly oriented for surface systems (e.g. Murray-Rust and Snellen, 1993; Renault, 2000; Renault and Vehmeyer, 1999). Reviews and application analysis are presented by Bos (1997) and Sanaee-Jahromi and Feyen (2001). Lamaddalena and Pereira (1998), Lamaddalena and Sagardoy (2000), and Pereira et al. (2001) give examples on related performance analysis applied to pressurised systems. A wide review on performance indicators for irrigation systems is presented by Malano and Burton (2001).

Another efficiency term often used is water-use efficiency (WUE). This is defined by the ratio between the crop biomass or grain production and the amount of water consumed by the crop, including rainfall, or the irrigation water applied, or the crop transpiration (Oweis et al., 1998; Zhang et al., 1998; Oweis and Zhang, 1998; Zhang and Oweis, 1999). The WUE indicator defined by those ratios is useful to identify the best irrigation scheduling strategies for supplemental irrigation (SI) of cereals (Zhang and Oweis, 1999), to analyse the water saving performance of irrigation systems and respective management (Ayars et al., 1999), and to compare different irrigation systems, including deficit irrigation (Howell et al., 1995; Scheneider and Howell, 1995). However, there is a source of confusion in terminology because the same term WUE is used to analyse plant performances when defined by the ratio between assimilation and transpiration rates (Steduto, 1996; Steduto et al., 1997). Sometimes the term WUE is used as synonymous of application efficiency (AE, %) or irrigation efficiency. Probably, the term WUE should be used as indicator of the plants performance as applied by crop physiologists, while the irrigation performance relative to crop yield would better be replaced by another term such as water productivity (WP), as adopted in this paper. In any case, it should not be used as synonymous of irrigation efficiency.

It is commonly said that improving irrigation efficiencies is paramount under water scarce situations because high efficiency would represent conditions of near optimal use of the water. This is generally true when the idea behind is that less water should be abstracted from surface or ground waters to produce a certain yield. However, when achieving high efficiencies would be considered as producing water savings, this is not entirely true. To avoid misunderstandings in the use of the term efficiency, Jensen (1996) proposed the term consumptive use fraction to designate the ratio between the quantity of water consumed by the irrigated crop and the amount of water diverted to the irrigation system, therefore, making a distinction between water used and water consumed.

Along these lines, Allen et al. (1997) and Burt et al. (1997) proposed 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 the irrigation system or sub-system under consideration. These concepts are summarised in Table 2. Using these concepts it can be concluded that water losses are

Table 2
Irrigation water consumption, use and losses (adapted from Allen et al., 1997 and Burt et al., 1997)

| | Consumptive | Non-consumptive and non-reusable | Non-consumptive but reusable |
|---|---|---|---|
| Beneficial uses | Crop ET | Leaching added to saline water | Leaching water added to reusable water |
| | Evaporation for climate control | Water incorporated in product | |
| Non-beneficial uses | Excess soil water and phreatophyte ET | Deep percolation added to saline groundwater | Reusable deep percolation |
| | Sprinkler evaporation | Drainage water added to saline water bodies | Reusable run-off |
| | Canal and reservoir evaporation | | Reusable canal spills |
| | Evaporated fraction | Non-reusable fraction | Reusable fraction |

only those corresponding to the non-beneficial consumptive uses and the non-reusable quantities of diverted water. However, in the case of saline environments, part of the water losses is beneficial to the crop and the soil because it is used for the leaching of salts and, therefore, cannot be avoided. The non-consumptive but reusable quantities of water are in reality not lost because other users downstream can use them again, or they can be reused in the same system when reuse facilities are available.

When not used for salts leaching, the reusable fraction, like the non-reusable one, is due to poor or less good management, hence, it is often considered lost. In fact it is a temporary loss of the system that contributes to the operation and management costs and may be detrimental when the competition among users is considered. However, under a hydrological perspective, or in terms of the overall water resources economy, it is not a loss.

These water-use indicators are yet far from common usage but they have the potential to be very useful for water resource planning and management at the basin and project, or system scales. For farm irrigation, indicators for the uniformity of water distribution are still of great usefulness.

Assuming the concepts above, it can be said that improving the irrigation efficiencies is of great importance under water scarcity conditions because high efficiencies correspond to increased beneficial uses of the water. Nevertheless, other complementary objectives related to those water-use indicators have to be considered as follows:

- controlling the non-beneficial consumptive uses, particularly those associated with soil evaporation, and evapotranspiration by phreatophytes and weeds receiving seepage and excess irrigation water;
- minimising the non-reusable fraction of the diverted water, thus, avoiding percolation to saline water tables or the disposal of run-off return flows into saline water bodies where the water quality would be degraded; and
- reducing the non-beneficial but reusable fraction by controlling deep percolation, seepage from canals, run-off return flows and canal excess water spills, which have negative impacts on operation and management costs and may be the cause for water-logging, competition by weeds, loss of nutrients and agro-chemicals, contamination of water bodies used for human consumption, and could cause yield and income losses.

These objectives are not explicitly used in the discussion that follows, but they constitute a coherent base to decide on the supply management and demand reduction measures and practices required to cope with water scarcity referred below. However, these measures and practices are not exclusive for water scarcity and many also apply to less stringent water availability conditions since a more efficient use of irrigation water is an essential trend in today's irrigation (NRC, 1996).

## 3. Supply management

### *3.1. General aspects*

The importance of supply management strategies to cope with water scarcity in irrigation is well identified in the literature and observed in practice. It is referred herein because there is a strong interdependence between supply and demand management. On the one hand, supply measures such as those referring to water of inferior quality can only be properly applied when farm irrigation is improved. On the other hand, the effective adoption of reduced demand management can be hampered by limitations in the supply system such as the delivery scheduling modes (cf. Goussard, 1996; Sanaee-Jahromi et al., 2000; Santhi and Pundarikanthan, 2000).

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 reviewed later.

Supply management may 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. (2002).

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 run-off, 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 semi-arid and arid zones (Tauer and Humborg, 1992; Prinz, 1996; Oweis et al., 1999; Sharma, 2001).

### 3.2. 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 (see, 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 (WHO) 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 may be classified as follows (Mara and Cairncross, 1989, Pescod, 1992):

- *High risk* (*high incidence of excess infection*): Helminths (*Ancylostoma*, *Ascaris*, *Trichuris* and *Taenia*).
- *Medium risk* (*medium incidence of excess infection*): Enteric bacteria (*Vibrio cholera*, *Salmonella typhosa*, *Shigella*).
- *Low risk* (*low incidence of excess infection*): Enteric viruses.

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. An analysis on the use of treated wastewater in small communities is presented by Oron et al. (1999). 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 (Arar, 1988). Adopting a level of treatment as low as possible but achievable is desirable, especially in developing countries. Treatment to remove constituents that may be toxic or harmful to crops, aquatic plants and fish is normally not economically feasible. On the contrary, the removal of toxic elements and pathogens that may affect human health shall be considered. 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) and Loudon (2001). Several studies on treatment and reuse of wastewater are presented by Goosen and Shayya (2001).

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. The infection of field workers may result from direct contact with the crop or soil in the area where wastewater is used. Prevention is then required to minimise health hazards. In general, three levels of public health risk are considered (Westcot, 1997):

1. Highest risk to consumer, field worker and handler, which include any crops eaten uncooked and grown in close contact with wastewater effluent, and landscape irrigation with public access.
2. Medium risk to consumer, field worker and handler, include pasture, green fodder crops, crops for human consumption that do not have direct contact with wastewater, crops for human consumption normally eaten only after cooking or the peel of which is not eaten, and any crop under (C) when sprinkler irrigated.
3. Lowest risk to the consumer but field worker protection is needed. It refers to crops not for human consumption, crops to be processed by heat, drying, canning or other processing that effectively destroys pathogens before human consumption, and animal fodder and feed crops that are sun-dried and harvested before consumption by animals (hay, silage).

International guidelines for the microbiological quality of irrigation water were established by the WHO (Mara and Cairncross, 1989). These standards are most often used for process control at wastewater treatment plants but should be enforced in monitoring irrigation systems using wastewater. Three categories of crops are identified corresponding to the risk levels enumerated above. The WHO guidelines concern the following:

- the number of intestinal nematodes (helminths), which arithmetic mean, number of eggs $l^{-1}$, shall be 1 for categories A and B earlier;
- the number of faecal coliforms, which geometric mean number per 100 ml shall be 1000 for category A and variable with local conditions for category B;
- the expected treatment level required, which corresponds to a series of stabilisation ponds designed to achieve the microbiological standard indicated above for category A, or equivalent to retention in stabilisation ponds for 8–10 days in case of category B, and pre-treatment as required by the irrigation technology but not less than primary sedimentation in case of category C.

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. Dissolved solids (TDS) in the irrigation water also affect the growth of plants and crop yields. TDS increase the osmotic potential and, therefore, growth and yield of most plants decline progressively as osmotic pressure increases accordingly to their sensitivity to the presence of salts in the soil and the irrigation water. Thus, when effluent and/or saline waters from groundwater or agricultural drainage are used, several factors related to soil properties must be considered as well as the phytotoxic effects of ions present in the water. However, long-term effects are not yet well known and more studies are required along these lines, e.g. the investigation described by Oron (1999) using drip irrigation and Yoon et al. (2001) relative to paddy rice irrigation.

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; Katerji et al., 2001). Thus, despite the relevance of the subject, this is not included herein except for the suitability of the irrigation methods relative to the use of wastewaters and saline waters, which is analysed hereafter.

## 4. Demand management

### 4.1. General aspects

Demand management for irrigation under water scarcity includes practices and management decisions of multiple nature: agronomic, economic, and technical, as summarised in Table 3. The objectives concern a reduction of irrigation requirements, the adoption of practices leading to water conservation and savings in irrigation, both reducing the demand for water at the farm, and an increase in yields and income per unit of water used. Virtual water, i.e. importing commodities having a large amount of water "virtually" embedded in the product to focus production on other commodities that require less water or that consist in well adapted cash crops, is considered a promising issue for demand management (Bouwer, 2000). However, impacts of related policies are very different when large, market

Table 3
Farm irrigation management under water scarcity

| 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 run-off 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 |

oriented farms are concerned or, on the contrary, small farms oriented to produce staple food, which are the majority in water scarce areas, would be affected. The first may easy adapt to new market orientations but the latter generally do not have the means and flexibility to change farming systems. Economic and social impacts would then be enormous if virtual water policies are applied without appropriate support to small farmers. These aspects, among others of economic and social nature, require in-depth and innovative research.

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, 1990; Tarjuelo and de Juan, 1999), including the aspects relative to water allocation (Reca et al., 2001; Shangguan et al., 2002). Therefore, only irrigation practices related to demand management are discussed herein.

Often, issues for irrigation demand management refer mainly to irrigation scheduling (Endale and Fipps, 2001), therefore, giving a minor role to the irrigation methods. However, a combined approach is required (Pereira, 1996, 1999), particularly when wastewater and low-quality saline water are used.

Irrigation scheduling requires knowledge on (a) the crop water requirements and yield responses to water (cf. Allen et al., 1998), (b) the constraints specific to each irrigation method and irrigation equipment (cf. Pereira and Trout, 1999), (c) the crop sensitivity to salinity when water of inferior quality is used (cf. Ayers and Westcot, 1985; Rhoades et al., 1992; Minhas, 1996), (d) the limitations relative to the water supply system (cf. Goussard, 1996), and (e) the financial and economic implications of the irrigation practice (e.g. El Amami et al., 2001). The improvement of the irrigation method and the system performance requires the consideration of several factors mainly those influencing the hydraulic processes, the water infiltration and the uniformity of water application to the entire field (Burt et al., 1997; Pereira, 1999). The aspects that could be more relevant to demand management under water scarcity are briefly discussed below.

### 4.2. Improvement of the farm irrigation systems

Several performance indicators are currently used in farm irrigation (Burt et al., 1997; Pereira, 1999). The uniformity of water distribution to the entire field is commonly evaluated by the *distribution uniformity* (DU, %), which is defined by the ratio among the average infiltrated depths in the low quarter of the field and in the entire field, both expressed in mm. In sprinkler and micro-irrigation, the *coefficient of uniformity* (CU, %) is often used. However, CU and DU are well related (Keller and Bliesner, 1990), thus, just DU will be referred to in the following analysis.

The main farm irrigation efficiency indicator is the *application efficiency*, which can be better defined by the ratio between the average low quarter depth of water added to root zone storage and the average depth of water applied to the field, both expressed in mm.

Factors influencing the distribution uniformity and the application efficiency are summarised in Table 4, showing that the application efficiency depends upon the distribution uniformity (Pereira, 1999). In general, the distribution uniformity values observed are the upper limits of the application efficiencies when keeping the system variables unchanged. Useful relations between irrigation uniformity and crop yields have

Table 4
Main system and management variables that determine farm irrigation performances

| Irrigation systems | Distribution uniformity | Application efficiency |
|---|---|---|
| Surface irrigation | | |
| System variables | | |
| | Unit inflow rate | Unit inflow rate |
| | Furrow, border, or basin length | Furrow, border, or basin length |
| | Hydraulic roughness coefficient | Hydraulic roughness coefficient |
| | Longitudinal slope | Longitudinal slope |
| | Levelling precision | Levelling precision |
| | Soil infiltration characteristics | Soil infiltration characteristics |
| | Furrow, border, or basin form | Furrow, border, or basin form |
| Management variables | | |
| | Time of cut-off | Time of cut-off |
| | | Soil water deficit when irrigating |
| Sprinkler | | |
| System variables | | |
| | Pressure available at the sprinkler | Pressure available at the sprinkler |
| | Pressure variation in operating set | Pressure variation in operating set |
| | Sprinkler spacings | Sprinkler spacings |
| | Sprinkler discharge | Sprinkler discharge |
| | Wetted diameter | Wetted diameter |
| | Sprinkler water distribution pattern | Sprinkler water distribution pattern |
| | Sprinkler jet angle | Sprinkler jet angle |
| | Wind speed and direction | Wind speed and direction |
| | | Soil infiltration characteristics |
| | | Application rate of the sprinkler |
| Management variables | | |
| | Maintenance | Maintenance |
| | | Duration of the irrigation event, |
| | | Soil water deficit when irrigating |
| Micro-irrigation | | |
| System variables | | |
| | Pressure at emitters | Pressure at emitters |
| | Pressure variation in operating set | Pressure variation in operating set |
| | Flow regime of the emitter | Flow regime of the emitter |
| | Emitter variations in discharge | Emitter variations in discharge |
| | Emitter coefficient of manufacturing variation | Emitter coefficient of manufacturing variation |
| | Filtering capabilities | Filtering capabilities |
| | | Hydraulic conductivity of the soil |
| | | Soil infiltration characteristics |
| Management variables | | |
| | Maintenance | Maintenance |
| | | Soil water conditions at irrigation |
| | | Duration of the irrigation |
| | | Irrigation frequency |

been made available (e.g. Warrick and Yates, 1987). However, they have not been explored enough in practice.

### 4.2.1. Surface irrigation

Several irrigation methods are used. In basin irrigation water is applied to levelled surface units (basins) having complete perimeter dikes and whose best performances are obtained when field surface is precisely levelled and the advance time is minimised. Basin irrigation is the most common method world-wide. Furrow irrigation is a method where water is applied to furrows using small discharges to favour water infiltration while advancing down the field. In border irrigation water also infiltrates while advancing but on short or long strips of land, diked on both sides and open at the downstream end. In general, surface irrigation systems are not able to apply small but only large irrigation depths.

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.

In surface irrigation, the uniformity DU depends mainly upon the system variables (Table 4), which, to some extent, may be modified or adapted by the irrigator. The management variable time of cut-off is controlled by the irrigator, but it depends on the system variables that determine the advance time. The application efficiency is dependent on the same variables as DU, and on the farm management variables time of cut-off and soil water deficit at time of irrigation. However, DU is also affected by the soil moisture conditions in cracking soils, particularly when due to limited water availability large time intervals are practised (Zairi et al., 1998). In such circumstances, when large and deep cracks exist, the water distribution is quite uneven and deep percolation is unavoidable, with more water being required to refill the soil than under less developed soil cracking (Zairi et al., 1999).

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.

The importance of uniformity in surface irrigation is well evidenced in literature. Sousa et al. (1995) have shown impacts of DU on maize yields and irrigation demand. 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. Among others, Pitts et al. (1996) present an interesting analysis of field assessment of irrigation performances.

Table 5
Potential water demand reduction in winter wheat basin irrigation in the North China Plain when inverted downstream slopes would be corrected, as influenced by the available inflow rates (Li and Calejo, 1998)

| Inflow rate ($l\ s^{-1}\ m^{-1}$) | Winter irrigation (mm) | First spring irrigation (mm) | Second spring irrigation (mm) | Third spring irrigation (mm) | Total (mm) |
|---|---|---|---|---|---|
| 2.5 | 94 | 104 | 79 | 47 | 324 |
| 3.0 | 80 | 82 | 67 | 34 | 263 |
| 3.5 | 70 | 74 | 61 | 25 | 230 |
| 4.0 | 64 | 68 | 53 | 16 | 201 |
| 4.5 | 54 | 58 | 50 | 16 | 178 |

An example from the North China Plain, where water for irrigation is becoming increasingly scarce, shows that a main factor to improve irrigation performances and reduce irrigation water use is the adoption of more even surface slopes in basin irrigation. The farmers' practice is to cut the irrigation inflow when the advance is completed. Therefore, by correcting the negative slope in the downstream part of the field the advance times could be reduced and, therefore, also the inflow times. Appreciable water savings could then be achieved as shown in Table 5. Results show that the improvement of the basin slopes is more effective in reducing the advance time and the time duration of the irrigation when the inflow rate is small: potential demand reductions are close to 320 mm when the unit inflow rate is 2.5 $l\ s^{-1}\ m^{-1}$, and near 180 mm for 4.5 $l\ s^{-1}\ m^{-1}$ (Li and Calejo, 1998).

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. An example from the old Huinong system in the Ningxia Province of China, in the upper reaches of the Yellow River, is presented in Fig. 1. This is an arid zone, with average rainfall of less than 200 mm per year, where hundreds of years of irrigation produced the salinisation of many areas. Farmers control soil salinity by over-irrigating. The reduction of the demand for irrigation is required due to the scarcity of water in the Yellow River basin. This implies that the leaching fraction should be appropriately limited. Fig. 1 compares the present infiltration depths simulated after appropriate model calibration (Fabião et al., 2001) when land surface would be kept non levelled with an improved situation adopting precise levelling. For the first case (Fig. 1a) the uniformity is poor and over-irrigation would be practised when the objective would be to apply a 10% leaching fraction to the entire field. Changing the inflow rate from the present 1.3–3.0 $l\ s^{-1}\ m^{-1}$ would not modify the irrigation performance. The gross irrigation depth would be much larger than the target. On the contrary, adopting precise land levelling leads to quite uniform infiltration depths (Fig. 1b) 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 DU 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.

When surface irrigated areas are supplied from collective irrigation canal systems, farm irrigation scheduling depends upon the delivery schedule, e.g. discharge rate, duration and

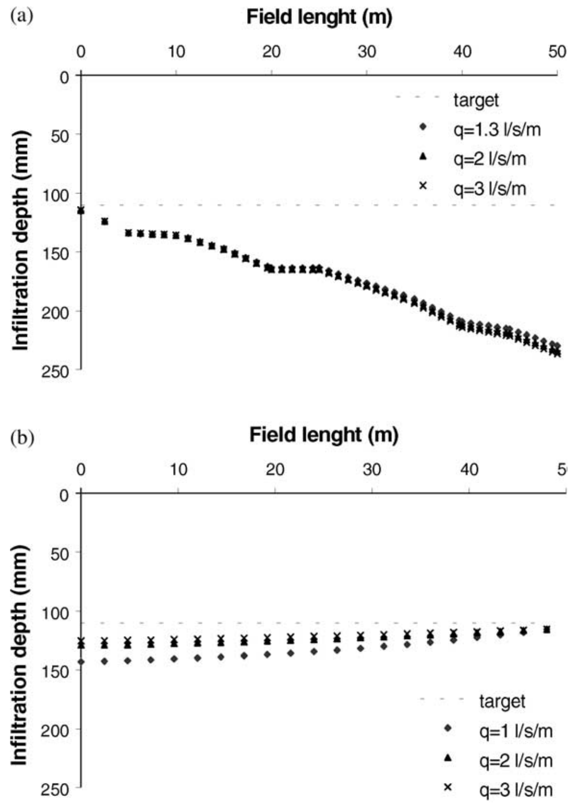


Fig. 1. Basin infiltration depth curves simulated for: (a) present field surface conditions, and (b) precision zero levelled basin, for a target infiltration depth of 100 mm and 10% leaching fraction, and inflow rates ranging from 1 to 3 $l\,s^{-1}\,m^{-1}$, Huinong Irrigation District, Ningxia, China (adapted from Fabião et al., 2001).

frequency, which are dictated by the system operational policies. Discharge and duration impose constraints to the volume of application, while frequency determines the timing of irrigation. Surface irrigation delivery systems are often rigid and the time interval between successive deliveries is too long. In this case, farmers apply all the water that is made available and often practice over-irrigation. Therefore, improving the farm irrigation systems with the aim of reducing the demand should go together with the betterment of the delivery systems to allow more flexibility for selecting the appropriate inflow rate and supply time.

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). An example of an improved irrigation schedule for winter wheat in the North China Plain (Table 6) shows that the irrigation demand can be reduced by near

Table 6
Comparing current and optimal irrigation depths for winter wheat in Xiongxian, North China Plain, for different climatic demand probabilities using basin irrigation (Fernando et al., 1998)

| Irrigation dates | Actual irrigation depths (mm) | | Irrigation depths under system constraint (mm) | | Target irrigation depths (mm)when land levelling would be improved | | |
|---|---|---|---|---|---|---|---|
| | Observed range | Observed average | More favourable slope | Less favourable slope | Average | Dry year | Very dry year |
| At planting | 90–230 | 156 | 70 | 75 | – | 70 | 70 |
| Winter | 116–142 | 129 | 105 | 115 | 90 | 90 | 90 |
| Spring | 116–140 | 124 | 100 | 110 | 80 | 80 | 80 |
| At heading | 119–143 | 133 | 80 | 85 | 80 | 80 | 90 |
| At filling | 84–117 | 97 | 70 | 75 | 80 | 90 | 100 |
| Total | | 640 | 425 | 460 | 330 | 410 | 430 |
| Demand reduction | | | 215 | 180 | 155 | 230 | 210 |

200 mm when both the irrigation system and the irrigation schedules are improved (Fernando et al., 1998).

#### *4.2.2. Sprinkler Irrigation*

Sprinkler systems include set, travelling rain-guns and continuous move lateral systems. Set systems can apply small to large water depths and are the best adapted for small farms. A wide range of sprinklers can be selected for a variety of crops and soils. Travelling guns generally have relatively high application rates, require high pressure, and are not appropriate for small fields or to apply either very small or very large depths. They are not suitable to irrigate heavy soils, sloping lands, sensitive crops and under arid windy conditions. The continuous move laterals are designed for large farms and to apply small and frequent irrigations but application rates are generally very high.

The irrigation uniformity depends essentially on variables characterising the system (Table 4), which are set at the design phase. Similarly, the application efficiency 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. An example of identification of problems in operating sprinkler systems is presented in Table 7. These results indicate that the systems are often less well designed causing problems that affect DU, and, therefore, the farmers do not really control the depths applied. Results shown by Pitts et al. (1996) are somewhat similar. Problems are aggravated when maintenance is poor (Louie and Selker, 2000).

Table 7
Main causes for low irrigation performances identified from field assessment in France (adapted from Dubalen, 1993)

| Problems | Travelling guns (% observations) | Solid set systems (% observations) |
|---|---|---|
| Application depths different from expected | | |
| 10–20% differences | 30 | 25 |
| Differences larger than 20% | 46 | 34 |
| Low uniformity due to | | |
| Excessive spacings | 65 | 70 |
| Pressure variation (>20%) | | 56 |
| Asymmetric wetted angle | 59 | |
| Variable advance velocity (>20%) | 39 | |
| Insufficient pressure | 38 | 20 |
| Excessive pressure | 10 | 22 |

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 design (Keller and Bliesner, 1990; Seginer, 1987) as well as to use DU when optimising crop patterns (Tarjuelo et al., 1996). 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.

*4.2.3. Micro-irrigation*

Micro-irrigation includes drip, micro-sprinkling, and sub-irrigation systems. These systems are generally designed to apply small and frequent irrigations.

Micro-irrigation uniformity, as for sprinkler DU, depends upon the system variables, i.e. with the exception of maintenance, the farmer can do little to achieve good distribution uniformity (see Table 4). The application efficiency, depends mainly upon the same system variables as DU and on management variables related to the duration of the irrigation and irrigation frequency. Therefore, the farmer may improve AE when adopting appropriate irrigation schedules but performances are limited by the system constraints.

Field evaluations also play an important role in advising farmers, creating information for design of new systems, and for quality control of design and services. Results of field evaluation show that irrigation performances are often lower then expected. Pitts et al. (1996) referring to the evaluation of 174 micro-irrigation systems in the USA, found an average DU = 70%, with 75% of cases having DU below 85%. The low DU were mainly due to inappropriate water filtration and poor selection of emitters, namely concerning their manufacturing characteristics. Results shown by Capra and Scicolone (1998) provide further evidence about these problems.

Uniformity in micro-irrigation affects the water saving capabilities of the systems and, mainly, crop yields. The review by Bralts et al. (1987) underlines the usefulness of uniformity for design. Santos (1996) shows that the best yield for tomato (near 102 t $ha^{-1}$) was achieved for 470 mm of applied water when uniformity was 90%, while the maximum yield decreased to 85 t $ha^{-1}$ using 500 mm when uniformity was only 60%. The maximum revenue was 12% higher in the first case. 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.

### 4.3. Suitability of the 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 the following:

- 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 run-off; and
- crop stress and yield reduction, including that due to inability to maintain adequate water availability in the soil.

From the analysis of the characteristics of the irrigation systems, the respective management limitations, or the easiness to apply the most appropriate practices to minimise those risks, the main aspects characterising the suitability of the irrigation methods to be adopted for saline water irrigation are summarised in Table 8.

In case of wastewater irrigation, the suitability of the irrigation methods is considered by minimising the following:

- 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.

Table 9 summarises the main aspects influencing the suitability of irrigation methods for applying wastewater.

When analysing Tables 8 and 9, it becomes apparent that the sprinkler systems and, to a certain extent, the 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). In case of effluents from agricultural processing industry, which generally are not associated with health, contamination and toxicity risks, sprinkler

Table 8
Suitability of the irrigation methods for irrigation with saline water

| Irrigation method | Salt accumulation in the root zone | Foliar contact, avoiding toxicity | Ability to infiltrate water and refill the root zone | Control of crop stress and yield reduction |
|---|---|---|---|---|
| Basin irrigation | Not likely to occur except for the under-irrigated parts of the field when uniformity of water application is very poor; leaching fraction difficult to control in traditional systems | It is possible only for bottom leaves in low crops and fodder crops, and during the first stage of growth of annual crops | Adequate because large volumes of water are generally applied at each irrigation and water remains in the basin until infiltration is complete | Adequate because toxicity is mostly avoided, salts are moved down through the root zone, infiltration is com pleted and irrigation can be scheduled for |
| Corrugated basin irrigation | Salts tend to accumulate on the top of the ridge; l eaching prior to seeding or planting is required for germination and crop establishment | Exceptionally because crops are grown on ridges | As for flat basins, above | As for flat basins but de pending on avoiding salt stress at plant emergence and crop establishment |
| Border irrigation | As for basin irrigation but infiltration control is more difficult as well as the control of the leaching fraction | As for flat basins | Because water infiltrates while flowing on the soil surface, run-off losses increase when infiltration decreases | Crop stress is likely to occur due to reduced infiltration so inducing relatively high yield losses |
| Furrow irrigation | Salts tend to accumulate on the top of the ridge; leaching is required prior to seeding/planting | Exceptionally because crops are grown on ridges | Salinity induced infiltration problems cause very high run-off losses | Crop stress is very likely to occur due to reduced infiltration so inducing significant yield losses |
| Sprinkler irrigation | Not likely to occur with set systems except for the under-irrigated parts of the field; leaching difficult or impossible with equipment designed for light and frequent irrigation | Severe leaf damage can occur definitely affecting yields, mainly if frequent irrigation would be used | Salinity induced infiltration problems including soil crusting may cause very high run-off losses | Crop stress is very likely to occur due to toxicity by contact with the leaves and fruits, and reduced infiltration, thus significant yield losses may occur |

Table 8 (*Continued*)

| Irrigation method | Salt accumulation in the root zone | Foliar contact, avoiding toxicity | Ability to infiltrate water and refill the root zone | Control of crop stress and yield reduction |
|---|---|---|---|---|
| Micro irrigation: drip and subsurface irrigation | Not likely to occur except for the under-irrigated parts of the field due to low uniformity, including due to clogging when water filtration is poor | Not likely to occur | Problems generally do not occur except when there are not enough emitters and under-irrigation is practised | These systems are able to provide for crop stress and toxicity control, so yield losses are minimised |
| Micro irrigation: micro-sprinkling and microspray | Not likely to occur except for the under-irrigated parts of the field due to low uniformity and clogging; leaching easy to control | Leaf damage can occur, definitely affecting yields of annual crops but less for tree crops | Problems are similar to those for set sprinklers, so run-off losses may be important | Toxicity due to direct contact with the leaves and crop stress when non uniformity and run-off occur may cause high yield losses |

Table 9
Suitability of the irrigation methods for irrigation with wastewater

| Irrigation methods | Human contact (health hazard) | Contact with fruits and harvestable yield (contamination hazard) | Salt accumulation in the root zone (salinity hazard) | Foliar contact (toxicity hazard) |
| --- | --- | --- | --- | --- |
| Basin irrigation and border irrigation | Likely to occur, mainly when water is controlled manually; preventive measures including cloth required | Not occurring for tree crops and vines, and most of horticultural and field crops; may occur for low vegetable crops such as lettuce and melon | Not likely to occur except for the under-irrigated parts of the field when uniformity of water application is very poor | Possible for bottom leaves in low crops (e.g. lettuce, melon) and fodder crops; possible during first stage of growth of annual crops |
| Corrugated basin irrigation | Likely to occur when water is controlled manually, less when automation is adopted; preventive measures including cloth required | Not likely to occur because crops are grown on ridges | Salts accumulate on the top of the ridge; leaching prior to seeding/planting is required for germination and crop establishment | Exceptionally because crops are grown on ridges and water flows in furrows between them |
| Furrow irrigation | Likely to occur, when water is controlled manually, less when automation is adopted | Not likely to occur because crops are grown on ridges | Salts tend to accumulate on the top of the ridge; leaching is required prior to seeding/ planting | Exceptionally because crops are grown on ridges |
| Sprinkler irrigation | Generally workers are not in the field when irrigation goes on but they may have contact with wetted equipment | Fruits and harvestable yield are contaminated | Not likely to occur except for the under-irrigated parts of the field due to low uniformity | Severe leaf damage can oc cur definitely affecting yields |
| Micro irrigation: drip and subsurface irrigation | Not likely to occur except contact with wetted irrigation equipment | Not likely to occur | Not likely to occur except for the under-irrigated parts of the field due to low uniformity | Not likely to occur |
| Micro irrigation: micro-sprinkling, microspray | Generally workers are not in the field when irrigation goes on but they may have contact with wetted equipment | Fruits and harvestable yield of vegetable crops may be contaminated but fewer in under-tree irrigation with no wind | Not likely to occur except for the under-irrigated parts of the field due to low uniformity | Severe leaf damage can occur definitely affecting yields of annual crops but not for trees |

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. Consequently, system selection is more complex than the relatively simple analysis in Tables 8 and 9.

### 4.4. 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. Teixeira et al., 1995; Liu et al., 2000; Sarwar and Bastiaanssen, 2001) or are based on extensive field trials (e.g. Oweis, 1997).

When strategies for deficit irrigation are derived from multi-factorial field trials, as for the supplemental irrigation of cereals, the optimal irrigation schedules are often based on the concept of WP or, as often named, WUE (e.g. Oweis et al., 1998; Zhang et al., 1998; Oweis and Zhang, 1998; Zhang and Oweis, 1999). The symbol WP (kg m$^{-3}$) is used herein. Table 10 shows typical results on wheat obtained from field trials conducted in a Mediterranean climate in northern Syria. The results show significant improvement in the WP of supplemental irrigation when crop water requirements are not fully satisfied compared with full irrigation. Highest WP of applied water was obtained at rates between one-third and two-thirds of full irrigation requirements (one-third and two-thirds of SI) depending upon the season rainfall. The application of nitrogen fertilisers improved WP but at deficit supplemental irrigation lower nitrogen levels were needed. This shows that under deficit irrigation other cultural practices may need to be adjusted. Planting dates for example interact significantly with the level of irrigation applied. Optimum levels of irrigation to maximise WP need to consider all these factors as shown in Table 10.

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. As shown in Fig. 2 for durum wheat, maximum WP drops at high yield levels, i.e. maximising WP implies lower yields. In areas where water is the most limiting resource to production, maximising WP may be more profitable to the farmer than maximising crop yield. This is because the water saved when deficit irrigation is applied becomes available to irrigate more land since the latter is not the liming factor. In northern Syria it was found by ICARDA that applying 50% of full supplemental irrigation requirements would reduce yield by 10–15% while applying the saved water to lands otherwise rainfed increased the total farm production by 38% (Oweis, unpublished work). However, these figures may change with rainfall availability. Such relation as in Fig. 2 is important to determine the proper strategies for irrigation in areas where land or water is the most limiting.

Table 10
Water productivity of rain water for rainfed conditions and of supplemental irrigation water ($WP_{SI}$), and gross, rainfall and irrigation ($WP_{GROSS}$) for durum wheat grain yield in north Syria as influenced by the sowing date and the nitrogen rate (Oweis and Zhang, 1998)

| Sowing date | N (kg ha$^{-1}$) | $WP_{SI}$ (kg ha$^{-1}$ mm$^{-1}$) | | | | | $WP_{GROSS}$ (kg ha$^{-1}$ mm$^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 50 | 100 | 150 | Mean | 0 | 50 | 100 | 150 | Mean |
| November | Rainfed | 8.0 | 10.2 | 11.1 | 10.8 | 10.0 | 8.0 | 10.4 | 11.0 | 10.7 | 10.0 |
| | One-third of SI[a] | 6.3 | 27.2 | 15.7 | 25.2 | 18.6 | 7.4 | 12.8 | 12.4 | 13.6 | 11.5 |
| | Two-thirds of SI | 3.0 | 8.6 | 10.8 | 15.4 | 9.5 | 6.0 | 9.8 | 10.9 | 12.7 | 9.8 |
| | Full SI | 4.1 | 6.9 | 8.9 | 11.8 | 7.9 | 6.0 | 8.8 | 10.1 | 11.5 | 9.1 |
| | Mean | 4.5 | 14.2 | 11.8 | 17.5 | | 6.9 | 10.5 | 11.1 | 12.1 | |
| December | Rainfed | 9.6 | 11.3 | 12.2 | 11.6 | 11.2 | 9.6 | 11.2 | 12.2 | 11.6 | 11.2 |
| | One-third of SI | 4.9 | 12.4 | 9.9 | 13.4 | 10.1 | 8.8 | 11.5 | 11.8 | 12.0 | 11.0 |
| | Two-thirds of SI | 4.9 | 9.1 | 10.8 | 13.8 | 9.6 | 8.0 | 10.6 | 11.8 | 12.4 | 10.7 |
| | Full SI | 1.7 | 7.4 | 7.4 | 11.2 | 6.9 | 6.3 | 9.7 | 10.2 | 11.7 | 9.5 |
| | Mean | 3.8 | 9.6 | 9.4 | 12.8 | | 8.2 | 10.8 | 11.5 | 11.9 | |
| January | Rainfed | 9.1 | 10.5 | 11.4 | 10.1 | 10.3 | 9.1 | 10.7 | 11.4 | 10.4 | 10.4 |
| | One-third of SI | 13.3 | 23.4 | 18.4 | 16.8 | 18.0 | 10.0 | 13.1 | 13.5 | 11.8 | 12.1 |
| | Two-thirds of SI | 8.8 | 12.0 | 12.9 | 16.3 | 12.5 | 9.0 | 11.1 | 12.1 | 12.5 | 11.2 |
| | Full SI | 5.6 | 9.7 | 9.3 | 13.7 | 9.6 | 7.8 | 10.4 | 10.6 | 11.9 | 10.2 |
| | Mean | 9.2 | 15.0 | 13.5 | 15.6 | | 9.0 | 11.3 | 11.9 | 11.6 | |

[a] One-third and two-thirds of SI when only that fraction of irrigation requirement is satisfied with supplemental irrigation.

### 4.5. Deficit irrigation scheduling strategies

The generation of irrigation scheduling strategies for deficit irrigation is commonly produced through simulation models after these have been calibrated or validated for the local conditions. These models must include appropriate yield–water functions, or crop

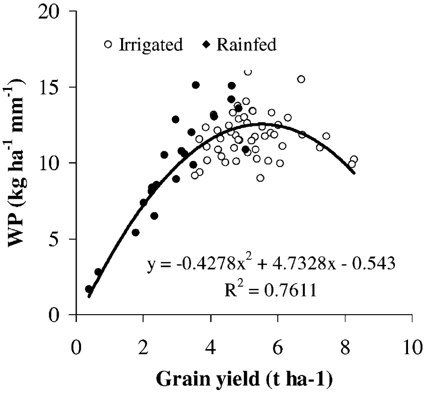


Fig. 2. Relationship between water productivity and grain yield for durum wheat in northern Syria (Zhang and Oweis, 1999).

growth and yield sub-models, to evaluate the yield impacts of water deficits (Pereira et al., 1995). The ISAREG model has been applied to establish irrigation schedules for drought in Portugal and Tunisia (Teixeira et al., 1995), and to evaluate alternative schedules for limiting the irrigation water demand in north China (Liu et al., 2000). It is used in several Mediterranean countries aiming at drought mitigation in irrigated agriculture. One application refers to supplemental irrigation of winter wheat and deficit irrigation of potato at Siliana, in the semi-arid central Tunisia, after validation at Hendi-Zitoune, central Tunisia (Zairi et al., 2001).

Results for the supplemental irrigation of wheat under average and very high climatic demand conditions using set sprinkler systems are presented in Table 11. The irrigation strategies are—SC: variable frequency (VF) and constant 40 mm irrigation depths; LDI: light deficit irrigation, adopting VF and one irrigation less than SC; DI, LID, VLID and EID: progressively more severe deficit irrigations by reducing one irrigation relative to the precedent strategy and adopting VF.

To each deficit irrigation strategy corresponds a relative evapotranspiration $ET_d/ET_c$ that induces a relative yield loss $Q_y = (1 - Y_d/Y_c)$, where $ET_c$ and $ET_d$ are the (potential) crop ET and the deficit crop ET, respectively and $Y_c$ and $Y_d$ are the grain yields corresponding to $ET_c$ and $ET_d$, respectively. An economic model (El Amami et al., 2001) was applied to evaluate the impacts of yield deficits on the farmers incomes and, therefore, to select if the full land should be irrigated with a deficit strategy or the irrigated land should be reduced in proportion to the available water. Results in Table 11 show that reducing the applied water leads to expected yield losses, which produce a decrease of the gross margins per unit surface cropped (GM $ha^{-1}$, expressed in USD $ha^{-1}$) but an increase in the gross margins per $m^3$ of water applied (GM $m^{-3}$, in USD $m^{-3}$). The percentage of land surface allocated

Table 11
Yield and economic results of alternative deficit irrigation strategies for a wheat crop in central Tunisia using sprinkler irrigation (Zairi et al., 2001)

| Deficit irrigation strategies | Season irrigation (mm) | Relative ET (%) | Relative yield loss (%) | Gross margin (USD $ha^{-1}$) | Gross margin (USD $m^{-3}$) | Optimal fraction area (%) allocated to each irrigation strategy |
|---|---|---|---|---|---|---|
| Average climatic demand conditions | | | | | | |
| SC | 240 | 100.0 | 0.0 | 1253 | 0.417 | 100/SC |
| LDI | 200 | 95.7 | 4.3 | 1228 | 0.491 | 100/LDI |
| DI | 160 | 87.5 | 12.5 | 1140 | 0.570 | 100/DI |
| LID | 120 | 78.7 | 21.3 | 1033 | 0.688 | 100/LID |
| VLID | 80 | 69.4 | 30.6 | 915 | 0.915 | 100/VLID |
| EID | 40 | 59.9 | 40.1 | 793 | 1.586 | 100/EID |
| Very high climatic demand conditions (severe drought conditions) | | | | | | |
| SC | 320 | 98.5 | 1.5 | 1102 | 0.275 | 100/SC |
| LDI | 280 | 93.2 | 6.8 | 1062 | 0.303 | 100/LDI |
| DI | 240 | 86.4 | 13.6 | 995 | 0.331 | 100/DI |
| LID | 200 | 78.8 | 21.2 | 910 | 0.364 | 50/DI + 50LID |
| VLID | 160 | 71.3 | 28.7 | 827 | 0.413 | 100/VLID |
| EID | 120 | 63.2 | 36.8 | 731 | 0.487 | 50/VLID + 50/VEID |
| VEID | 80 | 55.1 | 44.9 | 639 | 0.639 | 100/VEID |

to the crop for each irrigation strategy results from the economic balance between the financial return of the water and the land. Under average climatic demand conditions, results show that every deficit irrigation strategy corresponding to a reduction in water availability would be economically feasible since 100% surface would then be allocated to that irrigation strategy. On the contrary, for severe drought conditions the best economic response could imply a combination of different strategies. However, results show that deficit supplemental irrigation of winter wheat is generally feasible in this region of Tunisia, in agreement with results shown above for northern Syria.

A similar analysis performed for potato produced different results (Table 12). The deficit irrigation strategies are defined as in the case of wheat. When average climatic conditions prevail, the crop uses irrigation water in addition to relatively abundant rainfall, which makes all deficit irrigation feasible. Under drought, the climatic demand highly increases because rainfall is less available. Then, despite WP increases when less water is applied (results not shown), the GM $m^{-3}$ only increases for LDI and decreases afterwards for more severe deficits. Therefore, the best option for less available water is to crop only a fraction of the land and apply there the LDI irrigation schedule. The differences between wheat and potato result from different structure of production costs and prices of the products, particularly because wheat sub-products such as straw are highly valorised to feed animals during drought periods. Results indicate that establishing deficit irrigation to cope with water scarcity not only requires knowledge on crop demand for water and yield responses to water but also appropriate economic evaluation of alternative solutions.

Strategies for optimal deficit supplemental irrigation in rainfed areas depend upon rainfall amounts and distribution in addition to the sensitivity of crops to water stress at various growth stages. Zhang and Oweis (1999) have developed and used a quadratic wheat production function to determine the levels of irrigation water for maximising yield, net profit, and the levels to which the crop can be under-irrigated without reducing income

Table 12
Yield and economic results of alternative deficit irrigation strategies for a potato crop in central Tunisia under sprinkler irrigation (Zairi et al., 2001)

| Deficit irrigation strategies | Season irrigation (mm) | Relative ET (%) | Relative yield loss (%) | Gross margin (USD $ha^{-1}$) | Gross margin (USD $m^{-3}$) | Optimal fraction area (%) allocated to each irrigation strategy |
|---|---|---|---|---|---|---|
| Average demand conditions | | | | | | |
| SC | 160 | 100.0 | 0.0 | 3485 | 1.742 | 100/SC |
| LDI | 120 | 92.0 | 8.8 | 3037 | 2.024 | 100/LDI |
| DI | 80 | 80.5 | 21.4 | 2366 | 2.366 | 100/DI |
| LID | 40 | 68.3 | 34.8 | 1648 | 3.296 | 100/LID |
| Very high climatic demand conditions (severe drought) | | | | | | |
| SC | 320 | 100.0 | 0.0 | 3209 | 0.802 | 100/SC |
| LDI | 280 | 96.2 | 4.2 | 3032 | 0.866 | 100/LDI |
| DI | 240 | 87.5 | 13.8 | 2537 | 0.845 | 85/LDI |
| LID | 200 | 80.5 | 21.4 | 2159 | 0.863 | 71/LDI |
| VLID | 160 | 71.0 | 31.9 | 1612 | 0.806 | 57/LDI |
| EID | 120 | 60.1 | 43.9 | 976 | 0.650 | 42/LDI |

Table 13
Estimated amount (mm) and timing of supplemental irrigation for maximising wheat yield, the net profit or to attain a targeted yield under different rainfall conditions in north Syria (Zhang and Oweis, 1999)

| Rainfall (mm) | Supplemental irrigation (mm) | | | | | Time of irrigation |
|---|---|---|---|---|---|---|
| | $W_m$ [a] | $W_l$ [b] | $W_w$ [c] | $W_{cw}$ [d] | $W_t$ [e] | |
| Bread wheat | | | | | | |
| 250 | 430 | 336 | 260 | 161 | 158–254 | Stem elongation, booting, and grain filling |
| 300 | 380 | 286 | 210 | 111 | 108–204 | Stem elongation, flowering and/or grain filling |
| 350 | 330 | 236 | 160 | 61 | 58–155 | Flowering and/or grain filling |
| 400 | 280 | 186 | 110 | 11 | 0–144 | Grain filling |
| 450 | 230 | 136 | 60 | 0 | 0–55 | Grain filling |
| Durum wheat | | | | | | |
| 250 | 510 | 454 | 314 | 180 | 144–207 | Stem elongation, booting, and grain filling |
| 300 | 460 | 404 | 294 | 130 | 94–157 | Stem elongation, flowering and/or grain filling |
| 350 | 410 | 354 | 244 | 80 | 44–107 | Flowering and/or grain filling |
| 400 | 360 | 304 | 194 | 30 | 0–57 | Grain filling |
| 450 | 310 | 254 | 144 | 0 | 0 | – |

[a] Amount of water required for maximising grain yield.
[b] Amount of water required for maximising the net profit under limited land resources.
[c] Amount of water required for maximising the net profit under limited water resources.
[d] Amount of water required for deficit irrigation at which the net profit equals that at full irrigation.
[e] Amount of water required for targeted yield of 4–5 t $ha^{-1}$.

below that earned when full irrigation would be applied (Table 13). The analysis suggests that irrigation strategies to maximise crop yield and/or net profit as in the case of limited land resources should not be recommended. On the contrary, the analysis shows that for sustainable utilisation of limited water resources (and higher WP) a sound strategy would involve maximising profit. This conclusion is coherent with results obtained for Tunisia although the economic results do not fully agree because the structure of costs and prices is different in both countries.

The decision on optimal strategies under varying climate conditions is complex, especially in rainfed areas where rainfall variability is high. It was found by ICARDA work in Syria that spreading out the dates of sowing the wheat crop over the 3 months of November–January reduces the peak water demand during the supplemental irrigation period, in Spring. This reduction is greater when deficit irrigation is applied. An analysis was conducted using a simplified optimisation model to 4 years data (1992–1996) from field experimental research conducted on wheat in northern Syria. The results of the analysis showed that a multi-sowing date strategy would reduce the peak farm water demand by more than 20%, thus, a larger area could be supplied from the same source. However, optimal sowing dates that minimise farm water demand rate do not always maximise the farm income. The outcome depends on the irrigation water requirement and

Table 14
Optimal fraction ($A$) of the farm wheat cropped area to be sown at each date, minimised water demand rate, $R$ (mm per day), and the reduction $r$ (%) of the rate $R$ with respect to the early sowing date for different SI levels, wheat seasons 1992–1993 to 1995–1996 in north Syria (Oweis and Hachum, 2001)

| SI level | 1992–1993 | | | | | 1993–1994 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Fraction of area sown | | | $R$ (mm per day) | $r$ (%) | Fraction of area sown | | | $R$ (mm per day) | $r$ (%) |
| | $A_E$ | $A_N$ | $A_L$ | | | $A_E$ | $A_N$ | $A_L$ | | |
| One-third of SI | 0.78 | – | 0.22 | 4.07 | 12 | – | 0.36 | 0.64 | 4.65 | 14 |
| Two-thirds of SI | 0.19 | – | 0.81 | 4.50 | 5 | – | 0.74 | 0.26 | 4.75 | 20 |
| Full SI | – | 0.14 | 0.86 | 3.85 | 42 | 1.00 | – | – | 6.60 | – |
| | 1994–1995 | | | | | 1995–1996 | | | | |
| One-third of SI | 1.00 | – | – | 4.00 | – | 0.44 | 0.56 | – | 3.70 | 12 |
| Two-thirds of SI | 0.63 | 0.37 | – | 4.35 | 5 | 1.00 | – | – | 3.60 | – |
| Full SI | 0.46 | – | 0.54 | 5.30 | 13 | 1.00 | – | – | 4.20 | – |

$A_E$: early sowing, around mid-November; $A_N$: normal sowing, around mid-December; $A_L$: late sowing, around mid-January. SI: supplemental irrigation.

yield that correspond to each sowing date. Furthermore, the selection of sowing dates is greatly influenced by the level of water scarcity mainly related to rainfall distribution.

A similar analysis was performed for different supplemental irrigation levels. Table 14 presents the results expressed as the optimal fraction of the farm area to be sown at each date that minimise the overall farm water demand rate, $R$ (mm per day). The table also includes the percent reduction, $r$, of this demand rate as compared to the early sowing date. Applying deficit irrigation affects the optimal area allocated to each sowing date and generally reduces the overall peak water demand rate. However, this positive impact may not always result in maximum profit at the farm level. The irrigation costs also play a great role in this issue.

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.

## 5. Conclusions

The management of water under scarcity in irrigated agriculture includes multiple facets. These relate to the xeric regime, which is the cause for water scarcity, and to the nature of prevailing problems. Results for deficit irrigation presented herein make evident that related strategies show different economic responses under drought and are then more difficult to be applied, or even not feasible, when compared to non-drought conditions.

To build appropriate irrigation water management policies to cope with water scarcity, a wider agreement on concepts and performance indicators would be welcome. In general, policies should aim at reducing the non-beneficial water uses, particularly those corresponding to water consumption and to the non-reusable fraction of the diverted water. However, fully exploring these concepts, mainly for planning and management at basin and system scales, requires that appropriate procedures be developed.

Supply management aiming at higher reliability and flexibility of deliveries plays a major role to make reduced demand management effective because off-farm decisions affect farm irrigation systems management and irrigation scheduling decisions. Adding wastewaters and saline waters to the irrigation supply requires an appropriate control of health and environmental impacts. The impacts relative to wastewater reuse are related to the level of treatment of the effluents, the crops grown, the farming practices and the irrigation methods used. The main issues may concern monitoring, namely in relation to crop restrictions in areas using wastewater, and to the appropriate selection of suitable irrigation methods and practices. Similarly, for saline water use, monitoring and the appropriate choice of the irrigation methods and management should play also a major role for its safe use.

Reduced demand can be achieved by adopting improved farm irrigation systems and deficit irrigation. 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. When better uniformity is attained, conditions also exist to attain higher efficiencies and 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. Under such conditions maximising the return per unit of water may be more profitable than maximising the return per unit of land. This seems to be true for the supplemental irrigation of cereals but the consideration of other factors such as the level of fertilising and the sowing dates play also a major role. However, economic results at the farm level are greatly influenced by the amount of available rainfall when supplemental irrigation is considered. The review also shows that deficit irrigation of some crops may be feasible for average climatic conditions but not under drought, as in the example given of the potato crop. Water scarce areas need guidelines to determine irrigation schedules that maximise water productivity and farm profitability.

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