COMBATING DESERTIFICATION: WATER CONSERVATION AND WATER SAVING ISSUES IN AGRICULTURE

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Abstract

This paper refers to desertification in relation to other xeric regimes: aridity, drought and man-made water shortage. Their definitions are introduced and the respective water management issues discussed. The water conservation and water saving concepts are defined and the respective measures and practices are introduced focusing on man-made desertification and water shortage. Issues for water conservation and saving in agriculture are then analysed focusing: crop management practices, soil management for water conservation, demand management in irrigated agriculture, and supply management for irrigation.

Résumé

Cet article aborde le thème de la désertification par rapport aux autres régimes xériques : l'aridité, la sécheresse et la pénurie d'eau produite par l'homme. La définition de ces divers régimes est passée en revue afin d' analyser les aspects relatifs à la gestion de l'eau dans de telles conditions. Les concepts de conservation et d'économie d'eau sont discutés, en illustrant des mesures et des pratiques pour la gestion des cultures, la gestion du sol orientée à la conservation de l'eau, la gestion de la demande en agriculture irriguée et la gestion des approvisionnements en eau pour l'irrigation.

1. Desertification and Water Scarcity

At the edge of the XXI century, the sustainable use of water is not only a priority question for water scarce regions and for agriculture in particular, but for all users' sectors and regions. Imbalances between availability and demand, degradation of surface and groundwater quality, inter-sectorial competition, inter-regional and international conflicts, all bring the water issues to the foreground.

Decades ago, water was viewed as a non-limited natural resource because it was renewed every year in the course of the seasons. Man progressively appropriated this resource and used it with too few restrictions. Developments in controlling and diverting surface waters, exploring groundwater, and in using water for a variety of purposes have been made without enough care about conserving the natural resource, avoiding wastes and misuses, and preserving its quality. Thus, nowadays, water is becoming scarce not only in arid and drought prone areas, but also in regions where rainfall is relatively abundant. Water scarcity is now viewed under the perspective of the quantities available for economic, social and nature uses, and also embraces the quality of water because degraded water resources become unavailable or at least lesser available for human and other more stringent uses.

Worldwide, agriculture is the sector with the highest demand for water, largely overtaking the demand from other human and economic activities in water scarce regions. Thus, irrigated agriculture is often considered the main cause for water scarcity, and irrigation is accused of misuse of water, producing excessive water wastes, or degrading the water and land quality. However, irrigated agriculture is supporting the living of an enormous part of the world rural population and provides for a large fraction of the world's food. Recognisable efforts from innovation and practice, or from funding agencies and managers, are continuously providing issues to improve irrigation water management, control negative impacts of irrigation, conserve and save water, use low quality saline and wastewater, increase yields and farmers incomes. Similarly, great progress in engineering and management are producing new issues for water use and water quality control for non agricultural uses, including domestic and industrial uses. The sustainable use of water implies resource conservation, environmental friendliness, technological appropriateness, economic viability, and social acceptability of development issues. The adoption of these sustainability facets is a priority for using water in every human, economic and social activity particularly in water scarce regions.

Water scarcity may result from a range of phenomena. These may be produced by natural causes, may be induced by human activities, or may result from interaction of both, as indicated in Table 1 (Pereira et al., 2002a).

Table 1. *Xeric regimes*

Xeric regimes	Nature-produced	Man-induced
Permanent	*Aridity*	*Desertification*
Temporary	*Drought*	*Water shortage*

Aridity is a nature-produced permanent imbalance in the water availability consisting in low average annual precipitation, with high spatial and temporal variability, resulting in overall low moisture and low carrying capacity of the ecosystems.

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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, of unpredictable or less-predictable occurrence, resulting in diminished water resources availability, and reduced carrying capacity of the ecosystems. Many other definitions of drought exist; e.g. the U. S. Weather Bureau defined drought (Dracup et al., 1980) as a lack of rainfall so great as so long continued to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and the operation of power plants especially in these regions where rainfall is normally sufficient for such purposes.

These definitions clearly state that drought is mainly due to the break down of the rainfall regime, which causes a series of consequences including agricultural and hydrological hazards associated with the severity and duration of rainfall lack.

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 commonly associated with desertification. Desertification occurs in arid, semi-arid and subhumid 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, many of them focusing on land degradation, so giving to water a relatively less important role. This is the case for the definition used by the UNCCD, where desertification refers to the degradation of the land in arid, semi-arid and sub-humid zones resulting from various factors including climatic variation and human activities. However, these definitions need to be broadened in scope to focus attention on the water scarcity issues. When dealing with water scarcity situations, it seems more appropriate to define desertification in relation to the water imbalance produced by the misuse of water and soil resources, so calling attention to the fact that the misuse of water definitely is a cause for desertification.

Water shortage is also a man-induced but temporary water imbalance which may result from general excessive exploitation of available resources. For example withdrawals may exceed groundwater recharge, surface reservoirs may be of inadequate capacity and land use may have changed, revising the local ecosystem and altering the infiltration and runoff characteristics. Degraded water quality is often associated with water shortages and exacerbates the effects of water scarcity. There is no widely accepted definition for this water scarce regime and the term "water shortage" is often used synonymously with water scarcity. However it is important to recognise that water scarcity can result from human activity, either by over-use of the natural supply or by degradation of the water quality. This man-induced water scarcity is common in semi-arid and sub-humid regions where population and economic forces may make large demands on the local water resource, and where insufficient care is taken to protect the quality of the precious resource. Therefore, water shortage may be considered as a first or inductive stage of desertification.

Water quality is an expanding problem. Surface waters become more polluted - low dissolved oxygen and increased fecal coliforms - in developing countries, this trend being reversed in high income countries (The World Bank, 1992). Health problems are there particularly acute with 900 millions of people affected by diarrhoea each year and many other water vectored diseases are spread in the developing countries. This brings water shortage related to water quality to the foreground.

Desertification should be also seen under a broader perspective where the space scale for land is wide and embraces both agricultural and non-agricultural land as well as the respective water resources. Then impacts relate not only to the natural resources and the land productivity but also with the social and economic behaviour of populations living in the affected areas (Pereira et al., 2004). Assuming such a wide scale, it may be understood that when aridity conditions prevail in a given area, desertification is favoured by droughts and by man-made water shortages since these xeric regimes increase the human pressure on the natural resources and, therefore, create conditions for the degradation of land and the living conditions of related populations.

2. Water Management Issues

Policies and practices of water management under water scarcity must focus on specific objectives according to the causes of water scarcity. An integrated technical and scientific approach is essential to develop and implement the management practices appropriate to deal with water scarcity. Policies and practices must base on the assumption that water will not become abundant, so that water management policies and practices have to be appropriate to cope with water scarcity.

To cope with water scarcity means to live in agreement with the environmental conditions specific and dictated by limited available water resources. For millennia, civilisations developed in water scarce environments and the cultural skills that made it sustainable to live under such conditions are an essential heritage of those nations and peoples. Progress in the XX century questioned the traditional indigenous know-how, which has often been replaced by modern technologies and management rules directly imported from other areas having different physical and social environments. Water consumption and demand increased everywhere for domestic and urban uses, for agriculture and irrigation, for the industry and energy production, for recreation and leisure. However, such increase became particularly evident in the regions where water is scarce or, at least, not abundant. Therefore, the man- made xeric regimes are now adding to the natural water scarce conditions, generally aggravating the existing situation.

Solving water management problems faced in water scarce regions call for innovative issues to cope with water scarcity. Innovation includes the adaptation of the traditional know-how to the nowadays challenges, the adaptation of the external available technologies to the prevailing physical and social conditions, and the creation of new and well adapted technologies and management issues. Innovation must assume that man has to cope with the environmental constraints and that engineering and managerial solutions must be specific to the existing causes for water scarcity, including the man-induced desertification and water shortage.

Drought is often considered together with desertification since droughts favour mining of groundwater to face the lack of rainfall and surface waters, and the use of low quality and non-conventional water resources is then maximal, which may contribute to land degradation.

Water management under drought requires measures and policies that are common to other water scarcity regimes such as those oriented to avoid water wastes, reduce demand and make water use more efficient. But the peculiar characteristics of droughts imply specific measures. Inappropriate water management to cope with droughts is a way to induce desertification. A better understanding of droughts is essential to develop tools for prediction/forecasting of drought initiation and ending, at least to clearly recognise when a drought has begun or has come to an end. This is essential to timely and appropriately enforcing drought mitigation measures. An adequate lead-time - the period between the release of the prediction and the onset of the predicted hazard - is more important than the accuracy of the prediction because it makes it possible that decision and policy makers implement in time the policies and measures required to mitigate the effects of drought. In case of agriculture the lead-time is essential to make it possible that farmers take the decisions required, including relative to cropping patterns and cultivation systems. Early warning does not provide a lead-time as long as prediction but it definitely helps the timeliness of decisions.

Because droughts are nearly unpredictable, preparedness measures are paramount to cope with droughts. As they have pervasive long-term effects and their severity may be very high, appropriate reactive measures are required. The break in the natural water supply implies changes in water allocation and delivery policies, as well as in the management of water supply and irrigation systems. Water supplies may be reinforced using non-conventional waters, including wastewater and low quality waters, thus requiring the enforcement of appropriate policies to control the respective impacts. Diminished water supplies during droughts require that farmers and other users be able to adopt reduced demand and efficient water use practices. Incomes of farmers and other users may be drastically reduced, so financial support measures are also required complementing reactive measures. Among preparedness and reactive measures, water pricing and penalty policies may contribute to the effectiveness of drought management measures. Last but not least, the awareness of populations about drought water scarcity must be developed to create a worldwide behaviour oriented to reduce water wastes, induce water savings and favour water conservation practises.

Because desertification and water shortage are man-induced and are associated to problems such as soil erosion, land degradation, mainly through salinisation, over-exploitation of soil and water resources, and water quality degradation, require that policies and measures be oriented to solve the existing problems. Therefore, combating desertification and water shortage includes:

- re-establishing the environmental balance in the use of natural resources,
- enforcement of integrated land and water planning and management policies,
- restoring the soil quality, including the adoption of soil and water conservation measures,
- defining new policies for water allocations favouring reduced demand and water conservation practises,
- controlling ground-water abstractions and developing measures for recharging the aquifers,
- minimising water wastes,
- combating soil and water salinisation,
- controlling water withdrawals,
- adopting policies and practices for water quality management, and
- installing policies of economic incentives to users, including relative to water prices, and penalties for misuse and abuse of natural resources.

Coping with water scarcity requires that measures and policies of water management be in line with the challenging and widely accepted concept of sustainable development. It calls for new approaches on development and, therefore, on water and soil resources management. This is not only a question of new technologies and management issues for allocating and controlling the water and land uses. There is the need for considering the driving forces commanding the pressures on the resource itself, the behaviour of the users, and the human and social objectives. Despite the enormous progress of technological and managerial tools that are becoming available to improve management, we still have many gaps in knowledge and, mainly, in transferring scientific and technological knowledge into practice. Thus, adopting the concept of sustainability, water management to cope with water scarcity has to:

- be based on the knowledge of processes which can lead to resource degradation and to the conservation of natural resources;
- include resource allocation to non productive uses such as natural ecosystems;
- consider technological development not only for respond-

ing to production objectives but to control resource degradation and environmental impacts;
- value the non-productive uses of the land and water;
- prioritise the processes which help degradation processes to be reversed;
- include institutional solutions which support the enforcement of policies and rules and the social acceptability of decisions and measures for land and water management; and
- rely on clear objectives focusing not only on the natural resources by themselves and the economics of the returns from their use, but embracing also the human needs and aspirations.

Sustainable development facets base the issues referred above. Resource conservation and environmental friendliness are main issues in relation to water and soil. Appropriate technologies constitute an essential challenge to achieve policies and practices well adapted for problem solving. The economic viability of measures to be implemented is a condition for their adoption and a reason for financial incentives. The need for appropriate institutional developments is considered as a pre-condition for implementation of innovative issues, of technological, managerial, economic or social nature. Finally, the social acceptability of measures to cope with water scarcity is particularly related with the development of the social awareness on water scarcity problems and the inherent issues.

One promising issue is to consider water not only as a natural renewable resource but also as a social, environmental and economic good. Valuing water as an economic, marketable good may be insufficient since water acts not only for producing but is also supporting other natural resources and plays a major role in the human and social life, particularly when scarcity gives it a peculiar value. A coupled environmental, economic, and social approach is therefore required in valuing water in water scarce environments.

3. Water Conservation and Water Saving

3.1. Concepts

The terms water conservation and water savings are generally associated with the management of water resources under scarcity. Water conservation is used to every policy, managerial measure or user practice that aims at conserving or preserving the water resources, as well as combating the degradation of the water resource, including its quality. Water saving is adopted to every policy, managerial measure or user practice that aims at limiting or controlling the water demand and use for any specific finality, including the avoidance of water wastes and the misuse of water. In the practice both perspectives are complementary and inter-related. Although it is not easy to distinguish among them, these terms are not synonymous.

Water conservation and water saving measures and practices should be specific of the xeric regime and environmental conditions that prevail in a given area or region. However they have many facets that are common to all xeric regimes while the corresponding measures and practices should receive different importance and priority according to the water scarcity regime being considered. Those measures and practices are analysed by Pereira et al. (2002a) with reference to their relative importance for each xeric regime.

3.2. Water conservation and water saving to cope with desertification and water shortage

Desertification and water shortage are man induced and refer to problems such as land degradation by soil erosion and salinisation, over exploitation of soil and water resources, and water quality degradation. Therefore, they require that water conservation and water saving policies and measures combine with others oriented to solve the existing problems (Pereira et al., 2002a). Water conservation to combat desertification and water shortage should include:

(a) land and water uses planning and management for re-establishing the environmental balance of the natural and man-made ecosystems, as well as in the use of natural resources,
(b) appropriate reservoir and groundwater management rules, including artificial recharge and water quality preservation measures,
(c) water allocation policies that favour social and efficient uses of water, including criteria relative to water quality,
(d) measures and practices for water quality management and focusing on the control of related impacts on the environment, including monitoring,
(e) soil and water conservation practices in rainfed and irrigated agriculture, namely for erosion control,
(f) soil and crop management practices for restoring the soil quality, including soil moisture conservation,
(g) combating soil and water salinisation,
(h) strengthening the institutional framework for the implementation and enforcement of required policies and measures, and
(i) developing the public awareness for combating desertification and water shortage.

Water saving policies and practices play also a fundamental role in combating water scarcity due to desertification and water shortage. As for droughts, several measures and practices are generally common with those for coping with aridity (Pereira et al., 2002a). Others should be purposefully focusing the combat against desertification and water shortage:

(a) changes in crops and crop patterns for reducing the irrigation demand and taking advantage of soil moisture conservation,
(b) cropping and irrigation practices oriented to control non-point source pollution by agro-chemicals, fertilisers and erosion sediments,
(c) adoption of irrigation and drainage practices favouring

salinity management and reduced water demand,

(d) water recycling in industry and energy generation, and control of effluents quality to avoid pollution of surface- and ground-water,

(e) enforcing specific water price policies in relation to water use performances and the quality of effluents to favour adoption of practices that contribute to restoring the environmental balances,

(f) enforcing a policy of incentives and penalties in relation to users' adoption of tools and practices that contribute to restoring the water and soil quality and resource conservation,

(g) developing campaigns for end-users to adopt water saving and environmentally friendly tools and practices.

4. Water Conservation and Saving in Agriculture

4.1. Crop patterns and cropping practices

To cope with water scarcity, crops and crop varieties may be selected taking into consideration their tolerance to the water stress conditions characterising the environments where they are cultivated. In general, these crops correspond to centuries of domestication of plants native to these environments. However, new crops and new varieties have been introduced for the market not considering the prevailing environmental conditions and contributed to degrade the soil. But fortunately also other crop varieties are being introduced in water scarcity areas during the last decades following scientific plant breeding and improvement programmes.

Mechanisms of crop resistance to water stress include drought escape, avoidance and tolerance according to the nature of physiological and morphological processes and characteristics involved. Despite progress in plant breeding research, including genetic manipulation, results are still somewhat beyond expectations:

- it is too large the number of genes and characters with potential for altering the plant responses to water stress, thus making genetic manipulation difficult and slowly responsive,
- benefits of plant responses to water stress are commonly contradictory to yield responses, which create additional difficulties for plant breeding and improvement programs, moreover for the adoption by farmers of water stress resistance but low yield varieties,
- crop responses to water stress are influenced by other environmental and cultivation conditions, so making adaptive field tests more demanding and difficult.

Due to limitations of plant breeding programmes, research is also oriented to evaluate the photosynthetic, biomass and yield water use efficiency of crops (Steduto, 1996) commonly used in arid zones, mainly in connection with improved crop management techniques and practices. Among the most important practices are those relative to the selection of planting dates, responses to fertilisers, and soil management. Yield responses to supplemental irrigation are also considered when water is available during the water stress critical periods.

Water conservation in rainfed agriculture mainly refers to crop and soil management practices. Water conservation practices and techniques in crop management generally relate to three main approaches:

- Crop management to minimise the risks of crop failure and to increase the chances for successful crop yielding using the available rainfall. They refer to the selection of crops, crop varieties, planting dates, harvesting, and the use of supplemental irrigation for yield saving.
- Techniques and practices for controlling the water stress effects. They include soil management practices, the selection and management of the crop rotations and intercropping, the adoption of small planting densities, and appropriate fertilising strategies.
- Practices referring to increase soil water availability and control of soil water losses by evaporation and transpiration by weeds, as well as cultivation techniques to reduce transpiration and evaporation losses

4.2. Soil management for water conservation

Soil management practices are since long known to have positive impacts in water conservation. However, results depend upon the soil physical and chemical characteristics, the land forms and geomorphology, the climate and the implements used. All factors interact, thus creating variable responses.

Soil management practices for water conservation are summarised in Tables 2 and 3. They are often common with those for soil conservation, i.e. not only provide for augmenting the soil moisture availability for plant growth but also contribute to control erosion and soil chemical degradation. In many cases they contribute to improve the soil quality. Because these practices produce changes in soil infiltration and soil water storage, they may produce relatively important changes in the hydrologic balance at the local, field scale.

The soil management practices for water conservation can be grouped as follows:

- Improving water retention at the soil surface to control surface runoff and increase the time opportunity for infiltration. Since the time opportunity for infiltration is larger, the volume of water retained in the soil is increased; so more water becomes available for crop roots extraction. Because runoff is decreased the erosion by the surface water is also controlled. Practices included in this group are tillage methods for increasing the soil surface roughness and those relative to the creation of contour furrows, as well as surface mulching for roughness augmentation.
- Increasing the soil water storage capacity by modifying the soil physical properties that determine the soil water reservoir and soil water redistribution throughout the soil profile. Techniques include the control of soil compaction, the destruction of soil impermeable layers, the

Table 2. *Soil management techniques for augmenting soil infiltration and storage*

Soil management techniques	Benefits	Effectiveness
Water retention on the soil surface and runoff control		
▪ Soil surface tillage cultivation for increased surface roughness	▪ Storage of rainfall excess in micro depressions, larger time opportunity for infiltration	High (for low slopes)
▪ Contour and graded furrows	▪ Runoff and erosion control, and increased time for infiltration	High
▪ Residues and crop mulching	▪ Increased surface roughness and infiltration	High
▪		
▪ Furrow dikes	▪ Rain water storage in furrow basins and increased infiltration,	High
▪ Bed surface profile	▪ Runoff control and increased infiltration	Variable
Increasing soil infiltration rates		
▪ Organic matter for improving aggregation	▪ Improved soil aggregates and increased infiltration	High
▪ Conservation tillage	▪ Preserve soil aggregates and infiltration rates	High
▪ Mulches, crop residues	▪ Soil surface protection, higher infiltration reduced erosion	High
▪ Traffic control	▪ Decreased soil compaction and improved water penetration	Variable
▪ Chemicals for aggregates	▪ Preserve soil aggregates and infiltration rates conditions	High
Increasing the soil water storage capacity		
▪ Loosening tillage	▪ Increased soil porosity, and soil water transmission and retention	Variable
▪ Subsoiling for destroying natural or plough made hardpans	▪ Improved water transmission and storage, and deepening the soil depth exploitable by crop roots	High
▪ Deep tillage/profile modification in presence of clay horizons	▪ Increased water penetration and soil depth exploitable by roots	High
▪ Chemical and physical treatments of salt-affected soils	▪ Increased infiltration and available soil water	High
▪ Deep soil treatments	▪ Deeper roots and water storage volume	Variable
▪ Adding fine materials and hydrophilic chemicals to sandy/coarse soils	▪ Increase water retention in the soil profile	Economic limits
▪ Mixing fine and coarse horizons	▪ Increase water transmission and retention	Economic limits
▪ Asphalt barriers in sandy soils	▪ Decrease deep percolation	Limited
▪ Compacting sandy soils	▪ Slowing water penetration and controlling deep percolation	Variable
Control of acidity by liming, and salinity by gypsum application	More intensive and deep rooting, and improvement of aggregation	High

use of soil additives that improve water retention, the correction of soil salinity to improve soil water availability for the plants as well as the soil physical conditions, and the use of organic additives to favour soil aggregates. By favouring the quantity of water that can be redistributed through the soil profile, and the amount of water that infiltrates and is subtracted to runoff, these practices also contribute to control soil erosion.

• Increasing soil infiltration by combating the processes of soil crusting and soil sealing, including surface tillage methods, soil correctives and mulching for improving soil aggregates and aggregates stability. These techniques are common with soil conservation since they fight against the destruction of soil aggregates, which plays a main role in soil erosion.

• Controlling evaporation from the soil by using mulches to limit the amount of solar radiation available at the soil surface, and using tillage that limit the water fluxes to the evaporating surface.

• Runoff control through water harvesting. Differently from the above, runoff is not decreased but can be augmented in the area where it is produced, and is controlled to be infiltrated downstream where the crop is established. As described in Section of Chapter 6, water harvesting embraces a variety of techniques well proved in arid regions, including spate irrigation, water spreading and runoff farming.

• Runoff control in sloping areas by modifying the land form, thus decreasing the velocity of the surface runoff and increasing the time opportunity for water infiltration, thus to become available for crops use. These techniques are mostly known as soil conservation practices and include terraces, contour ridges, and strip cropping, which are in the origin of very beautiful landscapes in many regions of the world

5. Water Savings and Conservation in Irrigated Agriculture: Demand Management

5.1. General aspects

Demand management for irrigation includes practices and management decisions of multiple nature: agronomic, economic, and technical. Objectives concern a reduction of irrigation requirements, the adoption of practices leading to water savings in irrigation, both reducing the demand for water at the farm, and an increase in yields and income per unit of water used.

On farm management of water under scarcity can be summarised as follows:

• *Reduced water demand*

- Select low demand crop varieties / crop patterns

Table 3. *Soil management techniques for controlling evaporation and capturing runoff*

Soil management techniques	Benefits	Effectiveness
Control of soil evaporation		
▪ Crop residues and stones mulching	▪ Decrease energy available on soil surface for evaporation	Very high
▪ Surface tillage	▪ Control of upward water fluxes to the soil surface	High
Chemical surfactants	▪ Decrease capillary rise	Economic costs
Water harvesting (arid lands)		
▪ Micro-watersheds	▪ Runoff collection to be infiltrated in the cropped area	High
▪ Runoff farming	▪ Maximise runoff in collection areas to be infiltrated in the cropped area	High
▪ Water spreading	▪ Spate irrigation by diverting flood runoff	High
▪ Micro water-harvesting	▪ Planting in the furrow bottom to maximise rainfall infiltration	High
Runoff control in sloping areas		
▪ Terracing	▪ Reduce runoff and increase infiltration	Very High
▪ Contour ridges	▪ Runoff storage and increase infiltration	High
▪ Strip cropping	▪ Runoff retardation for infiltration	High

- Adopt deficit irrigation
• *Water saving / conservation*
- Improve irrigation systems uniformity and management
- Reuse water spills and runoff
- Surface mulch for controlling evaporation from soil
- Soil tillage for augmenting the soil water reserve
• *Higher yields per unit of water*
- Adopt best farming practices
- Avoid crop stress at critical periods
• *Higher farmer incomes*
- Farm for high quality products
- Select cash crops

Often, issues for irrigation demand management mainly refer to irrigation scheduling giving a minor role to the irrigation methods. However, a conjunctive approach is required. Irrigation scheduling is the farmers decision process relative to "when" to irrigate and "how much" water to apply to a crop. The irrigation method concerns "how" that desired water depth is applied to the field. The crop growth phase, its sensitivity to water stress, the climatic demand by the atmosphere, and the water availability in the soil determine when to apply an irrigation. The frequency of irrigation depends upon the irrigation method, i.e. on the depths of water which are typically associated with the on-farm irrigation system. Both the irrigation method and the irrigation scheduling are inter-related.

Irrigation scheduling requires knowledge about crop water requirements and yield responses to water, the constraints specific to each irrigation method and irrigation equipment, limitations relative to the water supply system, and financial and economic implications of the irrigation practice. To improve the irrigation method requires the consideration of the factors influencing the hydraulic processes, the water infiltration and the uniformity of water application to the entire field.

5.2. Water conservation and saving in surface irrigation

Several irrigation methods are used in practice. The main ones are basin irrigation, furrow irrigation and border irrigation. In traditional systems, the water control is carried out manually according to the ability of the irrigator, so it is difficult to control "how much" water is applied and over-irrigation often occurs. In modernised systems, fields are often precision levelled, and some form of control of discharge such as siphons, gated pipes, lay-flat tubes or gates, and some form of automation including surge flow valves, cablegation or automated canal gates are used. Thus, in these systems, it is possible to control "how much" water should be applied at a given irrigation.

In surface irrigation, the uniformity mainly depends upon the system variables such as unit inflow discharges, field length and slope, which can not be easily modified by the irrigator. He is in control of the management variable time of cut-off, but the latter depends also on other system variables, namely those determining the advance time. The application efficiency depends upon the same variables as uniformity, and upon the farm management variables time of cut-off and soil water deficit at time of irrigation. The farmer ability plays a major role in controlling the management variables but his capability to achieve higher performances is definitely limited by the system 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.

Improvements in surface irrigation systems that help to cope with water scarcity are in larger number and depend upon field conditions (Pereira et al., 2002a and b). They relate to changes in system variables to improve water advance conditions, increase uniformity of water distribution in the entire field, and control of deep percolation and runoff. They include land levelling, tools to control inflow discharges and volumes, farm hydraulic equipment for water distribution and automation, surge-flow, cablegation and cut-off systems, as well as automation. When water savings are required, improvements consist of irrigation with alternate furrows, adopting anticipated cut-off, and reuse of tailwater runoff.

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. Field evaluations may play a major role in the adoption of water saving irrigation by farmers because the respective management rules are based on the actual farm performances.

Improved design and modelling are also of great importance because these may lead to change the field and system characteristics to favour improved distribution uniformity. In fact design provides for the selection of the best combination of field sizes, slope, inflow discharges, and time of application to provide for controlled deep percolation and runoff, and for application of deficit irrigation.

5.3. Water conservation and saving in sprinkler irrigation systems

Main sprinkler systems are set systems, travelling guns, and continuous move laterals. The irrigation uniformity essentially depends on variables characterising the system, which are set at the design phase. Similarly, the efficiency depends upon the same system variables as uniformity, and upon the management variables concerning the duration and the frequency of the irrigation events. In general, the performance indicator having greater relation to enhanced management, to controlled water application and to higher productivity of the water is the distribution uniformity (DU), while efficiency often follows DU and largely depends upon the irrigation scheduling applied. The irrigator can do little to improve the uniformity of irrigation and is constrained by the system characteristics to improve the irrigation performances.

The improvement of sprinkler irrigation systems to cope with water scarcity includes a variety of measures (Pereira et al., 2002a and b) aiming at:

• providing for the conduits and laterals system to be able to produce adequate uniformity in pressure and discharge distribution within the operating set,

• adapting the system variables relative to the sprinklers to the soil infiltration and slope characteristics and wind conditions,

• making the system management able to cope with limited water availability.

The quality of design play a major role in making the systems able to be managed for water savings. 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.

5.4. Water saving and conservation with microirrigation systems

Microirrigation mainly include drip, micro-sprinkling, and sub-irrigation systems. Microirrigation uniformity, as for sprinkler systems, depends upon system variables, i.e., with exception of maintenance, the farmer can do very little to achieve good distribution uniformity. The application efficiency mainly depends upon the same system variables and upon the management variables related to the duration and frequency of the irrigation. Therefore, the farmer may improve the application efficiency when adopting appropriate irrigation schedules but performances are limited by the system constraints.

The quality of design and equipment are essential because they dictate the characteristics of the systems that determine the system performances. Design should be made for high performances, not for reduced water use. A well-designed system can be managed for water saving. Field evaluations also play an important role in advising farmers, creating information for design of new systems, for quality control of design and services, and for establishing water conservation and saving practices.

Improvements in micro-irrigation systems mainly concern:

• the achievement of high uniformities of pressures and discharges along the operating sets,

• the selection of drip and microspray emitters according to soil conditions, field slopes and crops grown,

• the adoption of system characteristics including automation and fertigation that make easier to adopt deficit irrigation.

5.5. Irrigation scheduling and deficit irrigation

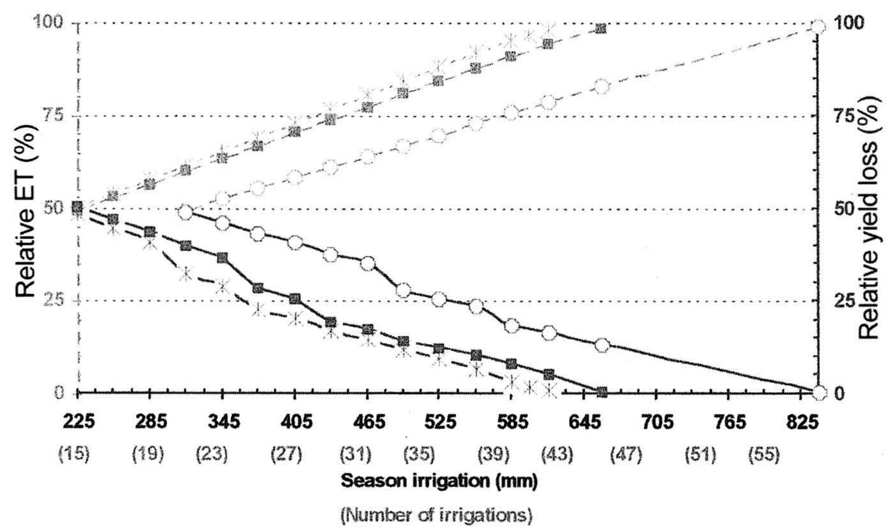
Research has provided a large variety of tools to support improved irrigation scheduling, i.e. the timeliness of irrigation and the adequateness of volumes applied. Irrigation scheduling tools include the observation of soil water content and or potential, of plant water status or related indicators, of meteorological variables relative to evapotranspiration, and the use of models and remote sensing. Many of these tools are still applicable in research only. Most of them require technical support by extension officers or technical advisers, and the expertise of the farmers. Therefore, large limitations occur for their use in the farmers' practice.

When surface irrigated areas are supplied from collective irrigation canal systems, farm irrigation scheduling depends upon the delivery schedule, e.g. rate, duration and frequency, which are dictated by the system operational policies. Discharge and duration impose constraints to the volume of application, and frequency determines the timing of irrigation. Surface irrigation delivery systems are often rigid and the time interval between successive deliveries is too long. Then, farmers apply all water that is made available and over-irrigation is often practised. Improving the on-farm irrigation systems should go together with the improvement of the delivery system to allow more flexibility in selecting the appropriate inflow rates and supply time.

Irrigation scheduling can only be applied when the farmers have control on the timing and duration of irrigation. Then, irrigation can be managed in relation to farmers' targets.

Deficit irrigation is an optimising strategy under which

Figure 1. *Relative evapotranspiration (---) and the relative yield loss (—) of the sugar beet crop to different deficit irrigation strategies in Vigia for average (—*—), high (—■—) and very high (—O—) demand conditions under center-pivot irrigation (Rodrigues et al., 2003)*



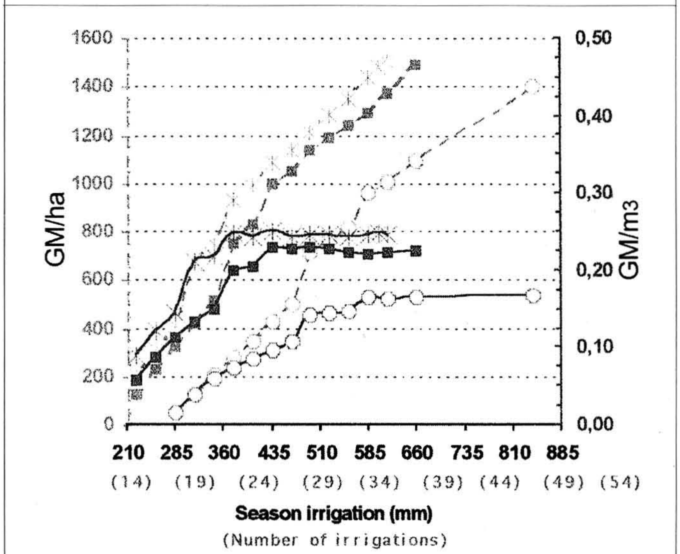
crops are deliberately allowed to sustain some degree of water deficit and yield reduction (English et al., 1990). The adoption of deficit irrigation implies appropriate knowledge of crop ET, of crop responses to water deficits, including the identification of critical crop growth periods, and of the economic impacts of yield reduction strategies.

Deficit irrigation implies the adoption of appropriate irrigation schedules, which are built upon validated irrigation scheduling simulation models or based on extensive field trials. 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 water productivity, which was defined before.

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 growth and yield sub-models to evaluate the yield impacts of water deficits.

An example for a study on the feasibility of deficit irrigation is provided in Fig. 1 and 2 for sugar-beet in southern Portugal. Fig. 1 shows how yield decreases when the net irrigation volume applied also decreases. Fig. 2 illustrates that the gross margins per unit surface steadily decrease with the irrigation volumes and that the gross margins per unit water applied are maintained or slightly increase until a minimum threshold of water applied and then sharply decrease. This result indicates that after such threshold is attained it is no more feasible to reduce irrigation.

Figure 2. *Gross margins per unit surface (---) and per unit volume of water applied (—) for alternative deficit irrigation strategies of sugar beet crop with center-pivot for average (—*—), high (—■—) and very high (—O—) climatic demand conditions (Rodrigues et al., 2003)*



6. Water Savings and Conservation in Irrigated Agriculture: Supply Management

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

When the improvement of farm irrigation systems was analysed in the perspective of demand management, it has been shown that the role of farmers is limited both by the farm system constraints and by the farmers' capabilities to be in control of the discharge rate, duration and frequency of irrigation. This last aspect is more evident when discussing deficit irrigation strategies. It may be said that adopting reduced demand strategies largely depends upon supply management.

Supply management may be considered under the perspective of enhancing reservoir and conveyance capacities to provide higher reliability and flexibility of deliveries required for improved demand management. However, supply management for irrigation also refers to the farm water conservation. Supply management includes:

- increased storage capacities, including large reservoirs with capacities for inter-annual regulation, and small reservoirs, namely for supplemental irrigation,
- improved irrigation conveyance and distribution systems, including compensating reservoirs and intermediate reservoirs for improving the flexibility of deliveries, and avoiding system water losses during periods of low demand,
- improved regulation and control, favouring deliveries to match demand,
- good maintenance of reser-

voir and conveyance system, which is a pre-condition for reliability of deliveries, and
- the development of new sources of water supplies to cope with extreme conditions of water scarcity, as is the case for droughts.

Supply management is also considered under the perspective of systems operation for delivery scheduling. The following aspects may be considered:
- 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 access to information, often comprising GIS, to support local or regional irrigation management programs,
- real time reservoir operation and management tools,
- decision support systems serving the reservoir operation and the water system management, and to help users to select water use options, including crop patterns, irrigation scheduling and irrigation systems,
- automation and remote control for regulation of irrigation reservoirs and conveyance and distribution systems, and
- planning for droughts to establish allocation and delivery policies, and operation rules.

The management of irrigation and multi-purpose supply systems for coping with water scarcity includes:
- use/reuse of low quality water, treated wastewater and saline water,
- conjunctive use of surface water, groundwater and non conventional waters,
- improved reservoirs operation mainly adopting
  - information systems, including remote sensing, GIS, and operation models
  - hydrological forecasting and drought watch systems,
  - optimisation, risk, and decision models
- improved management of conveyance and distribution systems through
  - information systems as a base source for management,
  - canal lining,
  - improved regulation and control of canal systems for higher flexibility in deliveries and high service performance,
  - low pressure pipe distributors for avoiding spills and leakage, and easy delivery scheduling,
  - change from supply oriented to demand oriented delivery schedules,
  - intermediate storage (in canal, reservoirs, farm ponds)
- involve farmers in delivery scheduling decisions
- use incentive water prices to induce farmers to save water and to irrigate by night
- maintenance and management
  - effective systems maintenance to avoid spills and leaks
  - water metering (flow depth and discharge)
  - monitoring system performances (physical, environmental and service)
  - personnel training
  - farmers' information

The effective combination of demand and supply management requires however appropriate information, training and farmers' participation. On the one hand, there is the need for training and assistance to farmers to improve on-farm irrigation systems and scheduling, and to implement water conservation and demand reducing practices. On the other hand, measures have to be adopted to implement effective farmers' participation in decisions relative to supply management. This includes the information to farmers on characteristics and limitations of the water supply systems. Finally, the training of irrigation operation agents and irrigation extension officers is a must.

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